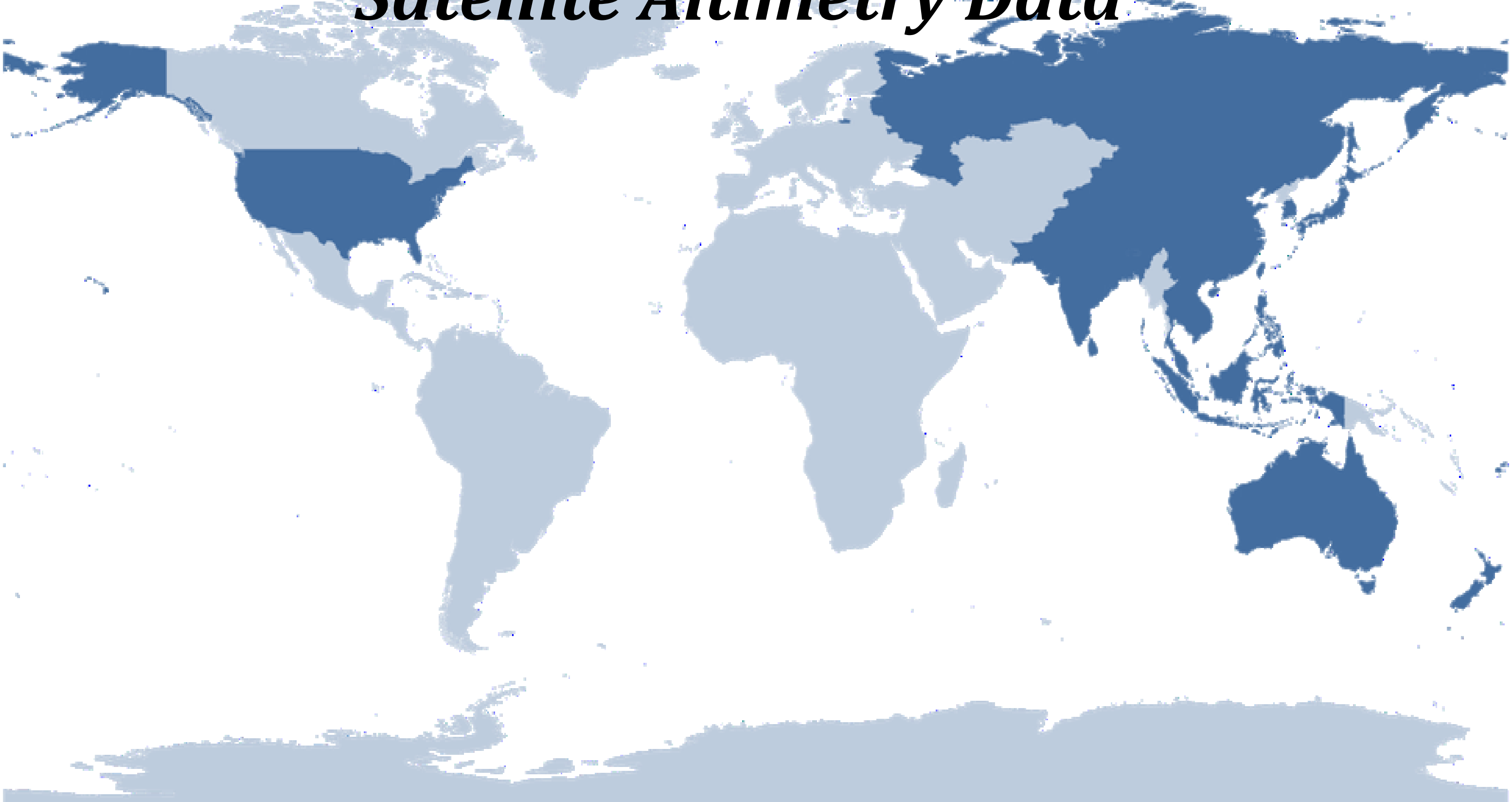
FINAL REPORT for APN PROJECT

Project Reference Number: ARCP2011-21NSY-Manurung

"Reconstruction of Sea Level Change in Southeast Asia (RESELECASEA) Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data"



The following collaborators worked on this project:

Dr. Parluhutan Manurung, Geospatial Information Agency (BIG), Indonesia, parluhutan@bakosurtanal.go.id

Prof. Robert R Leben, University of Colorado, USA, leben@colorado.edu

Dr. Stefano VIgnudelli, Consiglio Nazionale delle Ricerche in Pisa, Italy, vignudelli@pi.ibf.cnr.it

Dr. Jonson Lumban Gaol, Bogor Agricultural University, Indonesia, jonson_lumbangaol@yahoo.com

Dr. Benjamin Hamlington, University of Colorado, USA, bhamlington@gmail.com

Dr. Tong Phuoc Hoang Son , Nhatrang Oceanography Institute, Vietnam, tongphuochoangson@gmail.com

“Reconstruction of Sea Level Change in Southeast Asia (RESELECASEA) Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data”

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Final Report submitted to APN

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OVERVIEW OF PROJECT WORK AND OUTCOMES

Non-technical summary

Low lying and densely populated coastal areas with thousands of small islands spreading across South East Asia are highly prone to sea level rise caused by global warming. Accurate sea level change maps in South East Asia are of great importance to scientists and decision makers in the region interested in past and present sea level change, and the answer to the question of what likely projected sea level rise will be in the future. Improving the near-coast satellite altimetry data processing will extend the coastal sea level record back in time and allow accurate mapping of sea level change in the region as well as supporting various potential applications of sea level data in the coastal zone.

Objectives

The main objectives of the project were:

1. To provide numerical reconstruction and maps of sea level change in the South East Asia Region based on Cyclo Stationary Orthogonal Function (CSEOF).
2. To provide in house software for sea level reconstruction maps based on CSEOF
3. To explore know-how about coastal satellite altimetry processing and its applications.
4. To provide draft of papers to be published in national and refereed international journals.
5. To provide reconstructed sea level change maps and documents which are accessible to government, public and research communities.
6. To conduct trainings and workshops with participants consisting of scientists, students and government representatives.

Amount received and number years supported

The Grant awarded to this project was US$ 45,000 for one year basis.

Work Plan

Maps of sea level change in Southeast Asia Seas were reconstructed using CSEOF by fitting the satellite-derived sea level variability to coastal tide gauge observations. However, further efforts are still necessary to improve the accuracy of satellite in coastal area and shallow waters. The project demonstrated multi-disciplinary collaboration amongst scientists of various institutions as well as universities and government institutions in Southeast Asia by conducting two training courses and workshops. Software tools for basic satellite altimetry data processing and sea level reconstruction were distributed to the participants during the training workshops are also accessible via the RESELECASEA homepage, which is set up as a communication tool for the community interested in sea level information. With funding coming from this project, enhanced capacity at individual and institutional level was achieved through the exchange of ideas, transfer of technology, and upgrading of knowledge and skills.

Activity undertaken

Year	Date	Major Activities	Location
2011	17th Oct	A preliminary meeting to discuss training material, workshop preparation and sharing tasks. The Meeting was attended by Dr. Parluhutan Manurung, Prof. Robert Leben and Dr Stefano Vignudelli held during The 5th Coastal Altimetry workshop took place on 16-18 October 2011.	San Diego, USA
	16th Nov	1st Workshop on Coastal Altimetry	Bogor, Indonesia
	17-18 Nov	1st Training on Coastal Altimetry and Reconstruction of Sea Level Change	Bogor, Indonesia
	19 Nov	Kick off Meeting	Bogor, Indonesia
	20-23 Nov	Site visit to tidegauge for calibration	Benoa Port, Bali
2012	15th March	Presentation of APN Secretariate Meeting	Jakarta
	12-13 Nov	Training	Bogor, Indonesia
	14 Nov	Workshop	Bogor, Indonesia
	15-17 Nov	Coordination Meeting for writing the Project final report to APN	Jogyakarta, Indonesia

Results

1. Reconstruction maps of sea level change of South East Asian Seas
2. Publications: 7 papers published during the Project cooperation, 1 paper and 1 poster presented in two international seminars.
3. Draft of papers to be published: 3 papers as shown in Technical Report, Appendix 1, and Appendix 3.
4. Two training courses of which each was attended by 30 participants consisting of scientists and students.
5. Two workshops of which each was attended by over 80 participants consisting of scientists, students and policy makers
6. Workshops and Training materials and number of scientists trained on reconstruction of sea level maps and coastal altimetry data processing, (Appendix 4, 5, 8, 11 and 12)
7. A website for exchange of ideas and communication for scientists interested in sea level knowledge, (Appendix 6) and media coverage to increase public awareness on global change, (Appendix 9).
8. A list of recommendations to provide a future scientific roadmap to stakeholders in Indonesia, (Appendix 5)

Relevance to the APN Goals, Science Agenda and to Policy Processes

The project is in line with APN Science and Policy Agendas as it encompasses the reconstruction of sea level changes caused by global warming in the South East Asia. Reconstructed sea level, used to estimate the past to present sea level changes, is of great importance in forming strategy and policy for mitigation and adaptation to global warming. The project is carried out through collaboration and human capacity building amongst scientists that is relevant to APN Science and Policy Agendas. It contributes specifically to APN Goal 1, supporting regional cooperation, and Goal 3, improving scientific capabilities of Asian nations.

Self evaluation

The project was initiated aiming at two main scientific goals namely i) to explore knowledge on reconstruction map of sea level change in SE Asia Seas and ii) to explore knowledge on using altimetry data in the coastal region. To understand the past, present and future impact of global warming on sea level, we need to have capacity in sea level reconstruction techniques. We found that CSEOF could be incorporated into global sea level reconstructions and provide information on the regional scale . Regional coastal tide gauge data are being used to explore the possibility using of altimetry data in the coastal region to validate and possibly improving sea level reconstructions to provide better understanding of sea level in the SE Asia Region. We started to explore the idea in the first training and workshop held in November 2011. Participants were not only the research team members, but we also invited young students and researchers who are interested in learning about sea level reconstruction and altimetry data processing. We realized that most participants were novices in this area. However, this event increased interest in this area and it followed up by interaction by email and our skills are improving steadily. This can be seen in the progress of exchange of idea gathered in the second training and workshop held in a year after, in November 2012. We also have had the opportunity to collaborate on journal publications and posters. These developments demonstrate that our capacity is greatly improving and this is a fundamental step to develop better sea level change information in the Southeast Asia Region and to encourage the scientific community to explore the complexity of satellite altimetry data processing in the coastal region.

Potential for further work

Our encouraging results on reconstruction of sea level change maps in the Southeast Asia Seas are based on the tide gauge data archive from the year 1950 to 2010. The reconstruction model could be greatly enhanced if the reconstruction time period could be extended back to the year 1900 by using other ocean data, such as sea surface temperature, in the sea level reconstruction in addition to tide gauge data currently used. The reconstructed sea level change map needs to be further validated using local data; however, as the data archive in the region is relatively sparse and short, we need to explore other alternatives such as the use of along track altimetry. We understand that we still need to improve our results on retracking satellite altimetry in our region and we expect that we could further collaborate with satellite altimeter data providers, such as AVISO and PO.DAAC, to help us improve coastal altimetry in our region.

Publications

1. **Published Papers during the collaborations**

   1. Leben, R. R., Hamlington, B. D., Haines, B. J., 2012: SEASAT and GEOSAT revisited: using sea level measurements to improve satellite altimeter orbits, Jour. of Astro. Sci., 58:3.
   2. Hamlington, B. D., R. R. Leben, R. S. Nerem, K.-Y. Kim, 2011: The Effect of Signal-to-Noise Ratio on the Study of Sea Level Trends. J. Climate, 24, 1396–1408. doi: 10.1175/2010JCLI3531.1.
   3. Hamlington, B. D., R. R. Leben, R. S. Nerem, W. Han, and K.-Y. Kim, 2011: Reconstructing sea level using cyclostationary empirical orthogonal functions, J. Geophys. Res., 116, C12015, doi:10.1029/2011JC007529.
   4. Hamlington, B. D., Leben, R. R., Kim, K.-Y., 2012: Improving Sea Level Reconstructions Using Non-Sea Level Measurements, J. Geophys. Res., 117, C10025, doi:10.1029/2012JC008277.
   5. Liu Y., Weisberg R. H., Vignudelli S., Roblou L., Merz C. R., 2012: Comparison of the X-TRACK Altimetry Estimated Currents with Moored ADCP and HF radar Observations on the

West Florida Shelf, in *Special Issue "COSPAR Symposium"*, *Journal of Advances in Space Research*, 50 (8), 1085-1098, doi:10.1016/j.asr.2011.09.012.
6. Scozzari A., Gómez-Enri J., Vignudelli S., Soldovieri F., 2012: Understanding target-like signals in coastal altimetry: experimentation of a tomographic imaging technique, *Geophysical Research Letters*, 39, L02602, vol. 239, doi:10.1029/2011GL050237.
7. Cipollini P., Vignudelli S., Benveniste J., 2012: Coastal Altimetry Benefits from New CryoSat-2 Synthetic Aperture Measurements, Eos Trans. AGU, (accepted).

2. Papers and Posters Presented in International Seminars

1. Lumban Gaol, J., Manurung, P., Nababan, B., Pasaribu, B.P., Manurung, D., Aninda, Arhatini E.A., (2012). Sea Level Rise Derived Satellite Altimetry and Tide Gauge Data and Its Impact on the Coastal Zone of Indonesia. Pan Oceanic Remote Sensing Conference (PORSEC) 2012. Kochi Kerala
2. Manurung, P, et al (2011). Reconstruction of Sea Level Change in South East Asia (RESELECASEA) Using Tide Gauge and Satellite Altimetry Data. Presented in the Poster Session of Coastal Altimetry 5 Workshop, San Diego.

3. Draft of papers to be published in international journals

1. SEA LEVEL TRENDS IN SOUTH EAST ASIAN SEAS, written by R. R. Leben, M. Strassburg, B. D. Hamlington, P. Manurung, J. Lumban Gaol, B. Nababan, S. Vignudelli, and K.-Y. Kim.
2. AN INITIAL RETRACKING OF SATELLITE ALTIMETRY IN INDONESIA COASTAL WATER, written by P. Manurung, Dewangga R., Danu A, Meilani P., S. Vignudelli, J. Lumban Gaol, R. Leben.
3. VARIABILITY OF SATELLITE-DERIVED THE SEA SURFACE HEIGHT AND ITS RELATIONSHIP ON BIGEYE TUNA (THUNNUS OBESUS) CATCH IN EASTERN INDIAN OCEAN OFF JAVA, written by J. Lumban Gaol, B. Nababan, P. Manurung, K.H. Amri

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1. Church, J.A, White N.J., Coleman R., Lambeck K., Mitrovica J.X., (2004). "Estimates of the regional distribution of sea level rise over the 1950-2000 period," J. Climate, 17(13), 2004, pp 2609-2625
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Acknowledgments

Asia-Pacific Network for Global Change Research (APN), is the major funding source of the RESELECASEA Project, without whose financial support our activities would not have been possible. We are also grateful for the support provided by the institutions supporting research team members. A special thanks for Geospatial Information Agency of Indonesia (BIG)/BAKOSURTANAL to fully support two workshops, travelling to attend an important workshop related to satellite data processing and exploitation of tide gauge data archive and facilities. We are grateful for the generosity of University of Colorado to allow us to use the SE Asia Seas sea level reconstructions and generously provide travel support for Prof. Robert R. Leben to participate in the Second Workshop held in Bogor Indonesia. We thank CNR-Italy for providing travel support for Dr. Stefano Vignudelli to attend the first workshop in Indonesia and for use of their facilities for altimetric data processing. Our thanks also go to Bogor Agricultural University (IPB) for their support of students doing research on altimetry data for fisheries applications. Finally, we would also like to thank The Na Thrang Oceanographic Institution Vietnam for their participation in the research.

TECHNICAL REPORT

Preface

The RESELECASEA project reconstructed sea level change in South East Asian Seas by combining the global tide gauge data record, which spans many years but is sparse in spatial distribution, with the modern satellite altimetry record, which is just short of 20 years long but has essentially global coverage. The results show that the sea level trends in the region are some of the highest observed globally during the altimetric record, but the trends fluctuate on multi-decadal time scales due to wind forcing. Reconstructed sea level maps could be further validated using local tide gauge and along track altimetry data. Efforts have been made to explore use of coastal altimetry by conducting two workshops and training sessions and assisting the local community to build an autonomous capacity for development and processing of sea level information.

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1.0 Introduction

Since 1993 satellite altimetry has provided accurate measurements of sea surface height (SSH) with near-global coverage. These measurements have led to the first definitive estimates of GMSL rise and have improved our understanding of how sea level is changing regionally at decadal timescales. The relatively short satellite record, however, does little to answer the question of how the current state of the ocean compares to previous states. Tide gauges, on the other hand, have measured sea level over the last 200 years, with some records extending back to 1807. While providing long records, the spatial resolution of tide gauges is poor, making studies of GMSL and the large-scale patterns of low-frequency ocean variability difficult. Reconstruction of sea level overcomes these respective shortcomings of tide gauge and satellite altimetry records by combining the shorter but essentially complete global coverage offered by satellite altimetry with the longer but sparsely distributed tide gauge dataset. The work presented here focuses on sea level trends in the SEAS region as quantified by the satellite altimetry and sea level reconstructions. Funding from the Asia Pacific Network (APN) for Global Change Research of the project "Reconstruction of Sea Level Change in Southeast Asia (RESELECASEA) Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data – ARCP2011-21NSY-Manarung" motivated this focus on Southeast Asia.

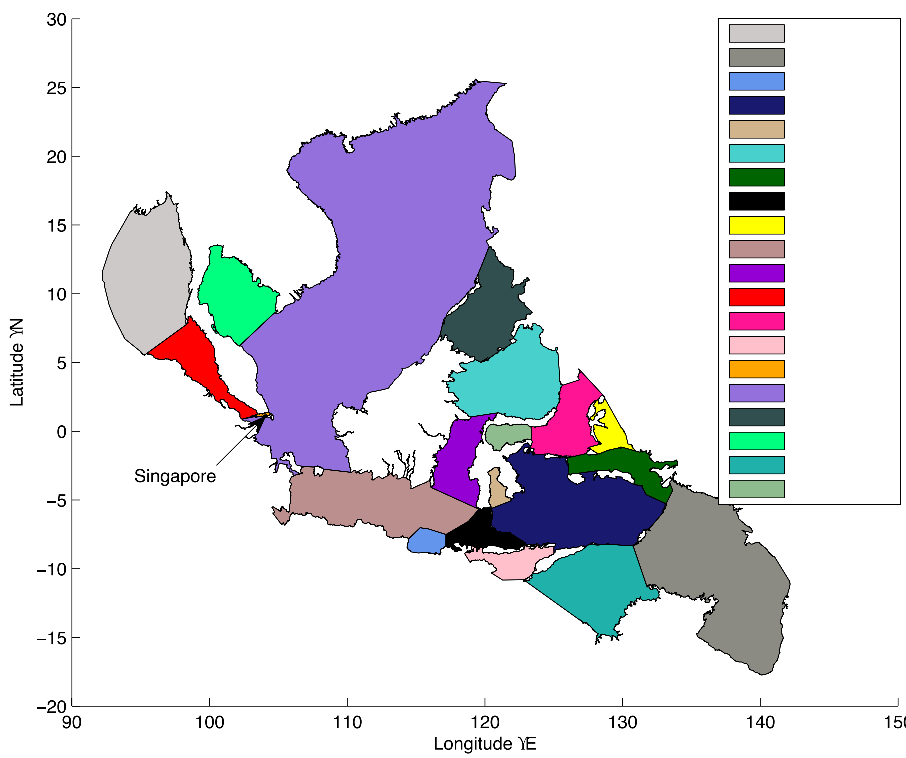

Figure 1. The 20 bodies of water (seas, straits, and gulfs) defined in the *Limits of the Ocean and Seas* (IHO,1953) for the SEAS region.

The SEAS region spans the largest archipelago in the global ocean and is comprised of a total of 20 seas according to the Limits of the Ocean and Seas published by the International

Hydrographic Organization (IHO) in 1953 (IHO, 1953). Figure 1 shows the regional seas, straits, and gulfs as defined by the IHO and delineated by a high-resolution coastline data set. The region has many low-lying and densely populated coastal areas including large urban and rural river deltas and thousands of small-inhabited islands. The Indonesian archipelago alone consists of 17,508 islands (6,000 inhabited) and encompasses the only tropical interoceanic through flow in the global ocean, providing a complex oceanic pathway connecting the Pacific and Indian Oceans. The Indonesian throughflow, and thus sea level, is driven primarily by free equatorial Kelvin and Rossby waves (Figure 2) originating along the Indian and Pacific equatorial waveguides (Wijffels and Meyers, 2004). The SEAS region is also one of the most biodiverse oceanographic regions on the planet. Southeast Asia's coral reefs have the highest degree of biodiversity of all of the world's coral reefs and it is estimated that only 10 percent of the marine species associated with coral reefs have been identified and described (Reaka-Kudia, 1997). As a result this region is increasingly impacted by sea level rise and a warming climate.

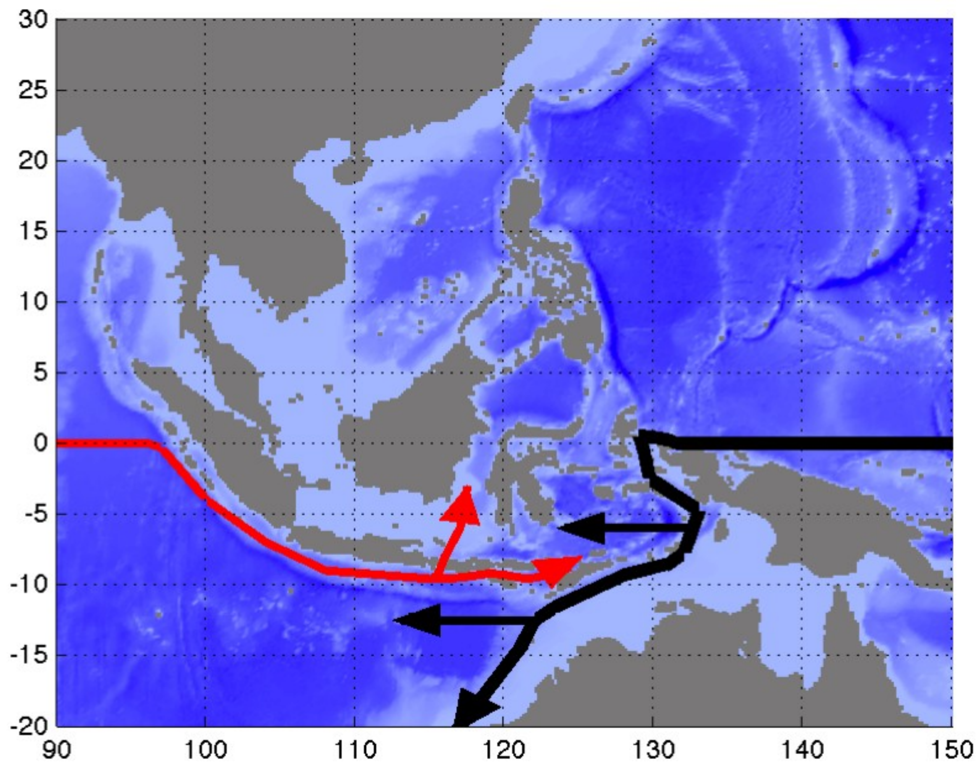

Figure 2. Schematic of remotely forced wave pathways into the Indonesian throughflow region (after Wijffels and Meyers, 2004). Red lines show the waveguide from the equatorial Indian Ocean, with energy spreading into the internal seas through both Lombok and Ombai Straits (red arrows). Black lines show the pathways for equatorial Pacific wind energy traveling down the Papuan/Australian shelf break and radiating westward- propagating Rossby Waves into the Banda Sea and South Indian Ocean (black arrows).

2.0 Methodology

Satellite Altimetry: The satellite altimeter dataset used in this study was produced and distributed by the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO;

http://www.aviso.oceanobs.com/) as part of the Ssalto ground-processing segment. The data set has quarter-degree resolution and was created from measurements spanning 1992 through 2009 using the following satellites: TOPEX/Poseidon, ERS-1&2, Geosat Follow-On, Envisat, Jason-1, and OSTM. These sea level measurements were updated and reprocessed by applying homogeneous corrections and inter-calibrations and referenced to a consistent mean. Then, the along-track data were gridded through a global space-time objective mapping technique. These data are used as a baseline for comparison as well as in four of the five sea level reconstructions used in this study.

Tide Gauge Data: Each reconstruction uses tide gauge data from the Permanent Service for Mean Sea Level (PSMSL; http://www.psmsl.org). PSMSL supplies a wide range of tide gauge data, but availability depends highly on the region and timeframe in question. Each reconstruction uses different tide gauge editing and selection criteria depending on time-series length, data gaps, area weighting, etc. These will not be discussed in this report but can be found in the respective references for each of the reconstructions.

Sea Level Reconstruction Methods: Sea level reconstructions are created by decomposing the training data into basis functions to explain the original variance, in this case satellite data and/or ocean model data. These basis functions are then interpolated back in time using in-situ measurements. Sea level measurements from tide gauges were used for the four univariate reconstructions. For the bivariate reconstruction, both sea level measurements from tide gauges and ship-board measurements of sea surface temperature measurements were used.

The reconstructions compared here use two basis function decomposition methods: empirical orthogonal functions (EOFs) and cyclostationary empirical orthogonal functions (CSEOFs). Both methods decompose the training data set into loading vectors (LVs) and principal component time series (PCTS) for each individual mode. CSEOFs differ from EOFs, however, in that they include a time dependence in the LVs, allowing extraction of non-stationary cyclostationary signals. See Kim et al. (1996) or Kim and Wu (1999) for more details. A selected number of modes are selected, which explain a subset of variance in the original training dataset, and are interpolated back in time to determine the PCTS to create the reconstructed sea level dataset. The five different sea level reconstructions used in this analysis vary based on the training data and reconstruction method used. A summary of basic information concerning each reconstruction is given in Table 1. More details on some of the reconstruction are given in the following sections. If more information is desired about any reconstruction, please refer to the corresponding references.

Hamlington et al. (2012) Bivariate Reconstruction (HLK/BV): In addition to AVISO and PSMSL data, HLK/BV uses sea surface temperature (SST) to create a bivariate reconstruction.

The SST training data are Optimal Interpolation SST (OISST; http://www.esrl.noaa.gov/psd/data/) data from NOAA, which are a combination of *in situ* and satellite measurements, as well as simulated SST values near sea ice. The historical *in situ* SST data come from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; http://icoads.noaa.gov/), averaged to a 2°x2° grid and known as superobservations (Smith et al., 1996).

To utilize SST measurements for an SSH reconstruction, basis functions of the SST training data are computed using CSEOFs. These basis functions are then transformed to have the same principal component time series as the SSH basis functions. The transformed SST basis functions and the SSH basis functions are then interpolated with the respective in-situ measurements to form a bivariate reconstruction. See Hamlington et al. (2012) for more details.

Table 1. Summary information on sea level reconstructions.

Reference	Abbreviation	Basis Function Method	Training Data	Observation Data	Training Data Time Period	Number of Modes	Percent of Variance	Reconstructed Time Period
Church et al. (2004); Church and White (2006)	*CW*	EOFs	Custom 1° by 1° monthly SSHA maps derived from TOPEX/ Poseidon, Jason-1 and OSTM (Jason-2) 10-day repeat altimetry using a 300 km Gaussian filter	Monthly sea level observations from 426 PSMSL tide gauge stations	1993 through 2009	20	84% of the non-annual signal	1950 through 2009
Hamlington, Leben, and Kim (2012)	*HLK/TG*	CSEOFs	AVISO weekly SSHA subsampled to ½° by ½°	Monthly sea level from 377 PSMSL tide gauge stations upsampled to weekly observations	1993 through 2009	11	80% of the non-annual signal	1900 through 2009
Hamlington, Leben, and Kim (2012)	*HLK/BV*	CSEOFs	•AVISO weekly SSHA subsampled to ½° by ½° •NOAA OISST weekly 1° by 1° SST	•Monthly sea level from 377 PSMSL tide gauge stations •Monthly SST ICOADS 2° by 2° observations	1993 through 2009	11	80% of the non-annual signal	1900 through 2009
Meyssignac et al. (2011)	*M/Alt*	EOFs	Annual Averaged AVISO	Annual averaged sea level observations from 91 PSMSL tide gauge stations	1993 through 2009	15	~ 88%	1950 through 2009
Meyssignac et al. (2011)	*M/Mean*	EOFs	•Annual Averaged AVISO •SODA 2.0 •Drakkar/NEMO model	Annual averaged sea level observations from 91 PSMSL tide gauge stations	1958 through 2007	15	??	1950 through 2009

Church and White (2011) Reconstruction (CW): CW utilizes a custom satellite altimetry training dataset, merging and filtering data from 3 different satellites, as described in Church et al. (2004).

Meyssignac et al. (2011) Mean Reconstruction (M/Mean): Meyssignac et al. (2011) created a mean sea level reconstruction dataset by averaged a satellite altimetry reconstruction with two model data reconstructions made using the SODA 2.0 (Carton and Giese, 2008) and the Drakkar/NEMO (Dussin et al., 2009) ocean models.

Estimating Sea Level Trends: Prior to any comparison, each reconstruction was annually averaged for consistency. Linear trends were computed over a variety of time spans and the uncertainty of each trends was found using standard error estimates for the trend term determined from the least squares linear regression.

SEAS Region Definition and Analysis: For the SEAS regional analyses, the region was subdivided into 20 separate bodies of water defined according to the *Limits of the Oceans and Seas* (1953). For each dataset, all points within a given boundary were averaged to determine an areal averaged mean time series for each body of water. If no points were present in a dataset, the nearest point was used. Linear trends were found after the calculation of subregion averages.

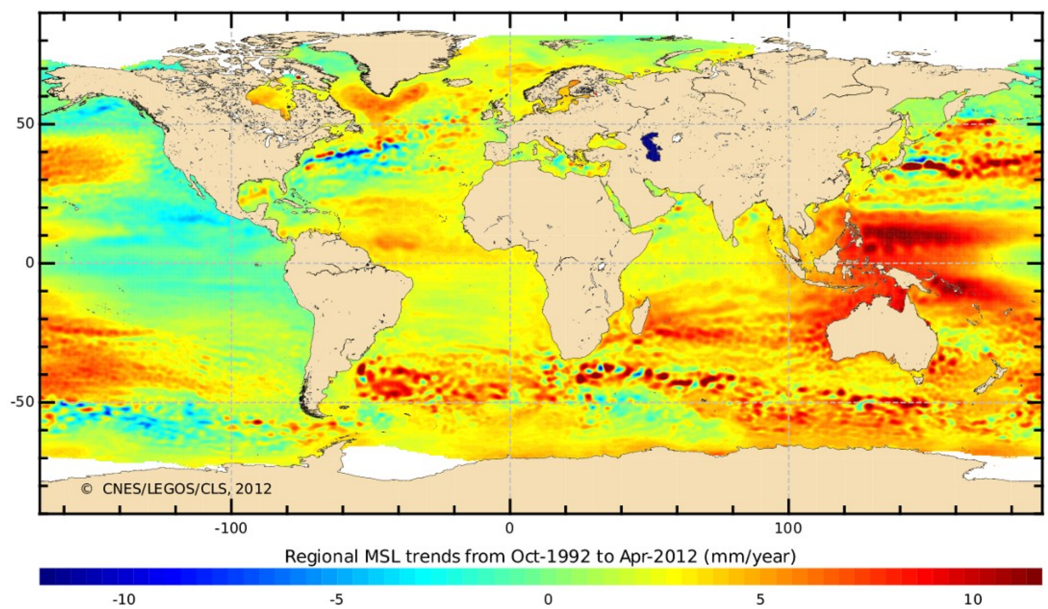

Figure 3. Regional sea level trends computed from October 1992 to April 2012 using AVISO SSH data.
http://www.aviso.oceanobs.com/fileadmin/images/news/indic/msl/MSL_Map_MERGED_Global_IB_RWT_NoGIA_Adjust.png

3.0 Results & Discussion

Sea level trends in the SEAS region are some of the largest observed in the modern satellite altimeter record (Figure 3). Regional sea level trends over the 17-year satellite altimeter record

1993 through 2009 are shown in Figure 4 for the AVISO data set and each of the sea level reconstructions during the training data set time period. Reconstructed sea level average trends in the SEAS agree with the AVISO values to within the estimated error.

To highlight the trend variability at the time scales observed over the current altimetric record we performed the following analysis:

1. Averaged all reconstructed data sets to form annual averages over the 1950 through 2009 record**.**
2. Calculated 17-year linear trends from the annual averaged data sets to produce 44 17-year trend maps from 1958 through 2001.
3. Performed a lagged correlation analysis (present versus past) of the 17-year trend time series for each data set.

A sample of the lagged correlation analysis is shown for the HLK/BV reconstruction in Figure 6. There are roughly three extrema in the 17-year trend variability of the global sea level reconstructions associated with independent 17-year time periods in the 60-year record: 1959-1975 – 17-year trend centered on 1967; 1976-1992 – 17-year trend centered on 1984; and 1993-2009 – 17-year trend centered on 2001. The 1959-1975 time period was correlated with 1993-2009 record, showing strong regional sea level trends in the western Pacific like those observed during the satellite record. On the other hand, anti-correlation is found between the 1976-1992 and 1993-2009 17-year trends, with the 1976-1992 time period exhibiting much smaller sea level trends in the western Pacific than those observed during the satellite record.

What is driving these changes in the western Pacific sea level trends? Merrifield et al. (2012) showed that, when detrended by GMSL, the western Pacific sea level is correlated with the low-frequency variability of the Pacific Decadal Oscillation (PDO) and the Southern Oscillation Index (SOI). This sea level signal is driven by anomalous decadal wind variability over the equatorial Pacific and propagates along the Rossby waveguide through the SEAS archipelago reaching as far south as Fremantle on the western Australian coast. Figure 6 shows the impact of the Pacific wind forcing induced sea level variability on the SEAS sea level trends determined from the bivariate reconstruction for each of the independent 17-year time periods. Figures 7, 8 and 9 show SEAS averaged sea level trends, error estimates, and SEAS averaged maps for each of the reconstructions over the two 17-year time periods, 1959-1975 and 1976-1992, and the 60-year time periods, 1950-2009, respectively.

4.0 Conclusions

1. Our initial comparisons of sea level trends show good agreement between global sea level reconstructions in areas and times of larger signal to noise associated with strong decadal sea level variability forced by low frequency wind forcing.
2. SEAS regions along the deepwater Rossby waveguide connecting the Pacific and Indian Oceans are most affected by this variability.
3. The good news for the SEAS region is the likelihood that recent strong sea level trends observed during the altimetry record will abate as trade winds fluctuate on decadal and multi-decadal time scales.

4. SEAS regional sea level trends during the 2010s and 2020s, thus, are likely to be less than the GMSL trend, similar to smaller sea level trends observed during in the 1976 through 1992 time period relative to GMSL.
5. Nevertheless, long-term sea level trends in the SEAS regions will continue to be affected by GMSL rise occurring now and in the future.
6. Sea level reconstruction techniques provide a useful tool for understanding sea level changes in the past, present, and future.

5.0 Future Directions

1. Recontructed map of Local sea level change as improvement of those global and regional
2. Validating SEAS Recontrcution map with tidegauge, temperature and altimeter derived sea level data
3. Retracking of satellite altimeter for more sea level data along the track.

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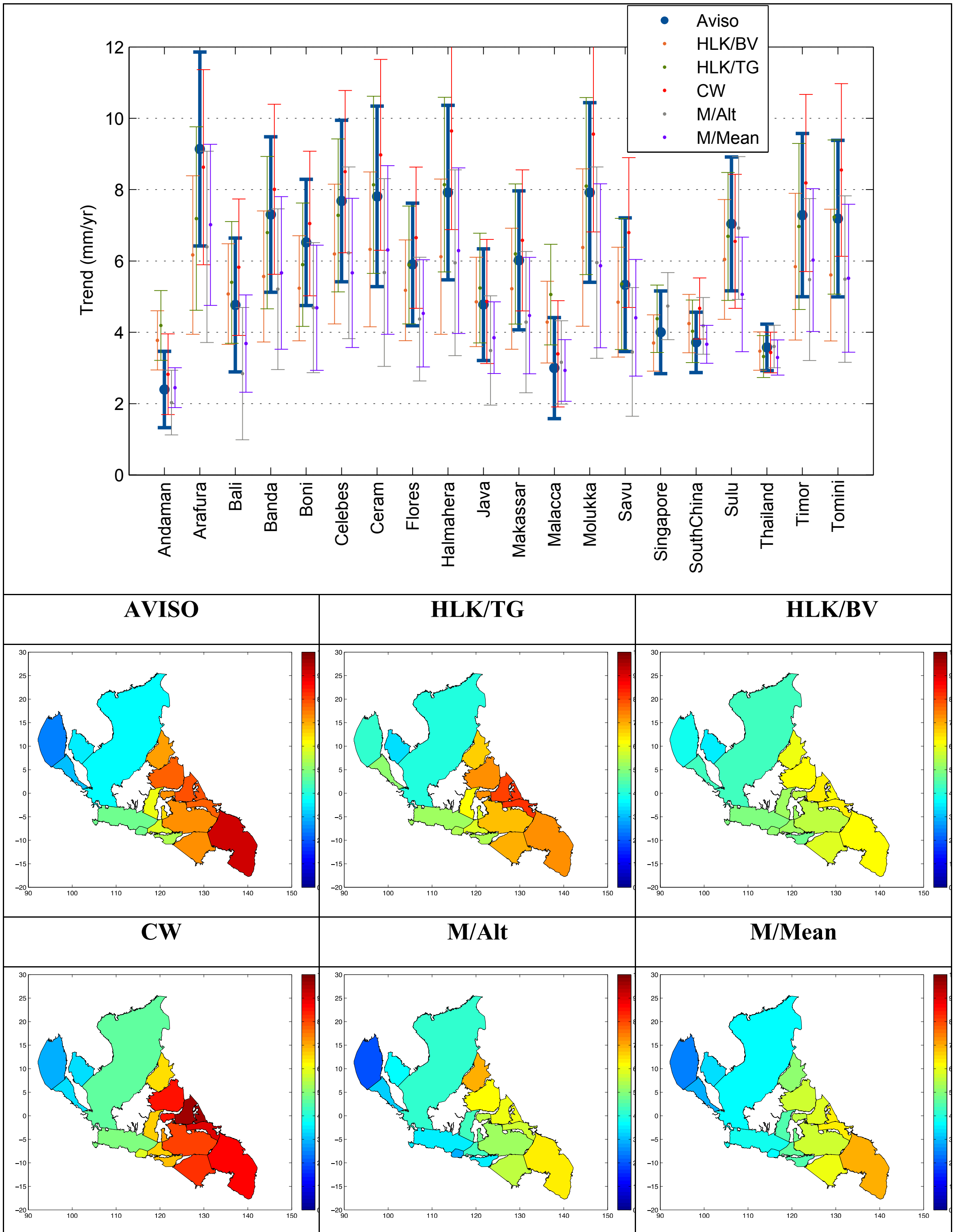


Figure 4. SEAS average sea level trends over the 17-year satellite altimeter record from 1993-2009 shown plotted as trend values with standard (upper plot) and as color maps (bottom panels) for AVISO and each of the reconstructions. Reconstructed average trends agree with the AVISO values (shown in bold) to within the estimated error.

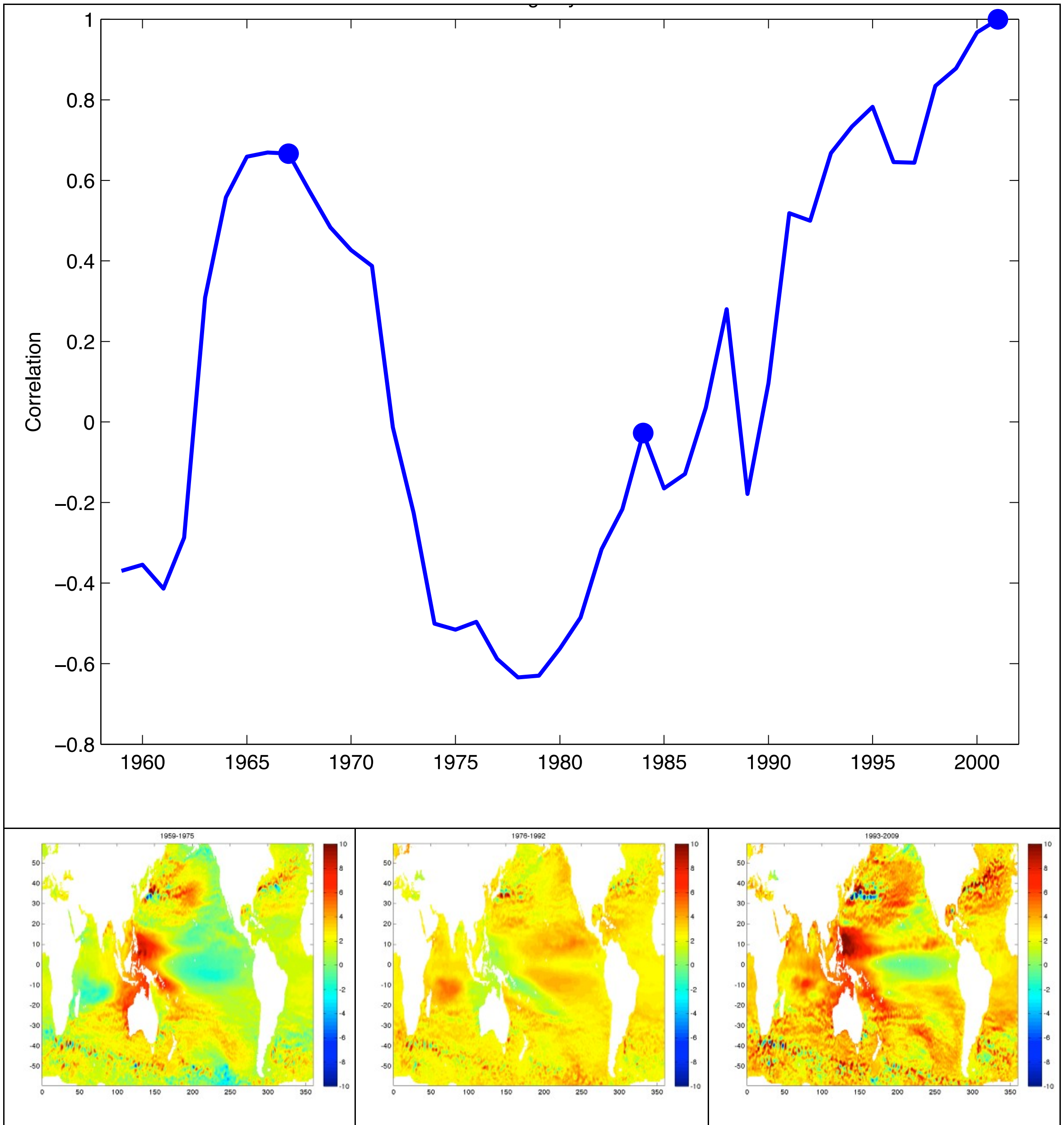


Figure 5. Lagged correlation coefficient (shown as the blue line in the upper plot) of the historical 17-year regional linear trend maps with the linear trend map from the satellite altimeter time period 1992-2009 centered on 2001 (leftmost blue dot). The bottom plots show the 17-year sea level trend maps in mm/year for the 1959-1976 (left), 1977-1992 (center), and 1992-2009 (right) time periods. The blue dots shown on the upper plot are the center points of the three 17-year windows.

Regional Sea Level Trends	SEAS Averaged Sea Level Trends

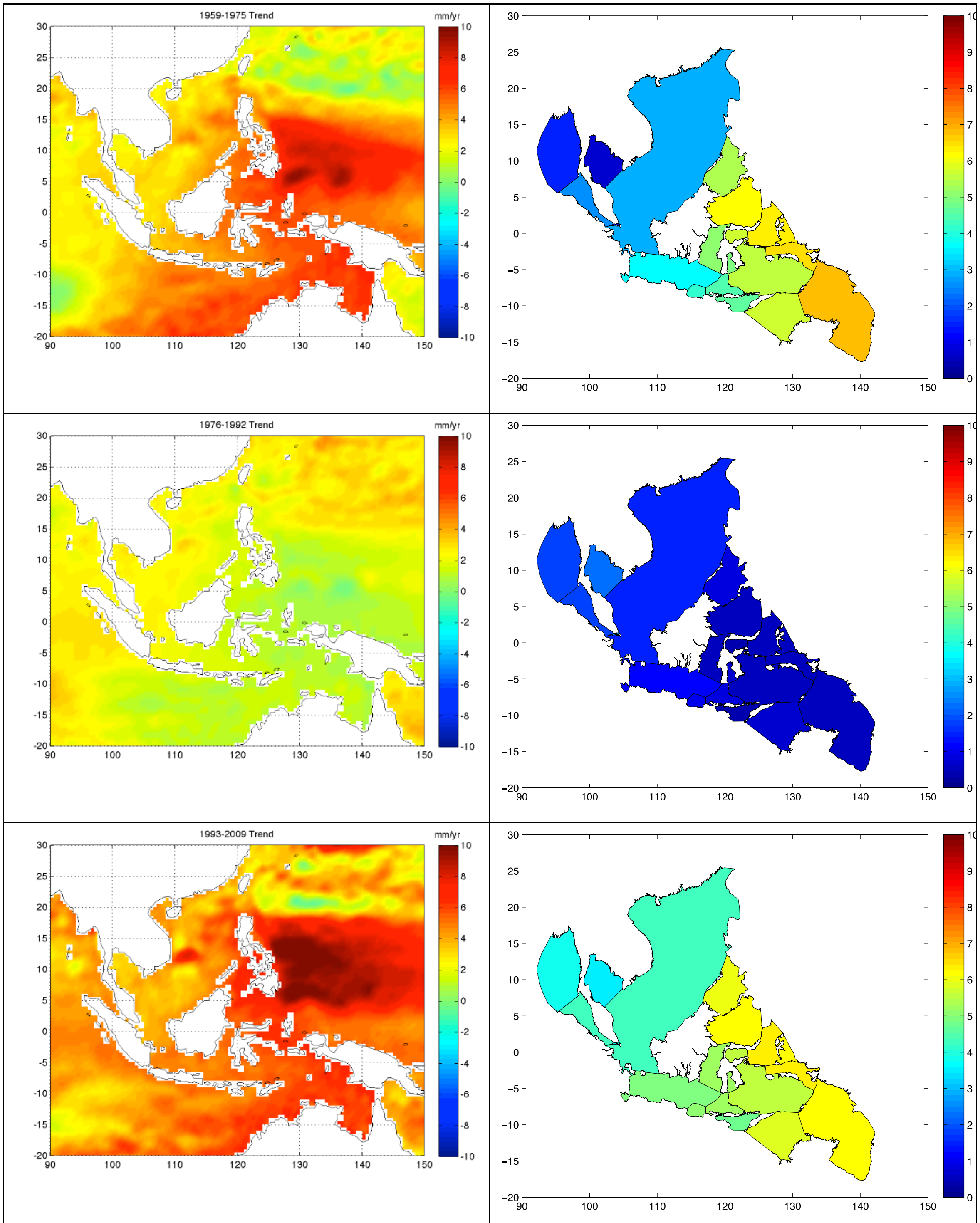


Figure 6. SEAS regional and averaged sea level trends for the (a) 1959-1975, (b) 1976-1992, and (c) 1993-2009 time periods from the bivariate sea level reconstruction (Hamlington et al., 2012).

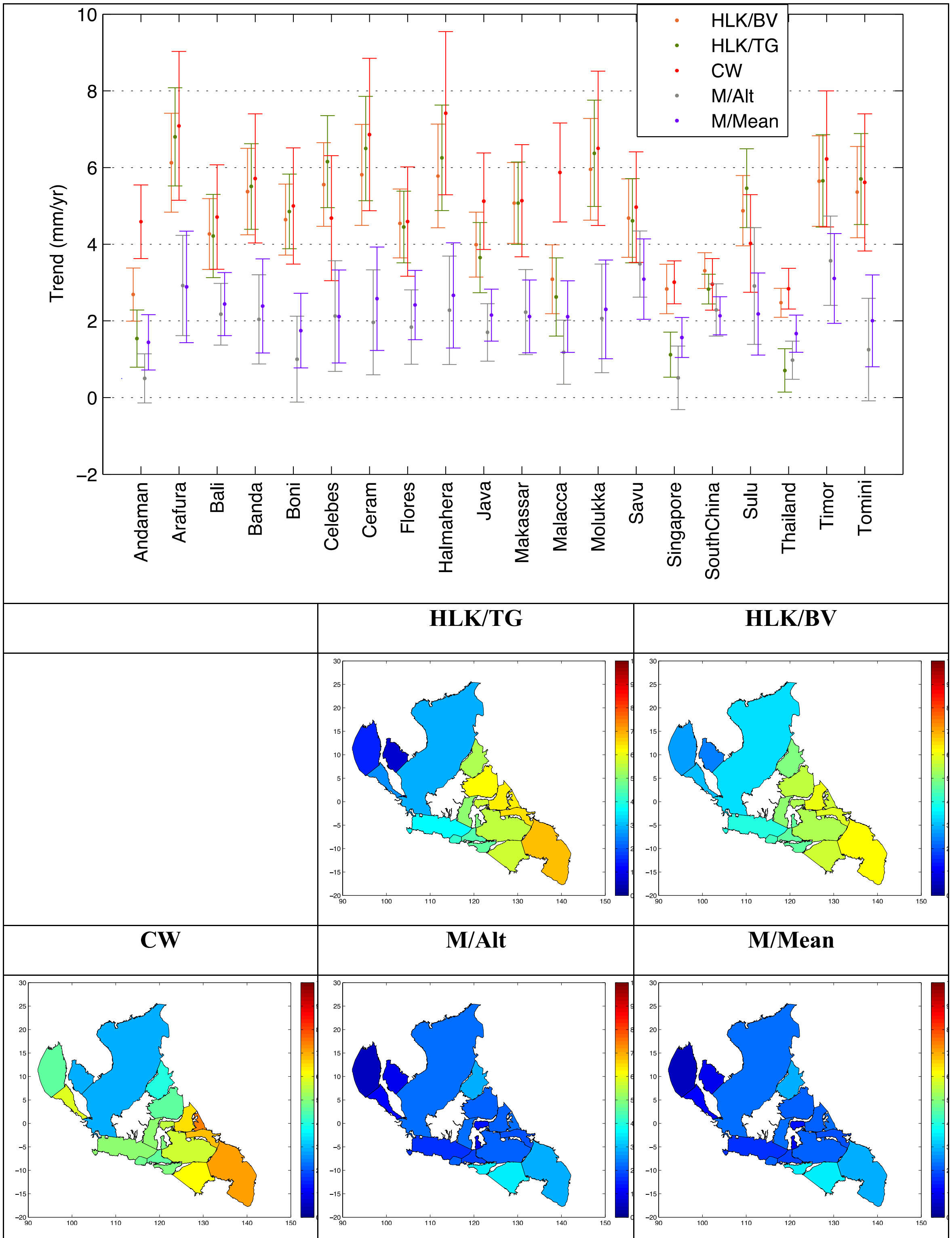


Figure 7. SEAS average sea level trends over the 17-year time period from 1959 through 1975 shown plotted as trend values with standard error (upper plot) and as color maps (bottom panels) for each of the reconstructions.

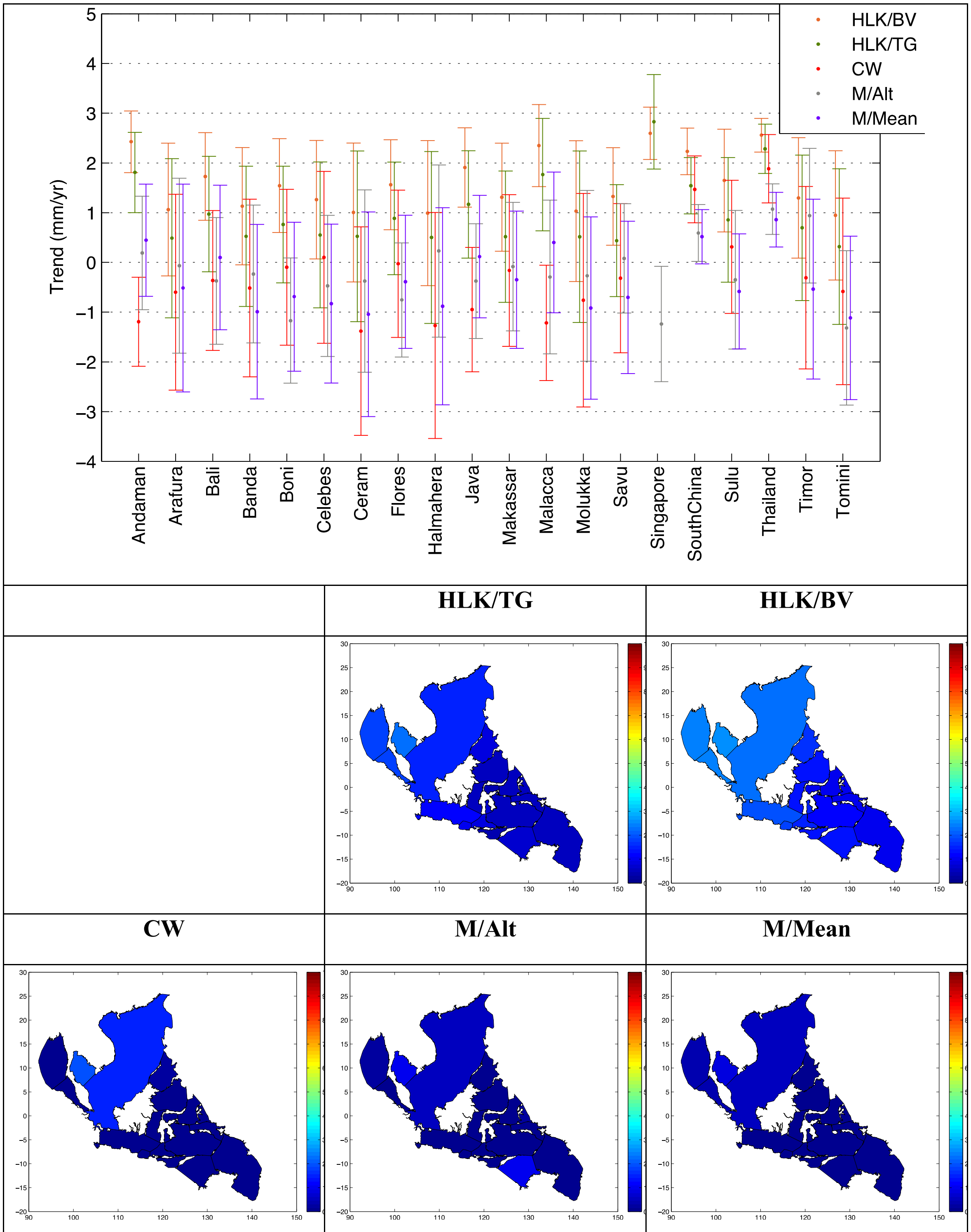
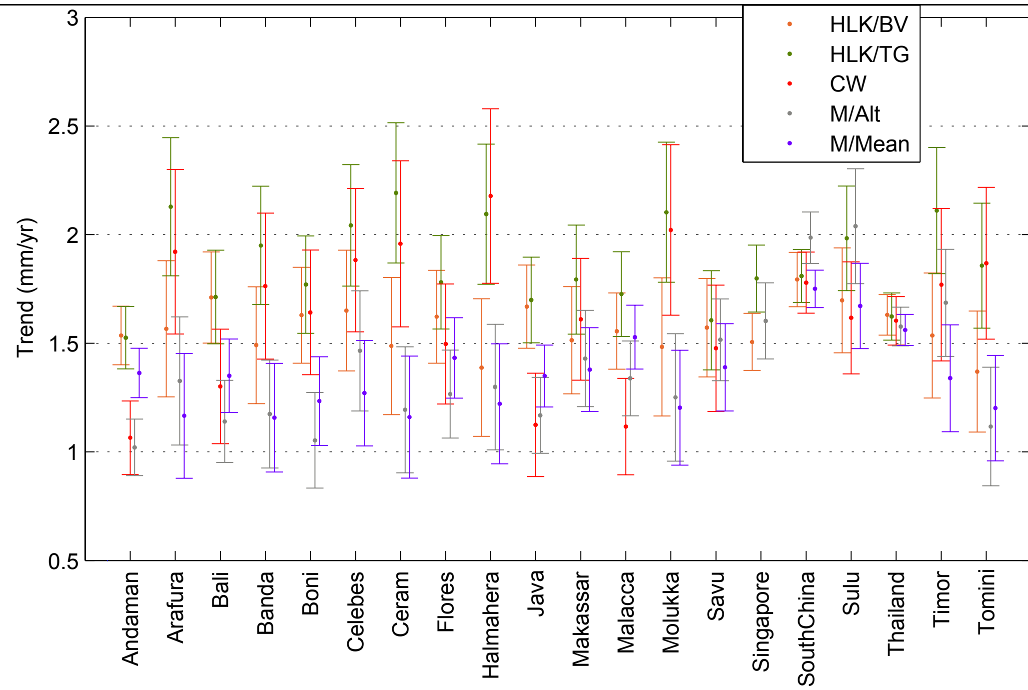
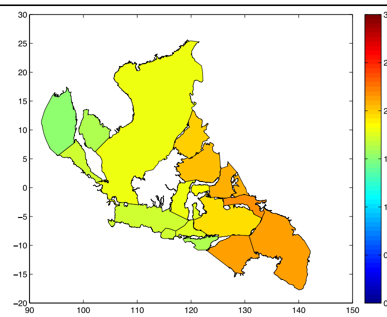


Figure 8. SEAS average sea level trends over the 17-year time period from 1976 through 1992 shown plotted as trend values with standard error (upper plot) and as color maps (bottom panels)

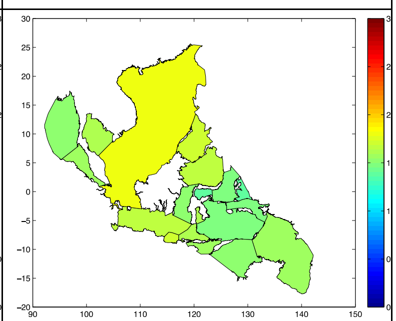
for each of the reconstructions.



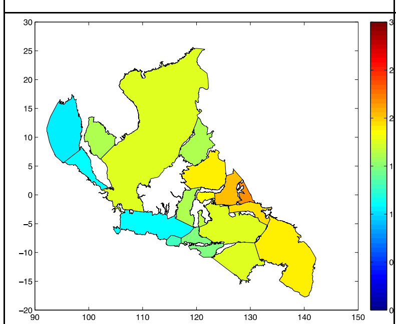
HLK/TG



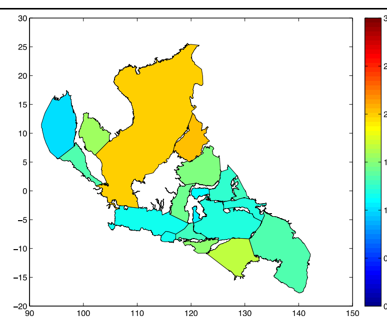
HLK/BV



CW



M/Alt



M/Mean

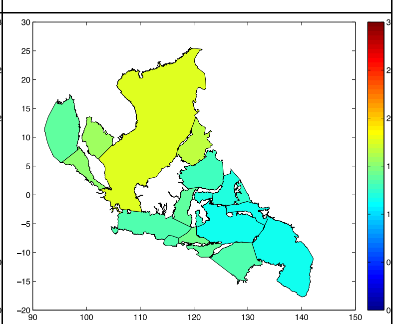


Figure 9. SEAS average sea level trends over the 60-year time period from 1950 through 2009 shown plotted as trend values with standard error (upper plot) and as color maps (bottom panels) for each of the reconstructions.

Appendix 1: AN INITIAL RETRACKING OF SATELLITE ALTIMETRY IN INDONESIA COASTAL WATER

AN INITIAL RETRACKING OF SATELLITE ALTIMETRY IN INDONESIA COASTAL WATER

P. Manurung [1], D. Rahardian [2], D. Adiran [3], K. Sumarta[3], M. Pamungkas[3], J. Lumban Gaol[3], S. Vignudelli[4], R.R Leben[5]

Abstract

Improving satellite altimetry data in the coastal zone is essential since the data is degraded resulting from different nature of atmospheric condition between land and sea as such as coastal topography and the sea states. Initial retracking was started by studying characteristic of waveforms, displayed in both 2D and 3D, classifying the waveforms, and investigating number of valid data. There are 3 retracking methods, namely Offset Centre of Gravity (OCOG), threshold and improved threshold, introduced. Results show that initial retracking of coastal altimetry should be further investigated by using more geophyisical data corrections, which is currently not available in the SGDR data provided by AVISO and PODAAC.

Introduction

Satellite altimetry continues to advance its role as one of the most effective remote sensing techniques by providing accurate space-based measurements of sea surface height. Multi-satellite altimetry missions currently sample the global ocean, supporting economic and engineering activities and improving understanding of ocean tides, current, circulation, mesoscale variability, and marine gravity and geoid. Recently, there has been great interest in using satellite altimetry to study low lying and densely populated coastal areas, such as Indonesia with its thousands of small inhabited islands. However, the accuracy of satellite altimeter data is highly degraded in coastal regions because the altimeter measurement system was primarily designed to accurately measure sea surface height measurements in the open ocean not near the coast. Therefore, coastal altimetry products are still experimental and must undergo further refinement. This research project is an initial effort to exploit the potential of altimetry in the coastal region by understanding the signal characteristics, visualizing 2D and 3D waveforms, and exploring retracking methodology for the study of coastal waters.

[1] Geospatial Information Agency (BIG), Jakarta, Indonesia
[2] Geomatic Department Sepuluh November Technological Institute (ITS)
[3] Department of Marine Science and Technology, Bogor Agricultural University, Kampus IPB, Darmaga Bogor 16680
[4] Consiglio Nazionale delle Ricerche, Pisa, Italy
[5] Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, ECNT 320, 431 UCB, University of Colorado, Boulder, CO, 80309-0431

Waveforms

Waveforms are the fundamental measurements of a radar altimeter. The profile of the altimeter waveform is a range function that is the convolution of three terms based on the specular reflection from the sea surface, the impulse response of the smooth spherical scattering surface, and the ocean-surface height distribution. If the sea surface is assumed to be linear, the statistics of surface elevation and slopes are Gaussian, meaning that the ocean-surface height distribution is assumed symmetric about some mean value. The standard model of altimeter waveform in the satellite processor is based on the Brown model, which is a function relative to the midpoint on the leading edge of the waveform. The range to the nadir sea surface point corresponds to this midpoint.

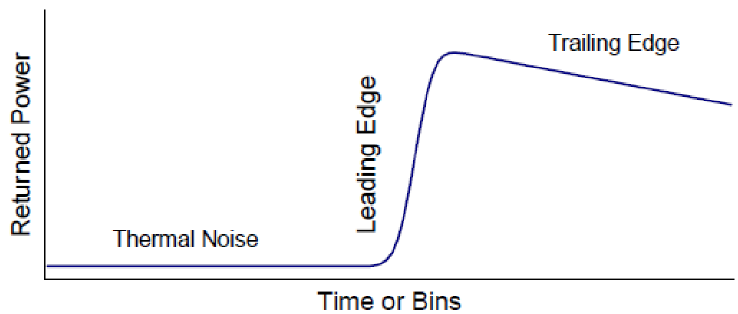


Figure 1. Waveform based on Brown model

A schematic altimeter waveform consists mainly of three parts, namely the thermal noise, the leading edge, and the trailing edge. Along the signal propagation through the atmosphere, noise affects the whole waveform mainly along the trailing edge. This noise makes it difficult to define the tracking point that is related to the mid-point on the leading edge of the waveform. Therefore, the tracking point is replaced by a tracking gate, which is selected before the satellite is launched. The on-board tracking algorithm tries to center the leading edge at the position of this gate. A post processing retracking is important in particular around the coastal regions since the ocean-like waveform data processing as implemented in the released product of AVISO and PODAAC is not sufficient to provide accurate costal sea surface height (SSH) as is discussed in the next section.

Coastal Waveform Retracking

The processing strategy applied in the open ocean cannot be successfully implemented to derive sea level in the coastal zone and shallow waters. Waveforms in coastal areas are contaminated due to variations in the atmospheric conditions, coastal topography, and sea states near the coast. Retracking is necessary to retrack the corrupted waveform. Retracking is a post processing procedure aimed at improving parameter estimates provided in GDRs. The main output of the retracker is a correction to the estimated range provided by the on-board tracker.

Many investigations have been made to improve the quality from the coastline outward to 50 km, which is the region that the data is flagged by the onboard tracking. , to possibly as close as 5 km from the coast, as shown in Figure 2. A coastal mask identifies those data segments in the

SGDR file, which require coastal processing.

Several algorithms have been developed to retrack waveforms based on either an empirical model or a deterministic model that is based on theoretical knowledge of microwave scattering. The latter is beyond the scope of our discussion since the processing is relatively complicated and most of the required corrections are not available in the SGDR. The former is considered a good candidate to further investigate retracking in the Indonesian region. A series of MATLAB scripts was developed in the research. The retracking scripts are based on offset center of gravity (OCOG), threshold, and improved threshold retrackers.

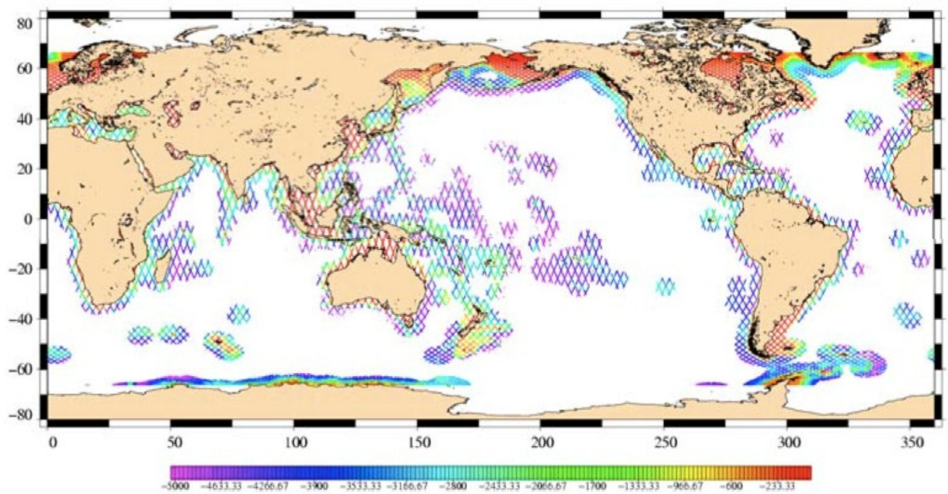


Figure 2. Most of the satellite data around 50 km to coastal line is flagged in onboard retracking (Courtesy of Pistach)

Offset Centre of Gravity Method

This is a relatively easy method to implement since it strongly depends on the statistics of the waveform samples. It is aimed at determining the center of gravity of each waveform based on the power levels within the gates. A schematic diagram of the offset center of gravity (OCOG) method is shown in Figure 3.

The method to compute A is the same as the method for the OCOG retracking by (1), P_N is the averaged value of power in the first gates, q is the threshold value, G_k is the power at the kth gate, where k is the location of the first gate exceeding T_h.

$$A = \sqrt{\sum_{i=1+n_1}^{N-n_2} P_i^4(t) \bigg/ \sum_{i=1+n_1}^{N-n_2} P_i^2(t)} \quad \text{...(1)}$$

$$W = \left(\sum_{i=1+n_1}^{N-n_2} P_i^2(t) \right)^2 \bigg/ \sum_{i=1+n_1}^{N-n_2} P_i^4(t) \quad \text{...(2)}$$

$$COG = \sum_{i=1+n_1}^{N-n_2} iP_i^2(t) \Big/ \sum_{i=1+n_1}^{N-n_2} P_i^2(t)$$ ....(3)

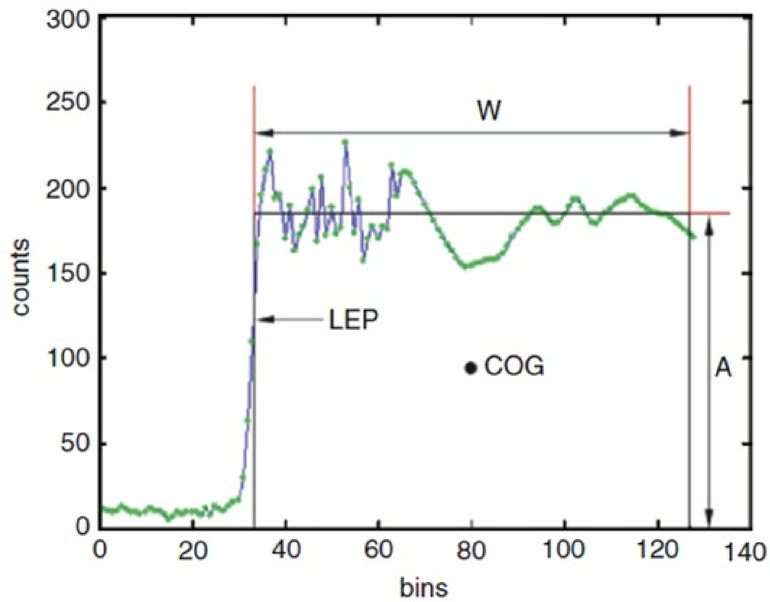


Figure 3: Schematic diagram of the OCOG method, as quoted from Vignudelle et al (2011)

Where:

A	= Amplitude of waveform (db)
W	= Width *Waveform (m/s2)*
P	= *Waveform Power (N)*
N	= Total number of samples in the *Waveform*
n_1 and n_2	= Bins (*gate*)

The leading edge position (LEP) is given by:

$$LEP = COG - \frac{W}{2}$$ ....(4)

Threshold Method

This method is based on the rectangle computed using the OCOG method. The use of threshold can be introduced as 25%, 50% and 75% of the amplitude. Yang et, al (2012) investigated threshold value using certain criterion and for the initial step a moderate threshold value of 50% is introduced. The steps for the method are the following:

Compute the thermal noise:

$$P_N = \frac{1}{5}\sum_1^5 p^i$$ ....(5)

Compute the threshold level:

$$T_h = (A - P_N).q + P_N \qquad \text{...(6)}$$

The retracked range of the leading edge of the waveform computed by a liniear interpolation between the bins adjacent to T_h using

$$G_r = G_{k-1} + \frac{T_h + P_{k-1}}{P_k + P_{k-1}} \qquad \text{..(7)}$$

The method to compute A is the same as the method for the OCOG retracking by (1), P_N is the averaged value of power in the first gates, q is the threshold value, G_k is the power at the kth gate, where k is the location of the first gate exceeding T_h.

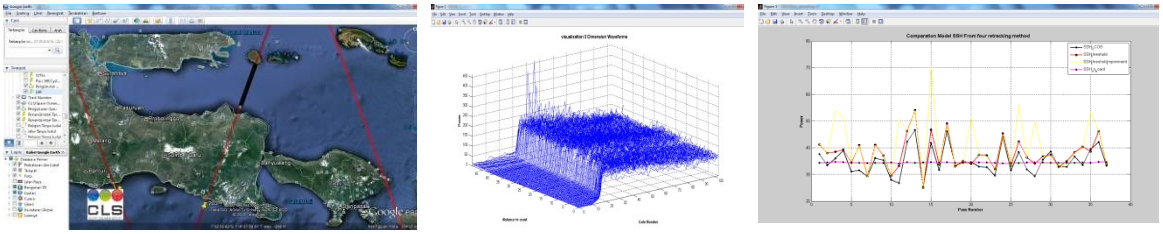
Improved Threshold Method

We implemented the method introduced by Guo et, al (2010) to find the start and end of the leading edge G_{start} and G_{end} and use OCOG method between G_{start} and G_{end} to compute the corresponding amplitude. At the final step the retracking gate is determined by estimating the location of bin with half of the amplitude.

Software Basic Design

In this research, we initated our excercise to explore how to process altimetry from raw data by writing a series of MATLAB script. The script, called *retracking.m*, was developed to read, display, and conduct retracking of the waveforms based on the OCOG, threshold and improved threshold methods. Output of the software can be also be incorporated into AVISO's BRAT software package for basic processing. As input, The code uses 20 Hz SGDR data as input, which is read in netCDF format as provided by AVISO.

The software provides a visual display of along track satellite altimetry from either descending or ascending ground tracks to help users visualize the location of the 3D or 2D waveforms and their quality during approach to the coast from the offshore or vice versa. Figure 4 shows some examples of the graphics displayed by the software. The number of waveforms shown from the shoreline is set as a flexible option in the software.. This is useful to display the waveforms and determine how close to the shoreline that the waveform can be used to determine sea level. The software is capable of extracting time series of sea level data at along track points or within a selected area. The along track sea level information is useful to provide Indonesian with data to fill gaps due to unavailable tide gauge data.



a) b) c)

Figure 4. Some examples of the matlab script developped to display a) Google map for diplaying the satellite track, b) 3D Display and c) comparison of the tracking methods.

Data and Area

The data used in this study are Jason-2 SGDR waveform product available from the AVISO and PO.DAAC websites. The original purpose of this study was to investigate the retracking of altimetry data in the coastal region. We have used two areas for our investigation, as shown in Figure 5, namely: the Eastern Java Island with deep water in the South and shallow water of the Java Sea in the North and ii) North Sulawesi, a semi enclosed deep sea.

a) b)

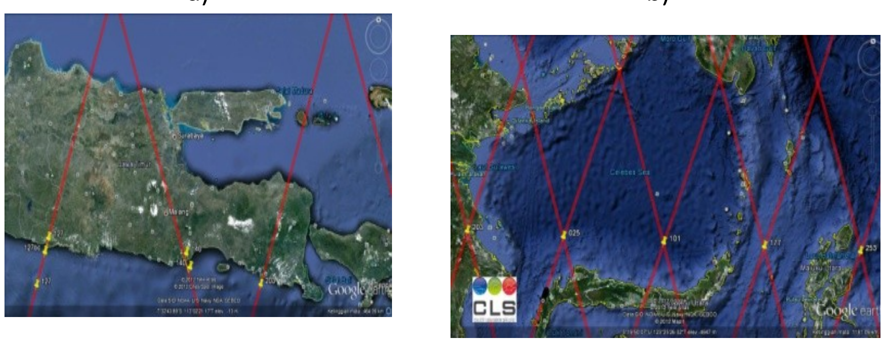


Figure 5: Jason-2 Satellite tracks in: a) Eastern Java, pass 140 and 203 cycle 92 and b) North Sulawesi pass 25, 101, 12, 190 cycle 129.

Results and discussions

Figure 6 and 7 show display of 3D waveforms with the distance of 30 km from the coastline of Eastern Java and North Sulawesi, respectively. It is clear that the waveforms are noisy when they are close to the shorelines and they are becoming more ocean-like when they are away from the shoreline. The 2D waveforms show clearly the peakiness of waveforms close to the coastline. The along track spacing of each waveform is about 300 meter and by using the visualization tools further classification of waveforms can be made to determine if further retracking is required or not.

Results of comparisons of retracking methods shows that SSH derived from SGDR data are about equal. This indicates that geometrical retracking should not be done alone but requires other geophysical corrections that are not available in the currently released data. In other words, retracking alone cannot fully improve the quality of SSH since the ranging accuracy is highly affected by poor geophysical and environmental corrections. OCOG method estimates the amplitude, width, and center of gravity of the waveform, and then determines the retracking gate with a predefined threshold value. The modified threshold retracking method employs the threshold value 50% to determine the retracking gate. Improved threshold retracker, which determines one or more sub-waveforms and retracking gates, and then selects a best retracking gate, which yields the smallest difference between the post-retracking SSH and previous referenced data, as shown in SGDR SSH data (on-board). Essentially, the kernel of any retracker algorithm is trying to find the true leading edge in the return waveform. It is of importance to determine the prior weight based on type, characteristic and geographical location of the return waveform. In fact, there is no standard reference model function that can be used for all cases. In the retracking process, those retrackers based on the functional fit will be sensitive to the shape of return waveform, and there is no guarantee of convergence.

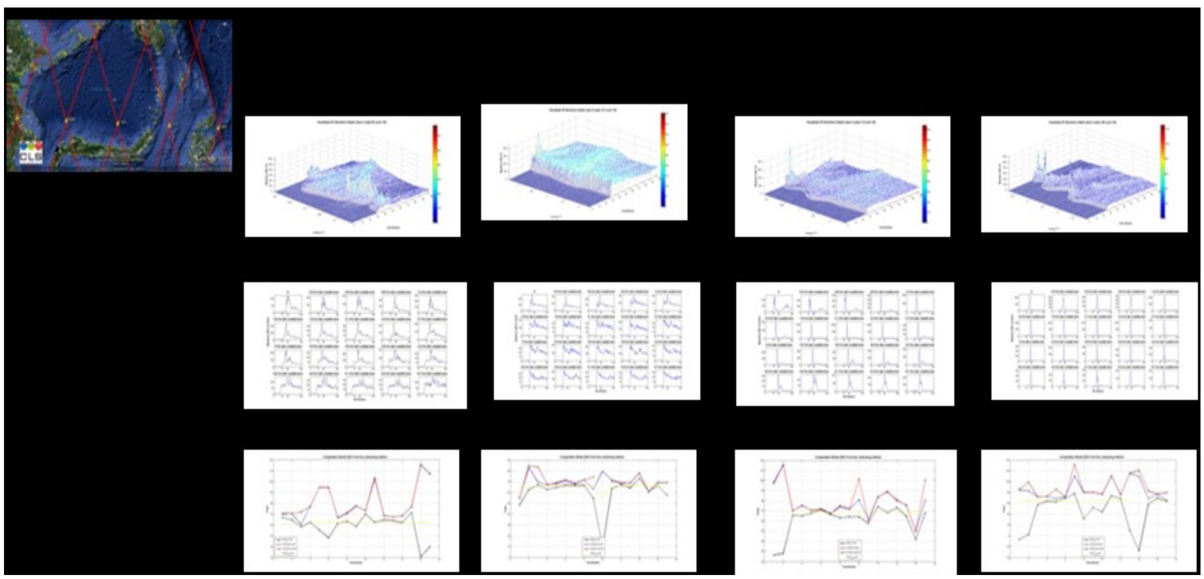


Figure 6: 3D and 2D waveforms and comparison between retracking methods using data pass 25, 101, 12 and 190 with cycle 129 in North Sulawesi

This preliminary retracking software will help users to extract time series of sea surface height data points along ground tracks, which cannot be done using existing ground measurements. This also should be useful to provide users in Indonesia the data required to fill gaps due to the unavailability of tide gauge data in some areas and offshore.

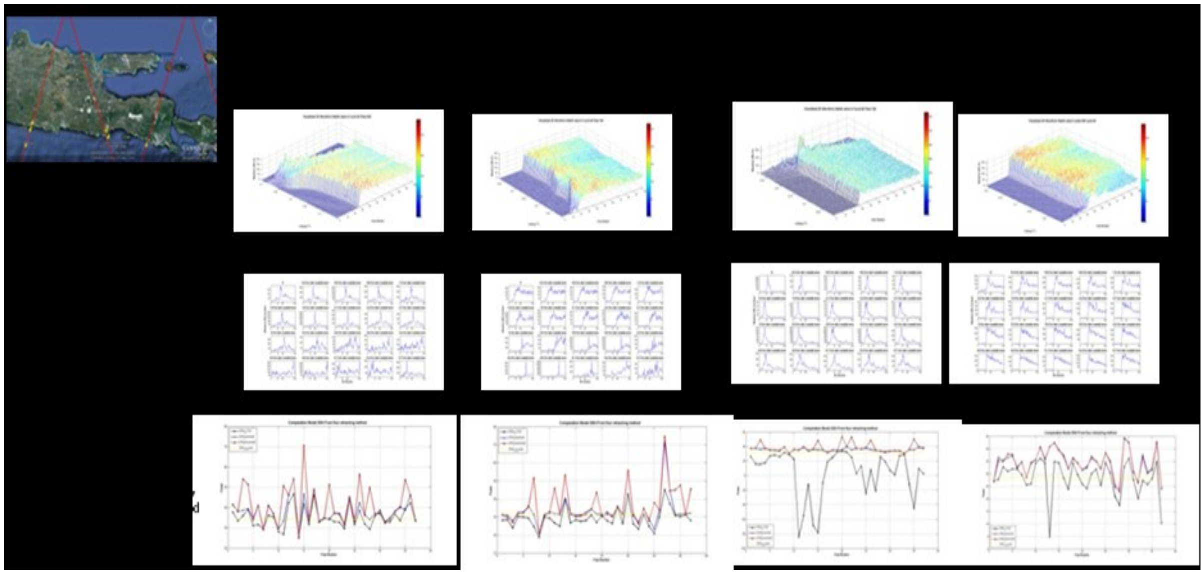


Figure 7: 3D and 2D waveforms and comparison between retracking methods using data pass 140 and 203 with cycle 92 in Eastern Java Island

Conclusion

The objectives for knowledge transfer and capacity building of this APN-support Project on coastal altimetry have been successfully achieved as demonstrated by providing a series of MATLAB scripts to read, process, and visualize altimeter data in the coastal Indonesia.

Efforts to provide better coastal datasets between 0 to 10 km along the coastal area were investigated by introducing retracking methodology. Our initial retracking results on suggest that more geophysical corrections should be introduced in the retracking methodology. It is expected that in the future more geophysical corrections will be released in the altimetry data products.

Last but not least, the initial attempts on studying signal altimetry data processing should be beneficial for the South East Asia Region to provide more quality sea level data. An initiative to set up regional cooperation with altimetry satellite data providers is required to provide more accurate coastal altimetry data products in the region, as it has been done in other regions.

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Appendix 2: Coastal Altimetry

Coastal Altimetry

Stefano Vignudelli, CNR Pisa Italy

The aim of this task was to increase uptake of coastal altimetry products and techniques by demonstrating their value for sea level studies in the Indonesia region and the surrounding areas. The work plan included two different steps: (1) spreading out the actual knowledge in terms of data, methods; (2) assisting the local community to build autonomous capacity of development and processing

This was achieved through two workshops (keynote talks and round tables), two training periods (lectures, documentation, practical exercises) and continuous technical and scientific support during the project duration. An important effort was dedicated to the transfer of know-how, namely software to read, process and visualize altimeter data. The retracking methodology was also seen as another key aspect to be focused.

In particular, much has been learned on how to handle data and interpret outputs. A series of Matlab scripts were made available to assess (qualitatively and quantitatively) the improvement gained from the adoption of specialized retrackers and corrections in the coastal zone. Some examples were presented to show the main functionalities.

The available network of in-situ sea level stations operated by Indonesia was also explored. A start has been made to assess the data quality for a potential exploitation in validation activities. This has not been studied in great detail so far, however, a first look gives some ideas of what could be done. One lesson learnt is that more quality-checking must be done in situ data before committing data to scientific validation.

A final aspect considered was the analysis of a coastal product. It should be recalled that coastal altimetry products are still experimental and undergoing to further refinements. Just before the end of the project we had access to the CTOH product. The files contain Sea Level Anomaly derived from the standard (denoted SGDR) retracker.

A reanalysis of altimeter data was done to qualitatively and quantitatively assess the temporal and spatial variability of the data. It was repeated through the data set but here we just provide an example of a satellite track from T/P and Jason 1/2 mission series crossing Indonesia. The method is essentially standard altimetry analysis for repeat cycles. At each point there are values of Sea Surface Height and Sea Level Anomaly (if no data drop out) and statistics can be computed as a measure of amount of valid data and ocean variability.

Results and findings of this analysis and comparison studies shows that the percentage of available valid data (expressed as percentage of total available data) is more than 90% in open sea (Figure 1). Zooming locally, some drops are observed in proximity of the coasts (Figure 2). The percentage of valid data (as a function of distance) is around 90% until 10 km from the coast (Figure 3).

SSH profiles for all passages along the track (Figure 4) exhibit the same behaviour (i.e. they follow the geoid). Each profile has a different colour corresponding to the colour bar on the left. The variability from cycle to cycle can be due essentially to the absolute dynamic topography, but as expected the dominant signal is the geoid that shows significant changes along the track. The root-mean-square variability of the Sea Level Anomaly along track considering the whole data set (from 1992 to 2010) is around 20 cm (Figure 5). The 2D plot of Sea Level Anomaly shows a clear spatial and temporal variability (Figure 6). The vertical white bands are where there is land. Figure 6 shows the Sea Level Anomalies to be larger and noisier near land. Improvements can be obtained only with more “upstream” work on raw data (i.e. retracking).

Figures for this section are grouped together in Annex 1

ANNEX 1

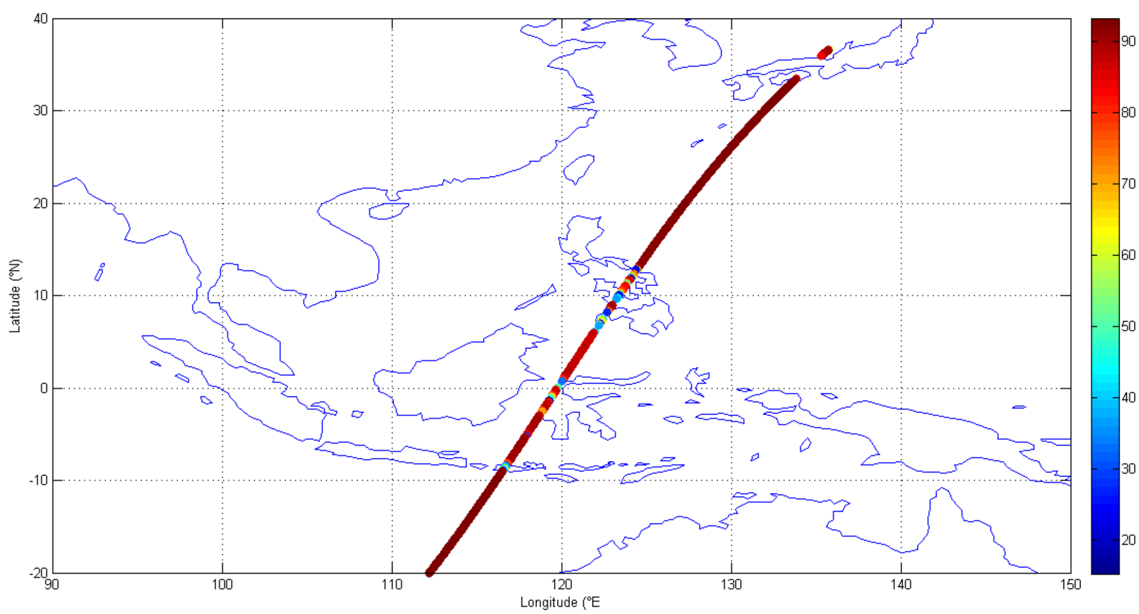

Figure 1

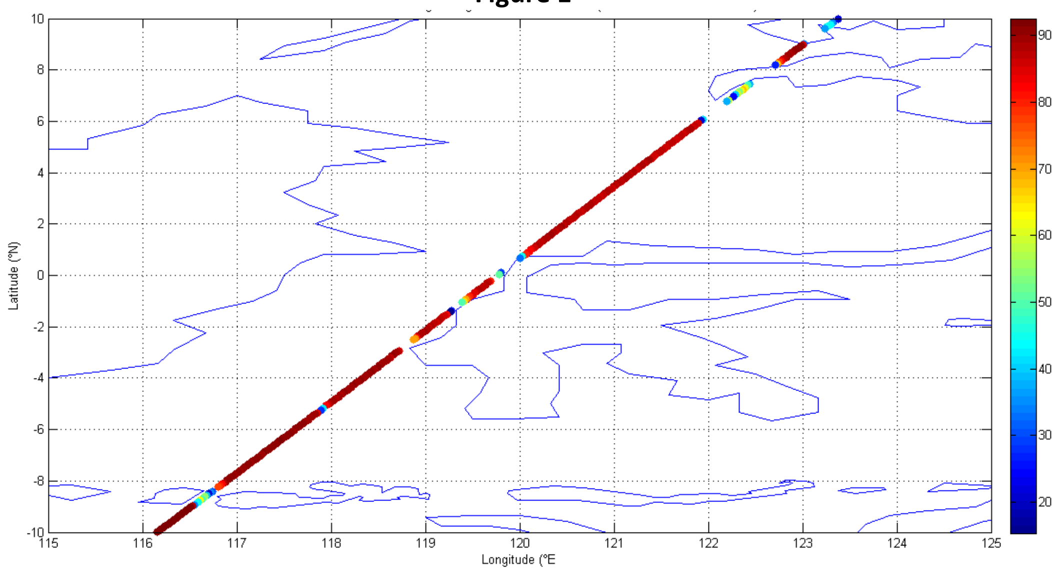

Figure 2

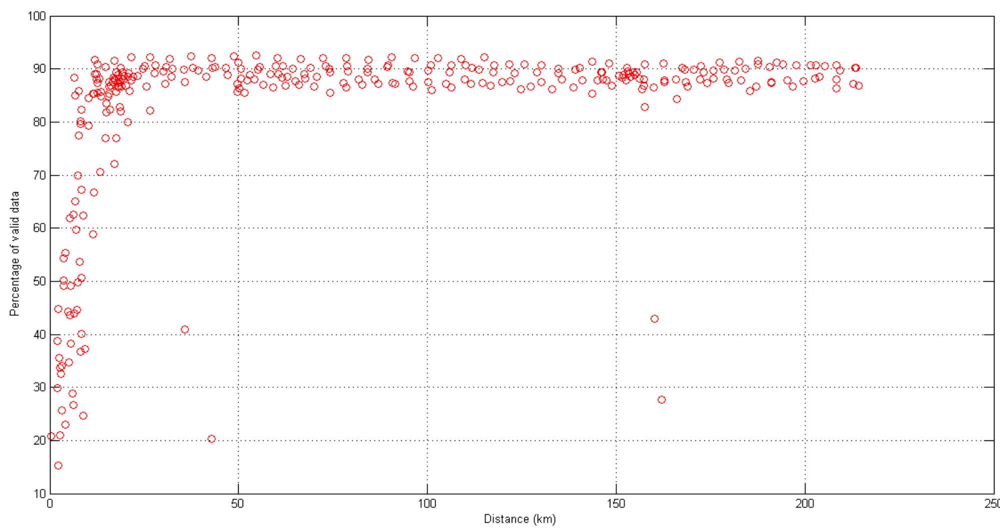

Figure 3

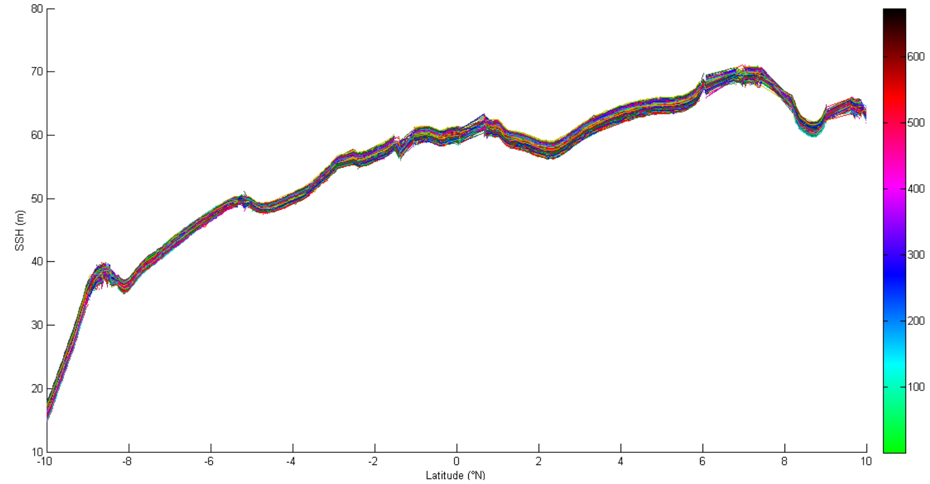

Figure 4

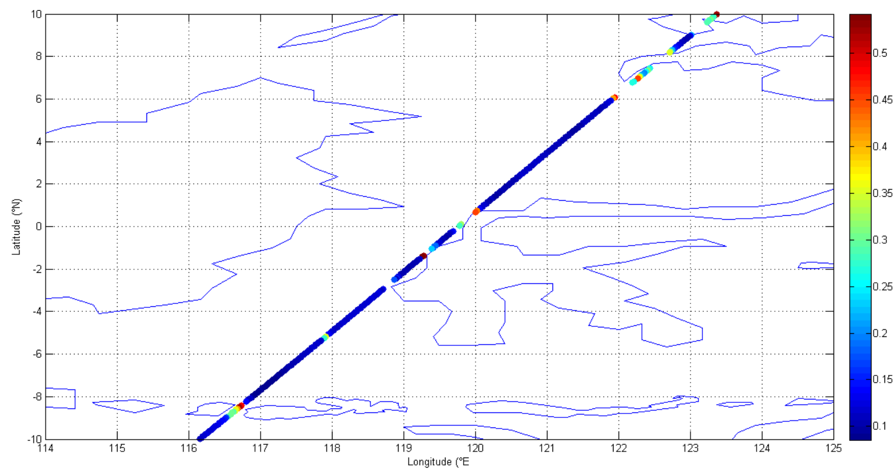

Figure 5

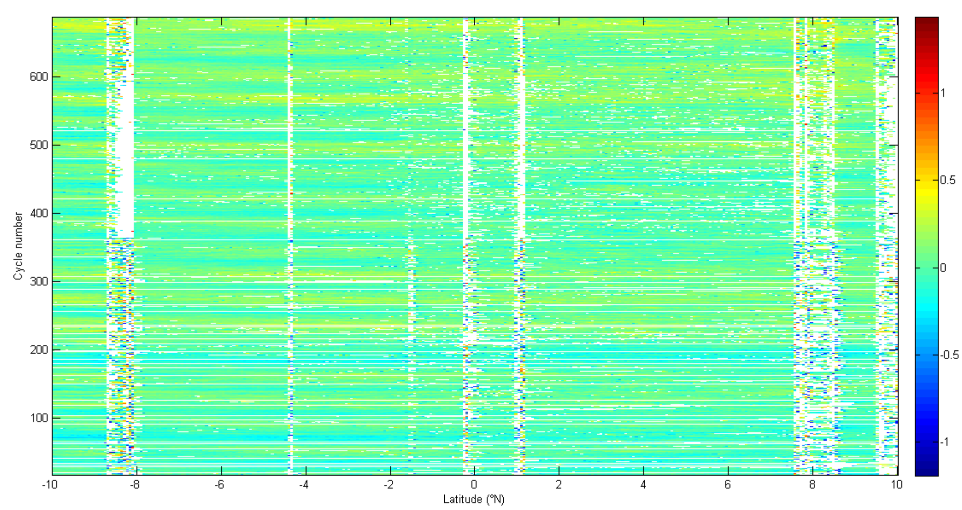

Figure 6

Appendix 3: Variability of satellite-derived the sea surface height

Variability of satellite-derived the sea surface height and its relationship on Bigeye tuna (*Thunnus obesus*) catch in eastern Indian Ocean off Java

J. LUMBAN GAOL*† B. NABABAN†, and P. MANURUNG‡, K.H. Amri†

†Department of Marine Science and Technology, Bogor Agricultural University, Kampus IPB Darmaga Bogor , Indonesia.
‡National Coordinating **Agency** for Surveys and **Mapping, Cibinong, Indonesia.**

The study was aimed to understand the climate variability impact on sea surface height anomaly (SSHA) of eastern Indian Ocean (EIO) off Java and related to bigeye tuna catch. A thirteen-year time series of SSHA and Hook Rate (HR) of bigeye tuna catch data were used in this investigation. The bigeye tuna HR was derived from logbooks of tuna fishing vessels operated in EIO during 1994-2005. The result showed that spectrum analysis both of SSHA and bigeye tuna HR indicating two dominant signals as representation of the annual and inter-annual variability. During El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) formed a large cold eddy in the eastern Indian Ocean and generally SSH was lower than normal year and bigeye tuna HR tend to increase. The overlaid between bigeye tuna HR and SSHA showed that the highest bigeye tuna catch was between the front zone of negative and positive SSHA. The increased of bigeye tuna catch during ENSO and IOD can be attributed to the development of eddy and shallower thermocline depth and enhancement biological productivity due to induced upwelling.

1. Introduction

The eastern Indian Ocean (EIO) region off Java (04ºS-16ºS and 105ºE-120ºE) has long been considered as an important area for Indonesian tuna bigeye fishing industry. Since 1992 the Indonesian government has been operating 20 units longliner in EIO consisted of 9 units of 100 GT and 11 units of less than 100 GT vessels. The dominant catch was bigeye tuna (73%) and others (23%) are yellowfin tuna, marlin and shark. The productive pelagic fisheries in this area were sustained through an enhancement biological production of seasonal upwelling during south east monsoon (Wyrtki, 1962, Susanto *et al.* 2001). This region was also affected by Indonesian through flow (ITF), i.e. the net flow of waters from Pacific to Indian Ocean (Godfrey *et al*. 1993, Gordon,

*Corresponding autor. E-mail: jonson_lumbangaol@yahoo.com

2005). Susanto *et al.* (2001) also concluded that the interannual variability of upwelling in this area was linked to ElNino Southern Oscillation (ENSO) through the ITF and was also influenced by Indian Ocean Dipole (IOD) (Saji *et al*. 1999, Webster *et al*. 1999, Shinoda *et al*. 2001, Feng and Meyers, 2003).

Several studies showed that the climate variability such ENSO influences fish distribution, community composition, species abundances, recruitment level and tropics structure (Lehodey *et al*. 1997, Kimura *et al*. 1997, Sugimoto *et al*. 2001, Lumban Gaol *et al*. 2002, White *et al*. 2004). Recently, Menard *et al*. (2007) found the strong association between tuna and climate series for the 4- and 5-year periodic modes i.e., the periodic band ENSO signal propagation in Indian Ocean.

In general, bigeye tuna habitat is influenced by the location of thermocline depth. When thermocline layer is deeper, fishing layer of bigeye tuna may also be deeper since the bigeye tuna will adapt to its optimum fishing layer between 10° and 15°C (Hanamoto, 1987). During ENSO event, the thermocline depth in EIO was about 20 to 60 m shallower than normal (Susanto *et al*. 2001), therefore, the effectiveness of a longline to catch bigeye tuna should be higher during ENSO event than normal climate condition. Scientists found that the correlation between thermocline depth and SSH was also significant in EIO (Bray *et al.* 1996, Susanto *et al*. 2001). In Benggal Bay, the evolution of SSH and the depth of 20°C (D_{20}) isotherm indicated that the temporal variability of the two were similar with low (negative) SSH corresponding to shallow (negative) D_{20} (Yu, 2003). Potemra (2005) also found that SSH had strong interannual variability in EIO. Therefore, the SSHA can be used as a proxy thermocline depth indicator which influences on the bigeye fishing layer. The objective of this study was to examine the relationship of climate variabity (ENSO and IOD) and sea surface height anomaly and its impact of bigeye tuna catch in estern Indian Ocean off Java.

2. Methods

We used remote sensing (altimetry and ocean color) data, XBT data, and bigeye tuna catch data set from diverse sources. The SSHA data were obtained from the Colorado Center for Astrodynamics Research (CCAR), Colorado University at Boulder courtesy of Dr. Robert Leben (Leben *et al.* 2002). The Chlorophyll-a data were obtained from SeaWiFS website (http://oceancolor.gsfc.nasa.gov/). The concentration of chlorophyll-a was estimated using Ocean Color-4 versus 4 (OC4v4) algorithm (O'Reilly *et al*. 2000). Meridional section of temperature was derived based on XBT measurement from World Ocean Data base-2005 (WOD-2005).

Data set of bigeye tuna catch was collected from several different sources i.e., a three-year (1997-1999) daily tuna catch, consisted of 14,000 setting of longline was obtained from 20 units longliner of tuna fishing operated in EIO, and a fourteen-year (1992-2005) monthly average of hook rate (HR) was derived from statistic report of fisheries company. Bigeye tuna catch rate index (hereafter referred to as HR) was calculated from the number of bigeye tuna caught in 100 hooks of longline. We computed a catch rate and plotting spatial distribution of bigeye tuna HR in EIO. The study area and the spatial distribution of bigeye tuna HR is shown in Figure 1.

The time series analysis were also carried out for analyzing variability of both SSHA and bigeye tuna HR. Statistical cross-correlation analysis was carried out for evaluating strength of time-lagged relationship between ENSO and SSHA represented by the following equations:

$$r_{xy}(k) = \frac{C_{xy}(k)}{S_x S_y} \quad \text{... (1)}$$

where,

$$C_{xy}(k) = \begin{cases} \frac{1}{n}\sum_{t=1}^{n-k} (x - \bar{x})(y - \bar{y}), k = 0,1,2,... \\ \frac{1}{n}\sum_{t=1}^{n+k} (y_t - \bar{y})(x_{t-k} - \bar{x}), k = -1,-2,... \end{cases} \quad \text{.................(2)}$$

$$S_x = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(x_t - \bar{x})^2} \quad \text{...................................... (3)}$$

$$S_y = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \bar{y})^2} \quad \text{.......................................(4)}$$

x : SSHA series of length n
y : SOI index series of length n
$r_{xy}(k)$: Sample cross correlation coefficient at lag k
S_x : Standard deviation of series X
S_y : Standard deviation of series Y
C_{xy} (k): Sample cross covariance at lag k

3. Result and Discussion

3.1. Result

The SSHA data collecting for period 1992 to 2005 and Chlorophyll-a concentration for period 1998 to 2005 since TOPEX satellite altimeter launched on October 1992 and ocean color SeaWiFS satellite on August 1997. The time series of monthly mean chlorophyll-a concentration, SSHA around of fishing ground, bigeye tuna HR, and SOI were shown in Figure 2. Spectral analysis of both SSHA and HR showed two dominant signals with period of 12 months and more than 32 months were representations of the annual and the interannual variability, respectively (Figure 3).

Negative SSH anomaly due to the **upwelling induced** by the southeast **monsoon during** June to October and positive SSH anomaly due to the downwelling during November to April in EIO off Java (Figure 2b). Chlorophyll-a concentration of phytoplankton was also higher during upwelling season from May to October (Figure 2a). Such SSHA extremes (negative) corresponded well with the duration of intense phase of El Niño and IOD (Saji *et al*. 1999, Webster *et al*. 1999, Susanto *et al.* 2001, Potemra, 2005).

Monthly mean of bigeye tuna HR showed that the bigeye tuna HR usually was higher when the upwellings occurred during southeast monsoon. During El Niño and IOD upwelling in EIO, thermocline associated wiht fishing layer of bigeye tuna was shallower and more intense. The yearly mean of bigeye tuna HR for the periode 1992 to 2005 tended to increase except in 1994 (Figure 4).

Cross-correlation analyses between monthly SSHA and SOI were conducted for the period 1993 to 2005 (Figure 5). El Niño had significant influence on variability of SSHA, with SOI negative (positive) correspond to SSHA negative (positive). These evidences can be seen from the highest cross-correlation coefficient (r) = 0.7 with time lag = 5 month. When El Niño occurred, SSH tended to lower so that the thermocline depth was shallower (Susanto *et al*. 2001). This will increase the effectiveness of bigeye tuna catch since the fishing layer of bigeye tuna is shallower.

Three years daily of bigeye tuna HR was overlaid on Hovmuller (time-longitude) plot of SSHA (Figure 6a). The result showed that the highest bigeye tuna HR were concentrated between the negative and positive of SSHA (Figure 6b). The front formed at the edge of SSHA negative and SSHA positive was a good fishing ground for bigeye tuna (Sund *et al*. 1981) because this front was often very active such as the current were strong and temperature varied rapidly.

The correlation between SSHA and bigeye tuna HR was significant with negative SSHA corresponding to high HR, especially in 12°S-13°S, where the eddy was observed and upwelling characteristics at the eddy core of cyclonic eddy (cold ring). This result was similar to study in North Atlantic mesoscale eddy where the bigeye tuna HR was higher in the eddy area than in the non-eddy area (Hsu, 2010).

3.2. Discussion

During El Niño 1997/98, the large meso-cyclonic eddies were observed in EIO (Figure 7a), and the SSHA around bigeye tuna fishing ground becomes lower (negative). Mesoscale eddy might be formed when a waters mass contained a barotrophic instability (Carton and Chao1999). An eddy-induce upwelling could export nutrient from deep to the euphotic zone (McGillicuddy and Robinson, 1997).

The SSHA negative can be related to shallower of thermocline depth as shown on meredional section of temperature where eddy observed (Figure 7d). When the thermocline shallower, the fishing layer (10^{o}-15^{o}C) of bigeye tuna is shallower so that the catchability of bigeye tuna was increased since longline gear was able to penetrate the depth where bigeye tuna were found (Hanamoto, 1987, Holland *et al.* 1990).

The eddy activities affect the distribution of large predators in the marine ecosystem and these predators consider different eddy structures (eddy core; eddy ring) and different eddy polarities (anticyclonic eddy; cyclonic eddy) different habitats (Hsu, 2010). Cyclonic eddies process also causes biological enhancement activities (Seki *et al.* 2001, Killoworth and Cipollini, 2004), as seen from higher of chl-a concentration in EIO (Figure 7b). Normally, the highest chl-a concentration in EIO is found when upwelling process occurs during southeast monsoon from June to October (Wyrtki, 1962, Purba, 1995, Susanto and Mara, 2005), but when El Niño event in EIO exhibited the continuous blooming to December (Figure 7b). Cholorophyll-a concentration is higher during El Niño and IOD event is may be one of causal factor of bigeye tuna more abundant so that the catchability is higher. Our result shows that the favorable tuna cath was concentrated in front between cyclonic and anticyclonic eddies (Figure 7a). The investigators believe that the front area has higher productivity than others because the front area can be as a feeding ground and also as a barrier for tuna (Sund *et al*. 1981).

Horizontal and vertical movements of various tuna are influenced by oceanographic conditions. The predominant bigeye tuna daytime distribution was between 220 and 240 m due to suitable temperature for bigeye distribution (Holland *et al*. 1990). Temperature and thermocline depth seemed to be the main environmental factors governing the vertical and horizontal distribution of bigeye tuna. The optimum temperature for fishing ranges between 10^oC and 15^oC (Hanamoto, 1987). The depth of isotherm 10^oC and 15^oC ($IT_{10}{}^o{}_{-15}{}^o$) in EIO varies from 150 to 400 m, whereas the tuna longline is normally set to reach seawater depths of 100 to 280 m. During El Niño event the thermocline depth in EIO is shallower 40-60 m than the normal condition effect of upwelling process (Susanto *et al*. 2001). This process is caused the $IT_{10}{}^o{}_{-15}{}^o$ becomes shallower. Seasonally, during southeast monsoon, upwelling process occurred in EIO causes the thermocline is shallower than during northeast monsoon, and usually bigeye tuna catch more abundant since the upwelling area is higher nutrient, phytoplankton, zooplankton, and small pelagic fish.

Strong interannual variability of SSH around tuna fishing ground agree with previous study (Patomra, 2005). Yu (2003), found that in Indian Ocean off Benggal, the interannual variability of SSH is quite similar to the depth of 20^oC (D_{20}) isotherm. The evolution of SSH indicated that the temporal variability of the two are similar, with low (negative) SSH corresponding to shallow (negative) isotherm D_{20} and vice versa. Therefore, we predicted that the shallower thermocline during El Niño/IOD event is one of causal factor of bigeye tuna HR higher than normal condition.

Beside the suitable temperature, prey is responsible for the abundance of bigeye tuna. Tuna are expected to be abundant in upwelling areas because of micronecton, unless the waters are too cool or turbid. The crab, an herbivore is most abundant in the upwelling areas where the highest phytoplankton stock occurs (Sund *et al.* 1981). Usually, the upwelling process in EIO starting from June to October, but during El Niño/IOD the upwelling extended until December. These phenomena caused the abundance of oily sardine to increase in EIO off Bali Strait (Lumban Gaol, 2003). Fisherman of fishing company (PSB) commonly used the oily sardine as bait for bigeye tuna longline, so extended abundance of oily sardine during El Niño can be attributed to the increase of bigeye tuna abundance. Brill and Lutcavage (2001), concluded that bigeye tuna tend to remain in surface layer only at night and descends at dawn as behaviors that apparently allow them to exploit effectively the organisms of the deep scattering layer as prey.

Acknowledgement

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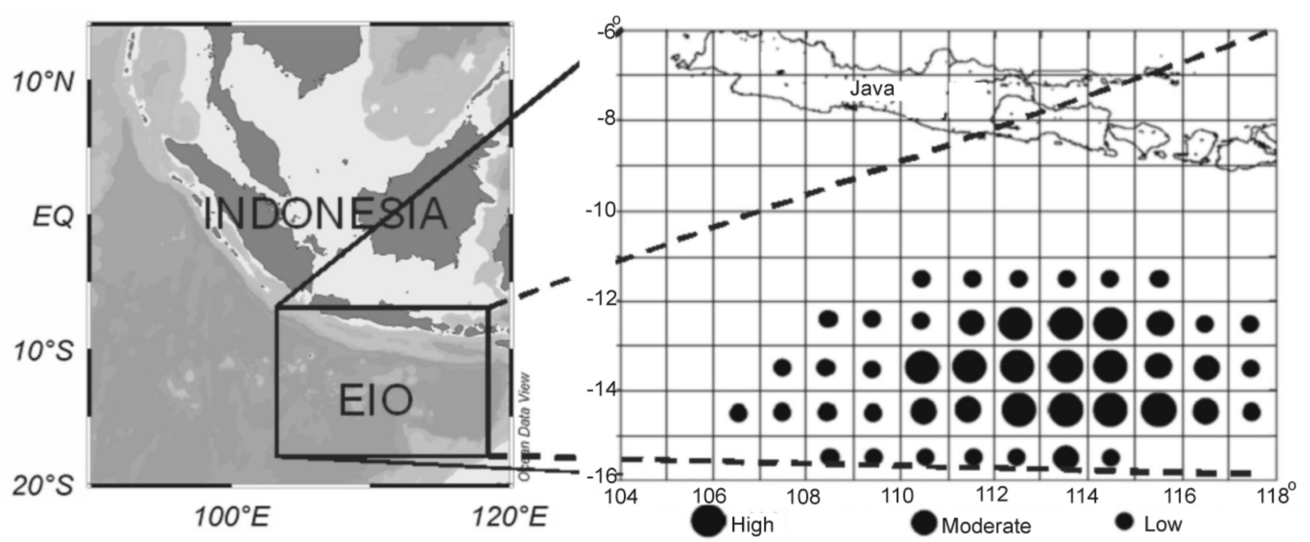

Figure 1. Area of study in Eastern Indian Ocean (EIO) and spatial distribution of monthly average bigeye tuna hook rate (the biggest, medium, and small circles shows that the area with high, moderate, and low frequency of HR > 0.8.

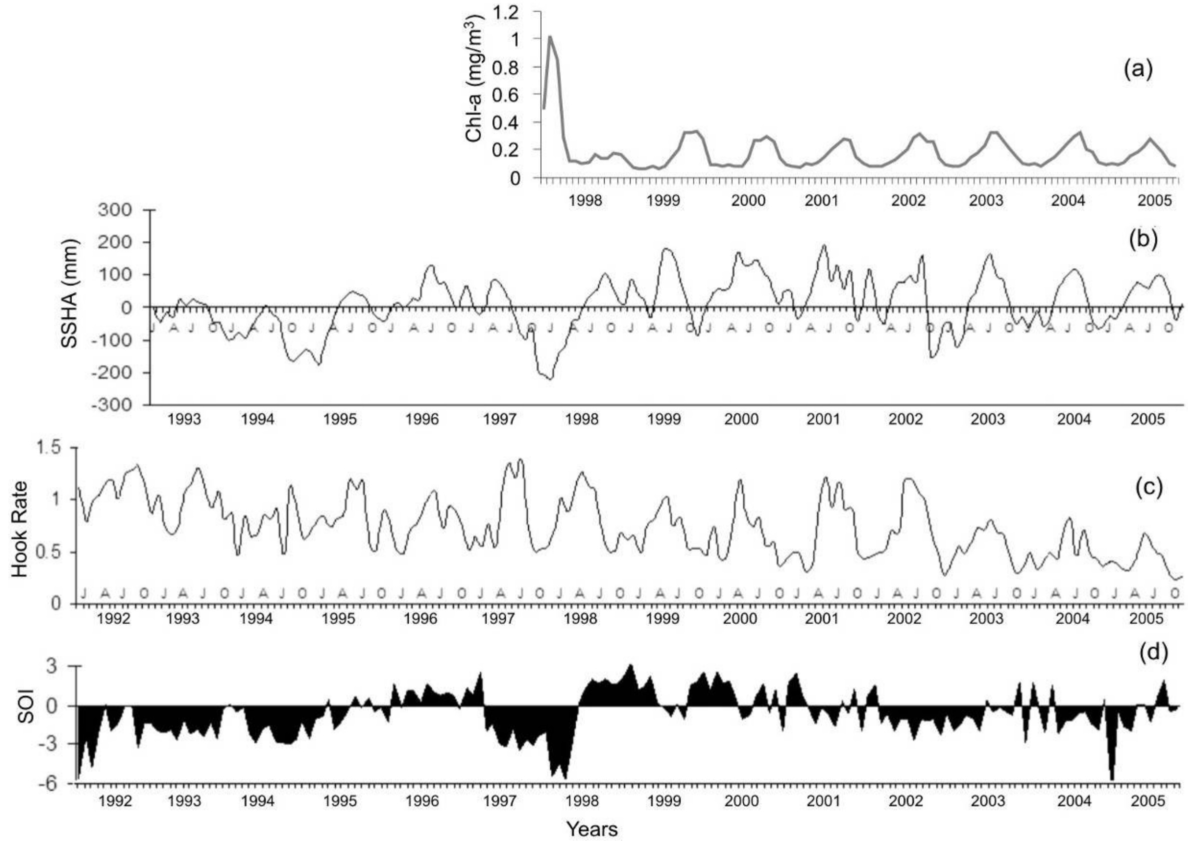

Figure 2. (a) Time series monthly mean of chlorophyll-a concentration (1998-2005) , (b) SSH anomaly (1993-2005), (c) bigeye tuna HR (1992-2005), and (d) SOI index.

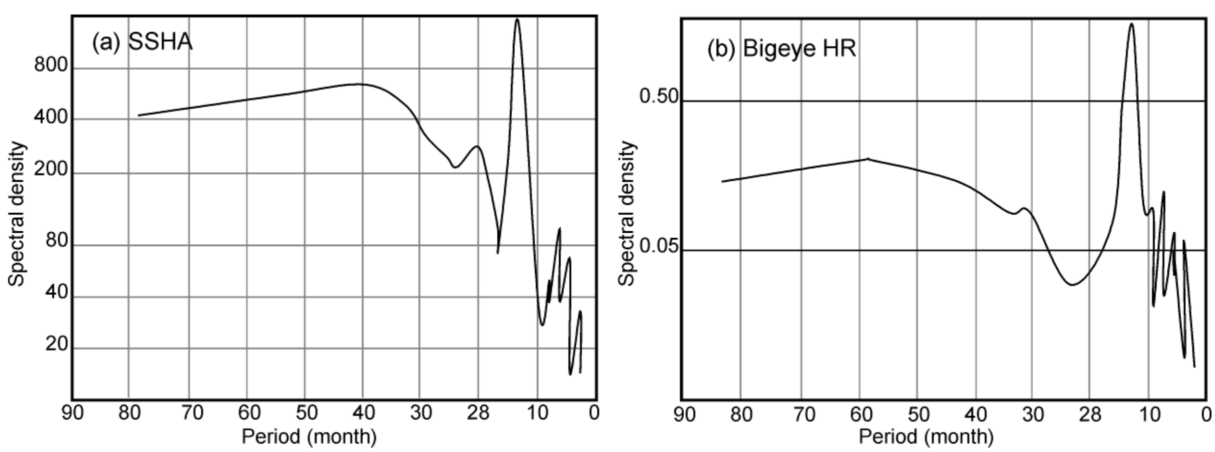

Figure 3. Spectral density of SSH anomaly (a), and Bigeye tuna HR in eastern Indian Ocean.

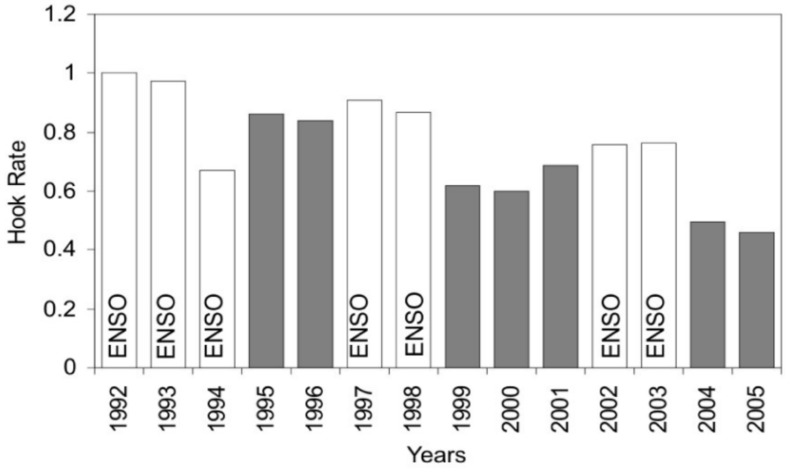

Figure 4. Yearly mean of bigeye tuna hook rate base on data of bigeye tuna (1992-2005).

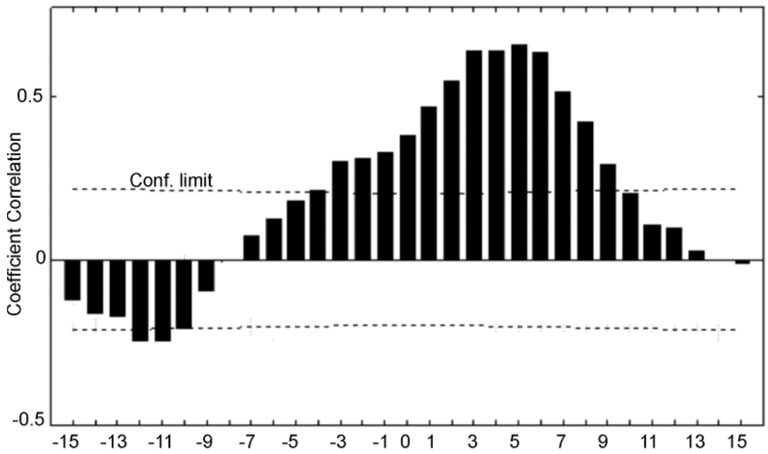

Figure 5. Cross correlation coefficient between SOI and SSH anomaly.

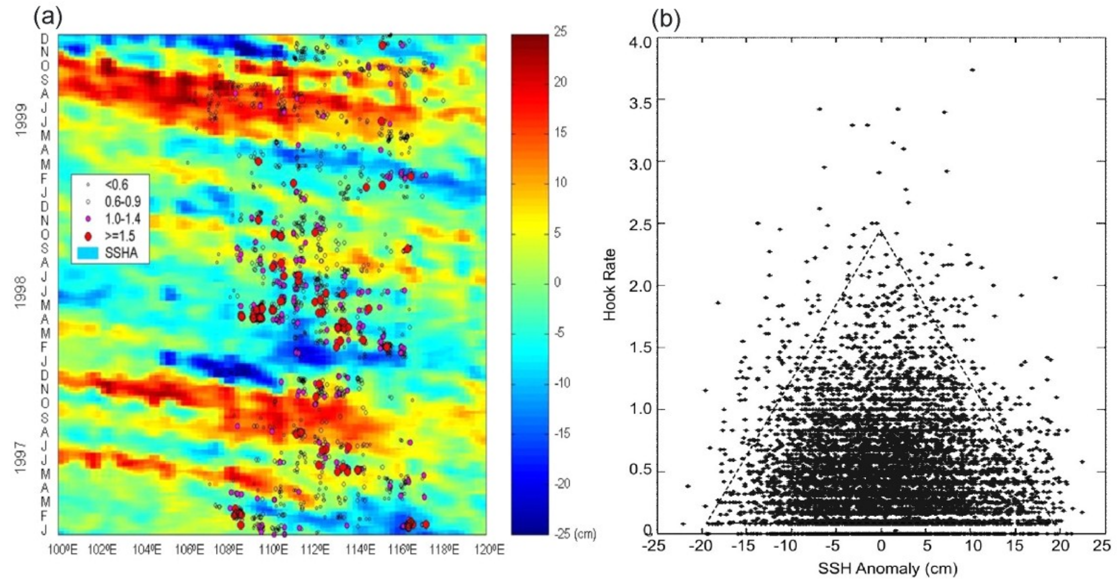

Figure 6. (a) Time-longitute Hovmuller plot between daily bigeye tuna HR and SSHA at 12^{o}S, and (b) Scatter plot of bigeye tuna HR and SSHA.

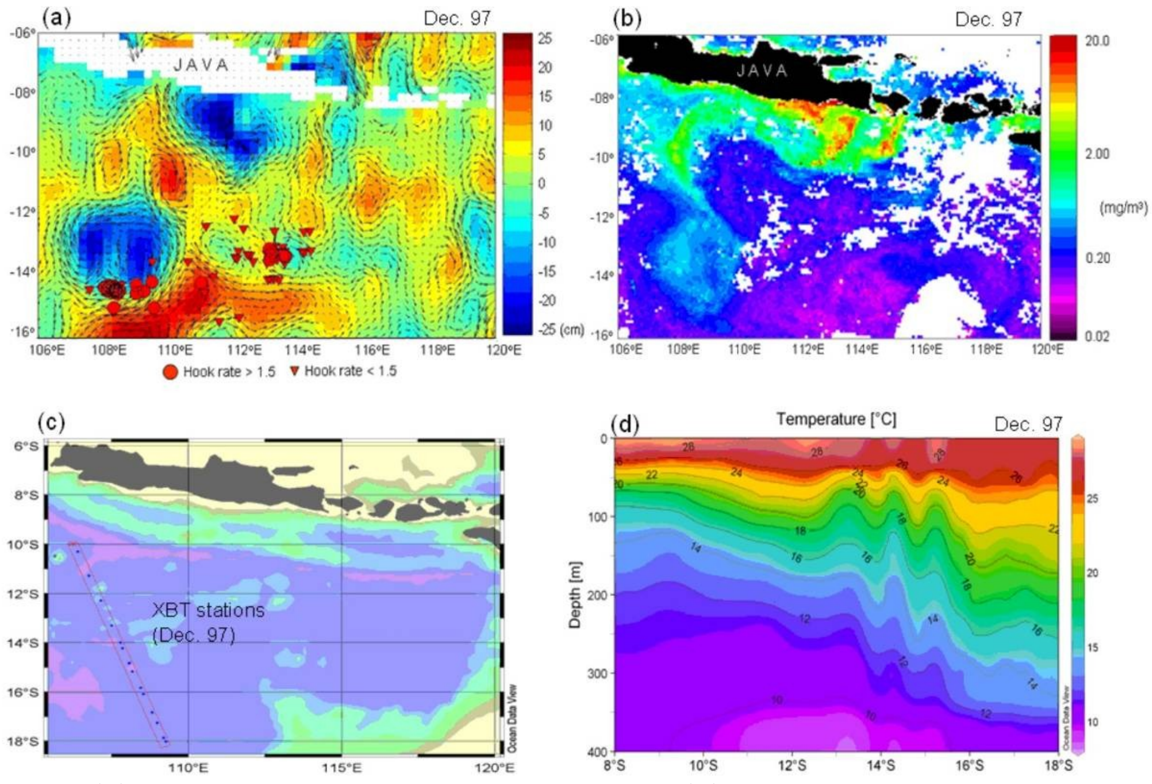

Figure 7. (a) Bigeye tuna HR overlaid on SSH anomaly, (b) Distribution of monthly mean (Dec. 1997) of chlorophyll-a, (c) XBT stations in EIO, and (d) meredional section of temperature when eddies well formed during El Niño.

Appendix 4: Workshop and Training on Coastal Altimetry 2011

4.1 Summary

The first workshop activities conducted at Royal Hotel, Bogor in 16 November 2011. The workshop involves training participants and policy makers, was attended by 150 participants. At the workshop invited speakers from several related institutions, such as the Ministry of Research and Technolgy, and Bogor Agricultural University and National Coordinating Agency for Surveys and Mapping (BAKOSURTANAL)

The training was conducted after the workshop with activities involving 2 lecturers. The number of participants were 35 local scientists and 1 person from Vietnam. The topics of training is basic of altimeter remote sensing and basic data processing with Matlab software. That material for training has been prepared by Dr. Robert Leben, and Dr. Stefano Vignudelli

4.2 Agenda of Workshop

International Workshop on Coastal Altimetry
16 November 2011 – Hotel Royal Bogor Indonesia

Session I (Moderator: Dr. Khafid)

08.30 – 09.00	Registration
09.00 – 09.20	Opening Dr. Asep Karsidi (Head of Bakosurtanal)
09.20 – 09.30	A Brief Introduction to the RESELECASEA Project **Dr. Parluhutan Manurung**
09.30 – 10.00	Sea Level Past Present and Future **Prof. Robert R Leben**
10.00 – 10.15	Photo Session, Press Release and Break

Session II (Moderator: Dr. Parluhutan Manurung)

10.15 – 10.45	Deepwater Satellite Altimetry **Prof. Robert R Leben**
10.45 – 11.00	A Brief Introduction to Tide Gauge Network of Indonesia **Dr. Khafid**
11.00 – 12.00	Coastal Altimetry **Dr. Stefano Vignudelli**
12.00 – 13.00	Break and Lunch

Session III (Moderator: Dr. Parluhutan Manurung)

13.00 – 13.45	Application to Ocean Monitoring and Marine Industry **Prof. Robert R Leben**
13.45 – 14.00	Application to Marine Fisheries **Dr. Jonson L Gaol**
14.00 – 14.15	Marine Atmospheric Modelling **Dr. Ibnu Sofian**
14.15 – 15.00	Application to Global Change Monitoring **Prof. Robert R Leben**
15.00 – 15.45	Future Satellite Altimetry Mission **Dr. Stefano Vignudelli**
15.45 – 16.00	Closing

4.3 List of Workshop Participants

International Workshop on Coastal Altimetry
The RESELECASEA Project

Hotel Royal Bogor, 17 November 2011

Asep Karsidi, Dr
Head of BAKOSURTANAL/BIG
Hp:
Email:

Nguyen Chi Cong
Vien Hai duong hoc
Vietnam
Hp: +84583590208
Email: nguyenechong@yahoo.com

Stefano Vignudelli, Dr.
ENR
Hp: ++39-030-3152504
Email: vignudelli@pi.ibf.cnr.it

Yusuf Surachman
Deputi Head of IDS, BAKOSURTANAL
Hp:
Email: iyung24@gmail.com

Budy Andhono
Sekretariws Utama BAKOSRTANAL
Hp:
Email:

Bisman Nababan
Bogor Agricultural University (IPB)
Hp: 081317325601

Poentodewo SSO, Dr. Ir, M.Surv.Sc
Deputy Head of Pemetaan Dasar, BAKOSURTANAL
Ph:021 8763066
email: putodewo@bakosurtanal.go.id

Robert Leben, Prof.
Univ of Colorado, USA
Ph : 013034992324
Email : leben@colorado.ed.id

Laily
ANTARA
Hp: 081365061460
Email: lailyantara13@yahoo.com

Leni Sofia, Dr.
UGM-Geodesi
Hp: 081804001460
Email : iheliani@ugm.ac.id

M. Hasanudin
P2O-LIPI
Hp: 081318575498
Email: hasanudin76@yahoo.com

Priyadi Dwi Santoso
P2O-LIPI
Hp: 08128329486

Email: s imson_nababan@yahoo.com

Teguh Prayogo
LAPAN
Hp:081511258787
Email: teguhpray060@yahoo.com

Dimas HS
Research
Hp:-
Email: dimas.h.s@gmail.com

Dominir
ITB
Hp: 085220104460
Email: ocea916@gmail.com

Treguh Fayakun A
Research
Hp: 081399910776
Email: goeh98@gmail.com

Budi Prabowo
Surveyor
Hp: 08129005490
Email :

Sri Pujiyati
ITK-IPB
Hp:08128431454
Email: sripujiyati@yahoo.com

Agus Ahmad Riza
DIREKTORAT PELABUHAN, HUBLA
Hp: 08151672659
Email: agusahmedriza@gmail.com

Muhammad Ramdhan
DKP
Hp:0751 751458
Email: m.ramdhan@kkp.go.id

Mathin Matulessy
IPB
Hp:081344568291
Email: marthinmatulessy@yahoo.com

Bambang Sudarsono
Geodesi UNDIP
Hp: 0813255503939
Email: bambang_f220@yahoo.com

Email: priy.ds@yahoo.com

Tofan Rindoyo
Dit. Kenavigasian, KEMNEHUB
Hp: 08121121021
Email: mdonar13@yahoo.com

Surono
Dit Pel Peng- DJPL
Hp: 08129752949
Email: suronocapt@yahoo.com

Stefano Vigujrui
ENR
Hp: +39-0503132804
Email: vignujrui@Pi.ibf.cnr.it

Aninda WisaksantiR. MS
ITK-IPB
Hp: 081991001350
Email: viva.ninda@gmail.com

Ulfi Perdanawati
RISTEK
Hp:08126785707
Email: ulfi@ristek.go.id

Maya Scorina P
BAKOSURTANAL
Hp: 081281557080
Email: maya_scoryna@yahoo.com

Athur yordan Herwindya, S.Kel
Staf Seksi Survei BPPT
Ph: 081237213929
Email: athur.yordana@bppt.go.id

Nani Widiawati
BAKOSURTANAL
Hp:
Email:

Joko Ananto, ST. M.Sc
Research
Ph:08119103763
email: j-ananto@yahoo.com

Ahmad Y SKom,
Research
Ph:
email: ahmaddyb@gmail.com

Khafid, Dr. Ing
Research, BAKOSURTANAL
Ph:08111492516
email: khafid67@yahoo.com

Huda
Puslitbang-SDA, PU
Hp: 082117700060
Email: huda.bahtiar@yahoo.com

Sri handayani
Research
Ph: 081310329284
Email; any_hakam@yahoo.com

Diyah Novita Kurnianti
Research
Ph: 081317991169
Email: diyahnovita@yahoo.com

Dyah Pangastuti
Research
Ph:08119104844
email: dyahpangastuti@yahoo.com

Win Is Bale
BAKOSURTANAL
Hp: -
Email: -

Yuni Cahyawati
BAKOSURTANAL
Hp: 081382208863
Email: yuni.cahyawati@bakosurtanal.go.id

Nyoman MN Natih
ITK-IPB
Hp:081314440065
Email: natih@ipb.ac.id

Risti E. Arhatin
lecturer
Bogor Agricultural University (IPB)
ph:08129697142
email: ristyend@yahoo.com

Leo Suban
Arpindo
Hp: 08129066059
Email :Leo.suban@gmail.com

Johnson MS
Research
Hp: 081382242709
Email: -

Danan SN
BAKOSURTANAL
Hp: 08157921748
Email: danansetyo@gmail.com

Ali Nurmoko
Research
Hp: -
Email: ali.nurmoko@gmail.com

Harry Ferdiansyah
Research
Hp:
Email: harrep@gmail.com

Dewayani
Research
Hp: 08121103177
Email: dewayani@gmail.com

Arif Rahman
RISTEK
Hp: 3169169
Email: arif@ristek.go.id

Agus Setiawan
BROK
Hp:08172335662
Email: setiawan.agus@gmail.com

Prayuda Hartanto
ITB
Ph; prayuda_12a7@yahoo.com
email: 085880039886

Ditha Daratama
ITB
Hp: 085220123366
Email: ditha13@gmail.com

Bimo Fachrizal Arvianto, S.Si
BAPPENAS
Ph:021 31934195
email: bimo.arvianto@bappenas.go.id

Dr. Jonson Lumbangaol,
BOGOR AGRICUTURE INSTITUTE (IPB) Kampus Darmaga Bogor
Ph;081317070990
email: jonsonrt@yahoo.com

Sri Suryo
RISTEK_P3TKP
Hp:08136579570
Email: suryo_dkp@yahoo.com

Fanani hendy khusuma
ITB
Ph:081321006464
email: fanani.hendy@gmail.com
Rully Rianoverdy
BAKOSURTANAL
Hp: 08561611714
Email: -

Santi Ardianti
PDKK-BAKOSURTANAL
Hp:-
Email: santiardianti@gmail.com

Mimin Siti Aminah
Pusat PDKK-BAKOSURTANAL
Hp:081511357000
Email:-

Wiweka, Dr.
Researcher
Hp: 08126141478
Email: wiweka@yahoo.com

Winhard Tampubolon
Research
Hp; 087845937007
Email: winhard@bakosurtanal.go.id

Andi Aswad
Ditnav DSPL
Hp:
Email : capt_andiaswad@yahoo.co.uk

Arief FA
PT FUGRO
Hp:-
Email: arieff@fugro.co.id

Mustafa Hanafi, Ir., M.Si
Perekayasa Madya
Jl. Junjunan No.236 Bandung
Ph: 081321680340
Email:- mhanafi_mgi@yahoo.com

Andhita triwahyuni
CRESOS Udaya of University
Ph; 08569818940
Email. Dhit4bimanyu@gmail.com

Ujang Udin Naro
BAKOSURTANAL
Hp:081574194069
Email :
Danih
BAKOSURTANAl
Hp;081317043395
Email:-

Ratih destarina
Research
Hp;085746100541
Email; dezta_keiran@yahoo.com

Nguyen Chi Cong
Vien Hai duong hoc
Vietnam
Hp: +84583590208
Email: nguyenechong@yahoo.com
Antony
KOMPAS
Hp:085729051144
Email: gal@kompas.com

Mia
RADAR BOGOR
Hp: 085682222140
Email; miaradarbogor@yahoo.com

Ardhasena Sopaheluwakan, Dr.
BMKG, Pusat Perubahan Iklim & Kwalitas udara
Ph:0811218563
email: ardhosena@bmkg.go.id

Boedi Hendrarto, ph.D
Ketua Jurusan Perikanan, PFIK-UNDIP
Ph:08122514658
Email: bhendrarto588@gmail.com

P Djalu
DIDHIDROS-AL
Hp:-
Email; mr.dj14673@yahoo.co.id

Supriyatna
STAF BALITKA-BAKOSURTANAL
Ph: 08121911837
Email: yats45@yahoo.com

Eko Yuli Handoko
ITS
Ph;085852605456, 031 5929487
email: ekoyh@geodesy.its.ac.id

4.4 Agenda of Training

International Training on Coastal Altimetry
& RESELECASEA Kick off Meeting
17-18 November 2011 – Hotel Royal Bogor Indonesia

Thursday 17 November 2011

Training Course Session I (Moderator: Dr. Jonson L Gaol)

08.00 – 10.00	Data Processing **Prof. Robert R Leben**
10.00 – 12.00	Re-tracking **Dr. Stefano Vignudelli**
12.00 – 13.00	Break

Training Course Session II (Moderator: Dr. Parluhutan Manurung)

13.00 – 15.00	Re-tracking (con't) **Dr. Stefano Vignudelli**
15.00 – 17.00	CSEOF **Prof. Robert R Leben**
17.00 – 19.00	Exercise and Consultation
19.30 – 21.00	Dinner

Kick off Meeting

Friday 18 November 2011

09.00 – 11.00	Research Products
11.00 – 12.00	Discussion on Field Validation
12.00 – 13.00	Break
13.00 – 15.00	Discussion on Publication
15.00 – 16.00	Agenda of Next Meeting (June 2012)
16.00 –	Closing

4.5 List of Training Participants

International Training on Coastal Altimetry
The RESELECASEA Project
Hotel Royal Bogor, 18 November 2011

Nguyen Chi Cong
Vien Hai duong hoc
Vietnam
Hp: +84583590208
Email: nguyenechong@yahoo.com

Robert Leben, Prof.
Univ of Colorado, USA
Ph : 013034992324
Email : leben@colorado.ed.id

Stefano Vignudelli, Dr.
ENR
Hp: ++39-030-3152504
Email: vignudelli@pi.ibf.cnr.it

M. Hasanudin
P2O-LIPI
Hp: 081318575498
Email: hasanudin76@yahoo.com

Bisman Nababan
Bogor Agricultural University (IPB)
Hp: 081317325601
Email: s imson_nababan@yahoo.com

Priyadi Dwi Santoso
P2O-LIPI
Hp: 08128329486
Email: priy.ds@yahoo.com

Teguh Prayogo
LAPAN
Hp:081511258787
Email: teguhpray060@yahoo.com

Teguh Fayakun A
Research
Hp: 081399910776
Email: goeh98@gmail.com

Budi Prabowo
Surveyor
Hp: 08129005490
Email :

Aninda Wisaksanti R. MS
ITK-IPB
Hp: 081991001350
Email: viva.ninda@gmail.com

Muhammad Ramdhan
DKP
Hp:0751 751458
Email: m.ramdhan@kkp.go.id

Athur Yorda Herwindya, S.Kel
Staf Seksi Survei BPPT
Ph: 081237213929
Email: athur.yordana@bppt.go.id

Mathin Matulessy
IPB
Hp:081344568291
Email: marthinmatulessy@yahoo.com

Khafid, Dr. Ing
Research, BAKOSURTANAL
Ph:08111492516
email: khafid67@yahoo.com

Huda
Puslitbang-SDA, PU
Hp: 082117700060
Email: huda.bahtiar@yahoo.com

Sri handayani
Research
Ph: 081310329284
Email; any_hakam@yahoo.com

Dyah Pangastuti
Research
Ph:08119104844
email: dyahpangastuti@yahoo.com

Dr. Jonson Lumbangaol,
BOGOR AGRICUTURE INSTITUTE (IPB) Kampus Darmaga Bogor
Ph;081317070990
email: jonsonrt@yahoo.com

Fanani hendy khusuma
ITB
Ph:081321006464
email: fanani.hendy@gmail.com

Eko Yuli Handoko
ITS
Ph;085852605456, 031 5929487
email: ekoyh@geodesy.its.ac.id

Roni Sinaga
Research Consultan
Ph: 081322395655
Email: rony_y2kdragon@yahoo.com

Joko Ananto, ST. M.Sc
Research
Ph:08119103763
email: j-ananto@yahoo.com

Ahmad Y SKom,
Research
Ph:
email: ahmaddyb@gmail.com

Dudy, Dr.
Department of Geodesy ITB
Hp: +6285888669236
Email: dudy@gd.itb.ac.id

Diyah Novita Kurnianti
Research
Ph: 081317991169
Email: diyahnovita@yahoo.com

Risti E. Arhatin
lecturer
Bogor Agricultural University (IPB)
ph:08129697142
email: ristyend@yahoo.com

Andhita Triwahyuni
CRESOS Udaya of University
Ph; 08569818940
Email. Dhit4bimanyu@gmail.com

Ratih Destarina
BAKOSURTANAL
Hp: 085746100541
Email; dezta_keiran@yahoo.com

Parluhutan Manurung, Dr.
BAKOSURTANAL
RESELECASE Project Coordinator
Hp: +6281510002628
Email: parluhutan@bakosurtanal.go.id

Sella Lestari
Department of Geodesi ITB
Ph:
Email: sella_own@yahoo.com

4.6 List of Training and Workshop Presentations

1. About The RESELECASEA Project by Dr. Parluhutan Manurung
2. Sea Level Past, Present, and Future Basic by Prof. Robert R Leben
3. Introduction to Deep Water Satellite Altimetry by Prof. Robert R Leben
4. Satellite Altimetry Applications: Ocean Monitoring and Marine Industry by Prof. Robert R Leben
5. Satellite Applications: Climate Monitoring by Prof. Robert R Leben
6. Future Satellite Altimetry Mission by Prof. Robert R Leben
7. Future Satellite Altimetry Mission by Dr. Stefano Vignudelli
8. Introduction to Deep Water Satellite Altimetry by Prof. Robert R Leben
9. Satellite Altimetry Applications: Ocean Monitoring and Marine Industry by Prof. Robert R Leben
10. CSEOF Matlab Code Readme by Prof. Robert R Leben
11. Future Satellite Altimetry Missions by Dr. Stefano Vignudelli
12. Coastal Altimetry Matlab Toolbox by Dr. Stefano Vignudelli

The full presentations are displayed in Appendix 11.

Appendix 5: Workshop and Training on Coastal Altimetry 2012

5.1 Summary

The second training has been conducted in Hotel Royal in Bogor on November 12-13 , 2012. The training activities with involving 5 lecturers have trained approximately 30 Indonesia local scientists who are able to process sea level from satellite altimetery data for coastal and offshore waters. The data were processed and analyzed by using Matlab software which has been prepared by Dr. Robert Leben, Dr. Stefano Vignudelli, and Dr. Benjamin Hamlington for Training Modules. Dr. Parluhutan Manurung was demonstrated the BRAT software for prosessing altimetry data, and Dr. Jonson L. Gaol presented the applications of altimetry data for assesssment of tuna fishing ground.

The second workshop conducted at Royal Hotel, Bogor in 14 November 2012 was attended by 80 participants. Invited speakers from several related institutions, such as the Ministry of Research and Technolgy, Bureau of Meteorology, National Institute of Aeronautics and Space Aerospace, Geospatial Information Agency (BIG) and Bogor Agricultural University.

5.2 Agenda of Training

International Training on Coastal Altimetry
The RESELECASEA Project

Hotel Royal Bogor, 12 – 13 November 2012

Training Course, Monday 12 November 2012

08.30 – 09.00	Registration
09.00 – 09.15	Opening
09.15 – 10.45	Basic theory of satellite altimetry and data products **Prof. Robert R Leben**
10.45-11.00	Break
11.00-12.30	Waveform in coastal altimetry Reading netcdf format and Matlab Tool **Dr. Stefano Vignudelli** **Dr. Parluhutan Manurung**
12.30-13.30	Break and Lunch
13.30 – 14.45	Data processing with BRAT **Dr. Parluhutan Manurung and team**
14.45-15.00	Break
15.00-17.00	Understanding CSEOF **Prof. Robert R Leben & Dr. Benjamin Hamlington**
17.00-19.30	Break and Dinner

Training Course, Tuesday 13 November 2012

08.00-09.45	Retracking Basic and Geophysical corrections in coastal region **Dr. Stefano Vignudelli & Dr. Parluhutan Manurung**
09.45-10.00	Break
09.15 – 10.45	CSEOF excercise; using tidegauge and altimeter data **Dr. Benjamin Hamlington**
10.45-11.00	Break
11.00-12.30	Validation of satellite altimetry with tidegauge **Dr. Stefano Vignudelli**
12.30-13.30	Break and Lunch
13.30 – 14.45	Satellite altimetry application for Fisheries **Dr. Jonson Lumban Gaol**
14.45-15.00	Break
15.00-17.00	Reconstruction of Sea Level change in SE Asia **Prof. Robert R Leben & Dr. Benjamin Hamlington**
17.00	Closing

5.3 List of Training Participants

International Training on Coastal Altimetry
The RESELECASEA Project
Hotel Royal Bogor, 12 – 13 November 2012

Parluhutan Manurung, Dr.
Geospatial Information Agency,
head of Centre Geodesy (BIG)
ph:
email: Parluhutan@bakosurtanal.go.id

Ibnu Sofyan, Dr.
Geospatial Information Agency,
Head of JKGPS (BIG)
ph:
email: ibnusofyan@bakosurtanal.go.id

Stefano Vignudelli, Dr.
ENR
Hp: ++39-030-3152504
Email: vignudelli@pi.ibf.cnr.it

Robert Leben, Prof.
Univ of Colorado
Ph : 013034992324
Email : leben@colorado.edu

Benjamin Hamlington, Dr.
Univ of Colorado
Ph : 013034992324
Email : bhamlington@gmail.com

Risti E. Arhatin
lecturer
Bogor Agricultural University (IPB)
ph:08129697142
email: ristyend@yahoo.com

Aninda W. Rudiantuti
lecture
Bogor Agricultural University (IPB)
ph:081991001350
email:anindarudiastuti@gmail.com

Elisa Harlia Sandi
research
Geospatial Information Agency (BIG)
ph:085647495669
email: elisa.liasandi@gmail.com

Dian Novianto
CRESSOS UNUD
ph:081327173093
email:Novianto_dian@yahoo.com

Furqon Alfahmi
Meteorologists, Climatology and
Geophysics (BMKG)
ph:085288141980
email: furqonnalfahmi@yahoo.com

Nugraha Widyatmono
CRESSOS UNUD
ph:08562764422
email:nugraha@alumni.undip.ac.id

Marthin Matulesy
Bogor Agricultural University (IPB)
ph:081280554063
email:marthmonatulesy@yahoo.com

Andhika Hermawanto
Meteorologists, Climatology and Geophysics (BMKG)
ph:081355106986
email:andhikaher@gmail.com

Meilani Pamungkas
lecturer
Bogor Agricultural University (IPB)
ph:081806235772
email:meilanipamungkas@gmail.com

Bisman Nababan
lecturer
Bogor Agricultural University (IPB)
ph:081317325601
email:Simson_nababan@yahoo.com

Arisauna M Pahlevi
Reseach
Geospatial Information Agency (BIG)
ph:085649421317
email:Arisauna.pahlevi@gmail.com

Dyah Novita K
Research
Geospatial Information Agency (BIG)
ph:081317991169
email:diyahnovit@yahoo.com

Joko Ananto
Research
Geospatial Information Agency (BIG)
ph:08119103763
email:j_ananto@yahoo.com

Rossi Hamzah
National Aeronautics and Space Institute (LAPAN)
ph:0856212163016
email: Rossi.hamzah@lapan.com

Dewangga
Surabaya Technology Institute 9ITS)
ph:08563141009
email: dewanggaeka@gmail.com

Kadek Surya Sumerta
Bogor Agricultural University (IPB)
ph:081280451227
email: kadeksuryasumarta@gmail.com

Eki Riyanti S
Research
Geospatial Information Agency (BIG)
ph: 081213430510
email: egryanti@gmail.com

Sri Handayani
Research
Geospatial Information Agency (BIG)
ph:081310329284
email: Any.hakam@yahoo.com

Buldan Muslim
Research
National Aeronautics and Space Institute (LAPAN)
ph:087722481132
email: mbuldan@yahoo.com

Teguh Prayogo
Research
National Aeronautics and Space Institute (LAPAN)
ph:081511258787
email: Teguh.prayogo@lapan.com

Deasy Tresnoningrum
Research
National Aeronautics and Space I
nstitute (LAPAN)
ph:08158791750
email: deasycito@gmail.com

LM Sabri
Lecturer
Diponegoro of University, UNDIP
ph:085623112131
email:sabri@yahoo.com

Bayu Triyogo
Research
Geospatial Information Agency (BIG)
ph:08119104847
email: Bayu_triyogo@yahoo.com

Yadi Aryadi
Research
Geospatial Information Agency (BIG)
ph:08119104852
email: yadi1975@yahoo.com

5.4 Agenda of Workshop

International Workshop on Coastal Altimetry
The RESELECASEA Project

Hotel Royal Bogor, 14 November 2012

08.30 – 09.00	Registration
09.00-09.15	Report on the Reselecasea Project
	Dr Parluhutan Manurung
09.15 – 09.40	Geospatial Information Supporting Global Warming Monitoring
	Head of BIG
09.40 - 10.00	National Initiative on Satellite-based Marine Monitoring
	Head of National Institute of Aeronautics and Space (LAPAN)
10.00 - 10.20	Opening Speech
	Minister of Reasearch and Technology
10.20 - 10.40	Break
	PRESS CONFERENCE (Media and TV) and Poster Session
	Session I: Moderated by: Dr. Parluhutan Manurung
10.40 - 11.10	Coastal Satellite Altimetry Progress Development and Applications
	Dr Stefano Vignudelli (CNR – Italy)
11.10 - 11.40	Reconstruction of Sea level Change in South East Asia
	Prof. Robert R Leben (CCAR Univ of Colorado, USA)
11.40 – 12.00	Discussion
12.00 – 13.30	Break
	Session II: Moderated by: Agus Hidayat (LAPAN)
13.30 - 13.40	Monitoring Tsunami based on Satellite Altimetry
	Dr Benjamin Hamlington (CCAR Univ of Colorado, USA)
13.40 – 14.00	Indonesian Tidal Model
	Dr Ibnu Sofian (BIG)
14.00 – 14.20	Satellite Altimetry Application for Fisheries
	Dr. Jonson Lumban Gaol (IPB)
14.20 – 14.40	Introduction to Satellite Altimetry Web Database
	Dr. Parluhutan Manurung (BIG)
14.40 – 15.00	Discussion
15.00 – 15.15	Break
15.15 – 15.45	**Recomendation of the Workshop**
15.45 – 16.00	Closing

5.5 List of Workshop Participants

International Workshop on Coastal Altimetry
The RESELECASEA Project

Hotel Royal Bogor, 14 November 2012

Imam Mudita
Research
Agency for the Assessment and Application of Technology (BPPT)
Ph:08567797916
email: Imam.mudita@bppt.go.id

Risti E. Arhatin
lecturer
Bogor Agricultural University (IPB)
ph:08129697142
email: ristyend@yahoo.com

Aninda W. Rudiantuti
lecture
Bogor Agricultural University (IPB)
ph:081991001350
email:anindarudiastuti@gmail.com

Dian Novianto
CRESSOS UNUD
ph:081327173093
email:novianto_dian@yahoo.com

Nugraha Widyatmono
CRESSOS UNUD
ph:08562764422
email:nugraha@alumni.undip.ac.id

M. Ramdhan
Reseach
Balitbang KP
ph:08217150745
email: m.ramdan@kkp.go.id

Yadi Aryadi
Research
Geospatial Information Agency (BIG)
ph:08119104852
email: yadi1975@yahoo.com

Elisa Harlia Sandi
Research
Geospatial Information Agency (BIG)
ph:085647495669
email: elisa.liasandi@gmail.com

Furqon Alfahmi
Meteorologists, Climatology and Geophysics (BMKG)
ph:085288141980
email: furqonnalfahmi@yahoo.com

Rossi Hamzah
National Aeronautics and Space Institute (LAPAN)
ph:0856212163016
email: Rossi.hamzah@lapan.com

Marthin Matulesy
lecture
Bogor Agricultural University (IPB)
ph:081280554063
email:marthmonatulesy@yahoo.com

Andhika Hermawanto
research
Meteorologists, Climatology and Geophysics (BMKG)
ph:081355106986
email:andhikaher@gmail.com

Meilani Pamungkas
lecturer
Bogor Agricultural University (IPB)
ph:081806235772
email:meilanipamungkas@gmail.com

Bisman Nababan
lecturer
Bogor Agricultural University (IPB)
ph:081317325601
email:Simson_nababan@yahoo.com

Arisauna M Pahlevi
research
Geospatial Information Agency (BIG)
ph:085649421317
email:Arisauna.pahlevi@gmail.com

Dyah Novita K
Research
Geospatial Information Agency (BIG)
ph:081317991169
email:diyahnovit@yahoo.com

Joko Ananto
Research
Geospatial Information Agency (BIG)
ph:08119103763
email: j_ananto@yahoo.com

LM Sabri
Diponegoro of University, UNDIP
ph:085623112131
email:sabri@yahoo.com

Dewangga
lecture
Surabaya Technology Institute (ITS)
ph:08563141009
email: dewanggaeka@gmail.com

Kadek Surya Sumerta
Lecture
Bogor Agricultural University (IPB)
ph:081280451227
email: kadeksuryasumarta@gmail.com

Eki Riyanti S
Research
Geospatial Information Agency (BIG)
ph: 081213430510
email: egryanti@gmail.com

Sri Handayani
Research
Geospatial Information Agency (BIG)
ph:081310329284
email: Any.hakam@yahoo.com

Buldan Muslim
research
National Aeronautics and Space Institute (LAPAN)
ph:087722481132
email: mbuldan@yahoo.com

Teguh Prayogo
research
National Aeronautics and Space Institute (LAPAN)
ph:081511258787
email: Teguh.prayogo@lapan.com

Deasy Tresnoningrum
Research
National Aeronautics and Space Institute (LAPAN)
ph:08158791750
email: deasycito@gmail.com

Bayu Triyogo
Geospatial Information Agency (BIG)
ph:08119104847
email:Bayu_triyogo@yahoo.com

Parluhutan Manurung
Geospatial Information Agency, head of Centre Geodesy (BIG)
ph: 081510002628
email: parluhutan@bakosurtanal.go.id

Danu Andrian
Bogor Agricultural University (IPB)
ph:085719529623
email:Danu.andrian24@gmail.com

Heron Surbakti
University of Sriwijaya
ph:085267009495
email: heronsurbakti@gmail.com

Suci Wulandari
Research and Technology (Ristek)
ph:08128102675
email: wulan@ristek go.id

Suryanta Bayuaji
Ministry of Environment (KLH)
ph:-
email: s.bayuaji@menlh.go.id

Tommy Nautico
Geospatial Information Agency (BIG)
ph:081298283789
email: tommy@bakosurtanal.go.id

Ari Rikin
Newspaper (Suara Pembaruan)
ph:081519354343
email: aririkin@gmail.com

Poentodewo SSO
BIG
ph:-
email:-

Poerwoko Djalu
Dishidros TNI AL
ph:082111884866
email:-

Stefano Vigwari
ENR
ph:++39-030-3152504

Ibnu Sofyan
Geospatial Information Agency, Head of JKGPS (BIG)
ph: 08128312873
email: ibnusofyan@bakosurtanal.go.id

Agung T Mandiri
Geospatial Information Agency (BIG)
ph:085222015730
email:-

Kardiman
Geospatial Information Agency (BIG)
ph:08129986647
email:-

Bob Leben
University of Colorado, USA
ph:013034992324
email : leben@colorado.edu

Rizka Windiastuti
Research
Geospatial Information Agency (BIG)
ph:081586064931
email: rizka@bakosurtanal.go.id

Tri Patmasari
Geospatial Information Agency (BIG)
ph:-
email: aryomassari@yahoo.com

Maya Scorina P
Geospatial Information Agency (BIG)
ph:081281557080
email: Maya_scorina@yahoo.com

Jonson L Gaol
IPB
ph:081317070990
email: Jonson_lumbangaol@yahoo.com

Maryani Hartuti
LAPAN
ph:08129695595
email: maryani.hartuti@lapan.go.id

Teguh Prayogo
LAPAN
ph:081511258787

email: vignuni@pi.ibfenr.it

M.Irfan Septiawan
Geospatial Information Agency (BIG)
ph:08119104850
email: irpanseptiawan@yhaoo.com

Haryono
Geospatial Information Agency (BIG)
ph:081310003232
email:haryono@gmail.com

Ipik Ropikoh
Bogor Agricultural University (IPB)
lecture
ph:-
email:-

Bisman Nababan
Bogor Agricultural University (IPB)
lecture
ph:
email:

Win Islamudin Bale
research
Geospatial Information Agency (BIG)
ph:08129632425
email: winisbale@yahoo.com

Enjang Syamsul B
research
Geospatial Information Agency (BIG)
ph:085252918485
email: esyamba_esb@yahoo.com

Arisauna M Pahlevi
research
Geospatial Information Agency (BIG)
ph:085649421317
email: arisauna.pahlevi@gmail.com

Adhya
Lecture
Ibnu Khaldun of university
ph:
email: araditnya@yahoo.com

email: Teguh.prayogo@lapan.go.id

Sri Handayani
research
Geospatial Information Agency (BIG)
ph:081310329284
email: any_hakam@yahoo.com

Marthin Matulesy
Lecture
Bogor Agricultural University (IPB)
ph:
email:
Iwan erik S
Bogor Agricultural University (IPB)
lecture
ph:
email:

Susilo
research
Geospatial Information Agency (BIG)
ph:081282654223
email: susilo@bakosurtanal.go.id

Marsono J
research
Geospatial Information Agency (BIG)
ph:081310071632
email: marsono@bakosurtanal.go.id

Arif
Geospatial Information Agency (BIG)
ph:-
email: arapka@gmail.com

Elisa HS
research
Geospatial Information Agency (BIG)
ph:085647495669
email: Elisa.liasandi@gmail.com

Patria Rahman H
LAPAN
ph:0816623465
email: patriarahmanhakim@yahoo.com

Jafkhairi
Newspapaer (ANTARA)
ph:081316559309
email:

Yuni Ikawati
Newspapaer (KOMPAS)
ph:0811106902
email: yun@kompas.com

Theodora S
Bogor Agricultural University (IPB)
ph:085243060584
email: nonasilubun@gmail.com

Yopi
Newspapaer (POS KOTA)
ph:081315376680
email:yduroh@yahoo.com

Abdul Basith
lecture
Gajah Mada University
ph:085725904600
email: abbasith@yahoo.com

Laily
news agency (ANTARA)
ph:081365061460
email: Lailyantara13@yahoo.com

Rossi H
LAPAN
ph:08562163016
email: Rossi.hanzah@lapan.go.id

Kisni
Newspaper 9PIKIRAN RAKYAT)
ph:081319214123
email: kismi82@yahoo.com

DENI
TRANS BOGOR
ph:085272291400
email: De.hardixan@gmail.com

Yudi
SINDO
ph:081317666136
email: yudi_sindo@yahoo.com

Ariffin T
APSPIG
ph:0811969204
email: Ariffin.tj@gmail.com

Sulawati
Geospatial Information Agency (BIG)
ph:-
email:-

Putra Irawan
Bogor Agricultural University (IPB)
ph:081264318181
email: putrairawan@yahoo.com

Joni efendi
Geospatial Information Agency (BIG)
ph:-
email:-

Lida
Newspaper (REPUBLIKA)
ph:087770060636
email: Puspaningtyas.lida@gmail.com

Dewati
news agency (ANTARA)
ph:08161646932
email:-

Rochayati
Geospatial Information Agency (BIG)
ph:082124175666
email: rochayatirachman@yahoo.com

Sepsha
VOI RRI
ph:082122186624
email: restian.voi@gmail.com

Solihin
LAMPU HIJAU
ph:0815844714257
email: mustakor@gmail.com

Sidik
Newspaper (RADAR)
ph:081800931414
email: bidik_kesap@yahoo.com

Yanto
JAKARTA GLOBE
ph:085692111391
email: vertosodele@yahoo.com

Yadi A
Research
Geospatial Information Agency (BIG)
ph:08119104852
email: yadi1975@gmail.com

Sofie Barlianto
Research
Geospatial Information Agency (BIG)
ph:081211084018
email: s.barlianto@gmail.com

Joko Ananto
Research
Geospatial Information Agency (BIG)
ph:08119103763
email: J_ananto@yahoo.com

Deden S
Geospatial Information Agency (BIG)
ph:-
email:-

Mahatmi
Geospatial Information Agency (BIG)
ph:
email:hatmy.bakosyabig@gmail.com

5.6 List of Training and Workshop Presentations

1. Report on the Reselecasea Project Dr Parluhutan Manurung
2. Basic theory of Satellite Altimetry and Data Products by Prof. Robert R Leben
3. Ccoastal Aaltimetry Comparison by Dr. Stefano Vignudelli
4. Reading netcdf format and Matlab Tool by Dr. Parluhutan Manurung
5. Data processing with BRAT by Dr. Parluhutan Manurung and team
6. Understanding CSEOF by Prof. Robert R Leben & Dr. Benjamin Hamlington (CCAR Univ of Colorado, USA)
7. Retracking Basic and Geophysical Corrections in Coastal Region by Dr. Stefano Vignudelli & Dr. Parluhutan Manurung
8. Reconstructing Sea Level Using CSEOF by Dr. Benjamin Hamlington
9. Satellite Altimetry Application for Fisheries by Dr. Jonson Lumban Gaol (IPB)
10. Reconstruction of Sea Level Change in SE Asia byProf. Robert R Leben & Dr. Benjamin Hamlington
11. Capturing the coastal zone: a new frontier for satellite altimetry by Dr Stefano Vignudelli
12. Sea Level Trends in Southeast Asian Seas by Prof. Robert R Leben
13. Tsunami Detection Using Satellite Altimetry by Dr Benjamin Hamlington
14. Satellite Altimetry Application for Fisheries by Dr. Jonson Lumban Gaol
15. Introduction to Satellite Altimetry Web Database by Dr. Parluhutan Manurung (BIG)

The full presentations are displayed in Appendix 12.

Appendix 6: Website of the RESELECASEA Project

The RESELECASEA Project website s provded to communicate between researchers interested in satellite altimetry data processing and its applications. Some main pages of the website are shown in Figure Appendix 6 and the website can be accessible with the following address:

www.altimetryina.com

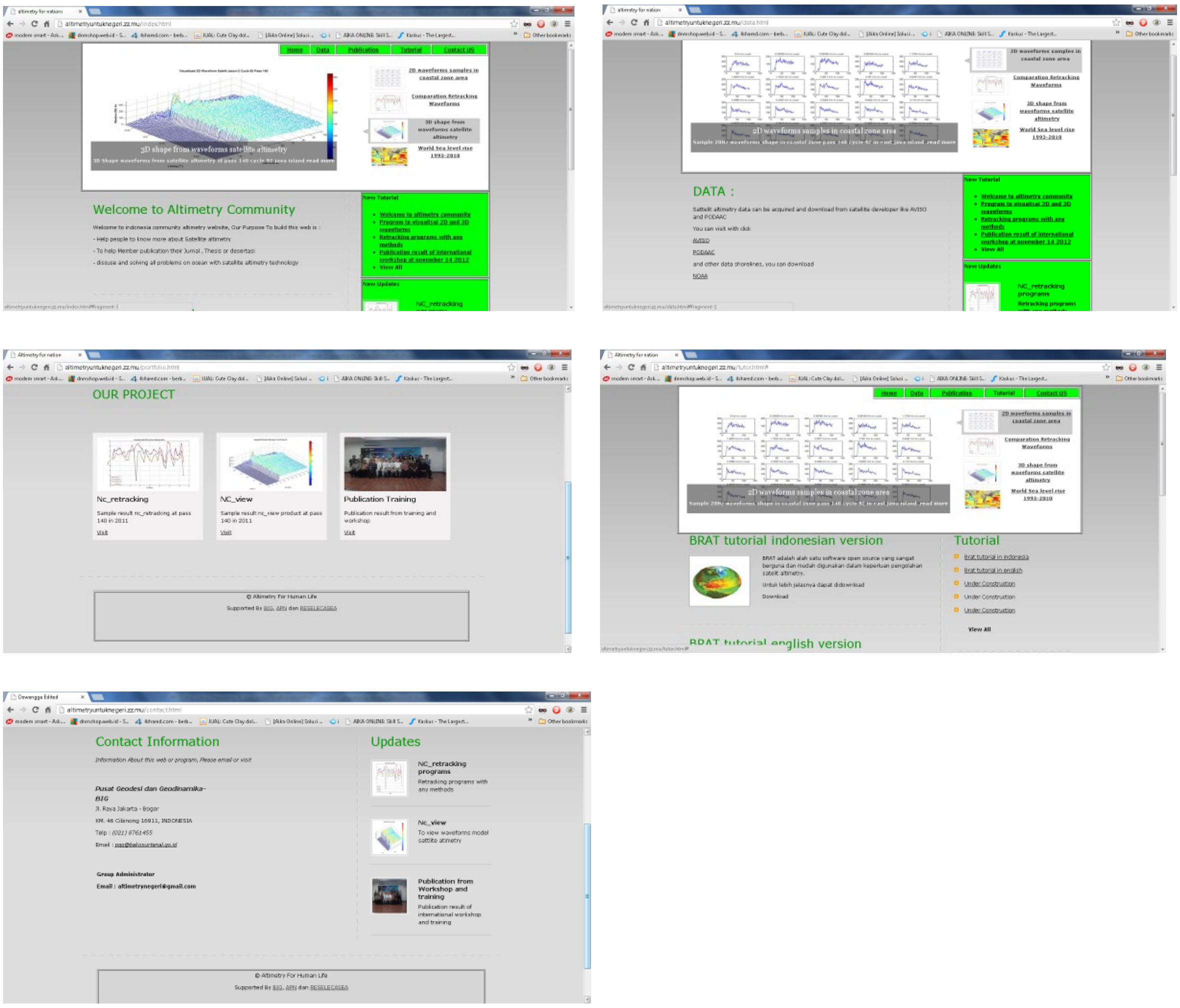

Figure Appendix 6: Display of main pages of the RESELECASEA Project Website.

Appendix 7: Funding sources outside the APN

The co-funding supports are provided by the agencies of research-team members. In-kind supports are not listed.

No	Agencies	Activities	Support (USD)
1.	BIG/BAKOSURTANAL	Workshop on Coastal Altimetry 2011 (Funding Source: DIPA BAKOSURTANAL, 2011)	15,000,-
2.	BIG/BAKOSURTANAL	Workshop on Coastal Altimetry 2012 (Funding Source: DIPA BAKOSURTANAL, 2012)	10,000,-
3.	BIG/BAKOSURTANAL	Supporting Dr. Parluhutan Manurung to Attend Coastal Altimetry 5 in San Diego USA (Funding Source: DIPA BAKOSURTANAL, 2011)	4,000,-
4.	CCAR Univ of Colorado	Supporting Prof Leben to attend Workshop and Training on Coastal Altimetry 2011 in Bogor Indonesia	4,000,-
5.	CNR Italy	Supporting Dr. Stevano Vignudeli to attend Workshop and Training on Coastal Altimetry 2012 in Bogor Indonesia	4,500,-
6.	IPB	Supporting Dr. Jonson Lumban Gaol to attend Pacific Ocean Remote Sensing Conference (PORSEC) 2012 in Kochi India. (Funding Source: DIPA IPB, 2011)	2,000,-

Tabel 1:. *List of Co-Funding Support*

Appendix 8: List of Young Scientists

NO	NAME	Main Activity	IMPRESSION and MESSAGE
1.	Dewangga Eka Mahardian (dewanggaeka@gmail.com)  Undergraduate student, Geomatic Departmet - Institut Teknologi Sepuluh November	Undergraduate Final Project	I am very happy to join this project and training activities in RELESECASEA Project. I build simple script retracking waveforms. Analysis and calculate about sea surface high retracking OCOG at south coastal area java island In future , I hope many training and workshop about retracking waveforms in ndonesia because the ndonesia about retracking waveforms in ndonesia is limited
2.	Meilani Pamungkas (meilani.pamungkas@gmail.com)  Undergraduate sttudent, Bagor Agricultural Institute (IPB)	Undergraduate Final Project	This Altimetry satellite training and workshop is really impressing me. It is cool and useful to enhance your knowledge about altimetry. Where in Indonesia it is not being studied yet. So many people are wonder what is altimetry and the function of altimetry satellite. Indonesia is a little bit late perhaps the lack of supporting facility and interest. So this kind training or workshop have to be developed and informed to Indonesia in order to minimize the gap between Indonesia and preceding state. Because Indonesia have to possess that wide ocean for exploration
3.	Kadek Surya Sumerta (kadeksuryasumerta@gmail.com)  Undergraduate student, Bagor Agricultural Institute (IPB)	Undergraduate Final Project	I am very grateful for the chance to understand about Altimetry and join The RESELECASEA Project. There are many applications to implement and give useful information for people and the government in this country. I hope many experienced scientist will participate and develop more advance programs so people can get the information about the sea

4.	Danu Adrian (danu.adrian24@gmail.com)  Undergraduate student, Bagor Agricultural Institute (IPB)	Undergraduate Final Project	I am very pleased to have the opportunity to join in the activities as participant in International Training on Coastal Altimetry (RESELECASEA Project) and Coastal Satellite Altimetry Workshop. The training and workshop are very interesting and gave me the knowledge of how a satellite capable of monitoring the condition of the sea. I think to be implemented in the territory of Indonesia is very good, because Indonesia is an archipelago country. I think these programs is great and interesting, I hope every year will always be a program like this and always evolving.
5.	Marthin Matulessy (marthinmatulessy@yahoo.com)  Postgraduate student, Bagor Agricultural Institute (IPB)	Postgraduate Thesis	As participants Workshop and Training Coastal altimetry me as a graduate student at the Bogor Agricultural University respond strongly this activity, as one of the newly occupied areas of science, the future with the use of satellite altimetry can explore all the fisheries and marine resources. Activities mentioned above I have followed since the year 2011, and I hope the future will do the same activities aimed at the development of resources in the field of altimetry
6.	ANINDA WISAKSANTI RUDIASTUTI (anindarudiastuti@gmail.com)  Young researcher, Bagor Agricultural Institute (IPB	Research	"An enormous gratitude for the opportunity joined the APN project. It is very good experience for young scientist to start exploring altimeter. This project brings a lot of positive things in science. Particularly, overall training from APN project went well organized with pretty solid load, and with several experts in altimetry who are very helpful in understanding and provide lots of information about data sources and processing. This project providing knowledge and enhancing skills in using altimeter data as important in sea level reconstruction or determining coastal vulnerability. This project also helped provide insight, guidance and knowledge in facing the global warming issue that affect sea level rise, especially for island states like Indonesia. Participation in this APN project activity has given me the opportunity to follow a tutorial on microwave remote sensing (altimeter) organized by PORSEC and

			given spur to explore more in altimetry and write to improve the capacity building . Thank you APN.”
7.	Lukman Raharjanto (lukmanraharjanto@gmail.com)  Undergraduate student, Geomatic Department - Institut Teknologi Sepuluh November	Undergraduate Final Project	In future , I hope many training and workshop about altimetry in indonesia and so can increas knowledge about altimetry and ocean effect in indonesia.
8.	Dwipayana  dwipayanakusuma@gmail.com	Undergraduate Final Project	Development of altimetry satellites monitoring quality on the high seas has been so great and conscientious, but for coastal and shallow seas such as the Indonesian archipelagic waters, altimetry satellite data is still not good due to its accuracy dropped dramatically due to distortion of the signal when passing around the coastal margins. Data processing is quite complicated and need specialized knowledge
9.	Fanani Geomatic Department Bandung Institute of Technology	Research Interest	-
10.	Sella Lestari Geomatic Department Bandung Institute of Technology	Research Interest	=

Appendix 9: Media Coverage

Workshop activities of the RESELECASE Project held in November 2011 and 2012 were covered by national paper, electronic and TV Media with the following list:

1. Sea Level Rise in the Eastern of Indonesia is Higher (Kenaikan Permukaan Air Laut di Indonesia Timur Lebih Tinggi
   Kompas, 16 November 2011
   http://nasional.kompas.com/read/2011/11/16/12265499/kenaikan.air.lau...

2. Agency BIG HOLDS INTERNATIONAL WORKSHOP ON COASTAL SATELLITE ALTIMETRY.
   ANTARA - The Indonesian National News Agency, November 14, 2012
   http://www.accessmylibrary.com/article-1G1-308573284/big-holds-int...

3. Kenaikan Muka Laut 2,8 Milimeter Per Tahun
   Kompas, Rabu, 17 November 2012
   (Note: Kompas is the leading national newspaper in Indonesia)

4. Permukaan Air Laut Indonesia Naik 2-8 mm per Tahun
   Suara Pembaruan, Rabu, 14 November 2012
   http://www.suarapembaruan.com/nasional/permukaan-air-laut-indonesia

5. Satelit Altimetri Bisa Pantau Kenaikan Muka Air Laut
   Technology-indonesia Pembaruan, Rabu, 14 November 2012
   http://www.technology-indonesia.com/component/content/article/385-sa

Kenaikan Air Laut di Pantai Indonesia Timur Lebih Tinggi

Penulis : Antony Lee | Rabu, 16 November 2011 | 12:26 WIB

Antony Lee/KOMPAS

Kenaikan Air Laut di Pantai Indonesia Timur Lebih Tinggi

BOGOR, KOMPAS.com - Kenaikan permukaan air laut di kawasan Pantai Indonesia Timur ternyata lebih besar ketimbang kenaikan di kawasan Pantai Indonesia Barat. Hal ini berdasar hasil analisis pengamatan satelit altimeter.

Hal itu disampaikan Asep Karsidi, Kepala Badan Koordinasi Survei dan Pemetaan Nasional (Bakosurtanal) dalam sambutan ketika membuka International Workshop on Coastal Satellite Altimetry di Kota Bogor, Jawa Barat, Rabu (16/11/2011).

"Kenaikan permukaan air laut global sebesar 3 milimeter per tahun baru meyakinkan para ahli setelah data altimeter membenarkannya. Nilai nominal kecepatan kenaikan 3 mm per tahun sepertinya bisa menyesatkan, tidak akan membahayakan kehidupan bumi karena besarnya dapat dikatakan cukup kecil bagi amatan mata kita," tuturnya.

Namun, kata dia, dampak ikutannya akan terlihat bukan saja bila dilihat dampak jangka panjang misalnya kenaikan 100 tahun akan menjadi 30 sentimeter. Selain itu, dampaknya secara regional juga bervariasi.

Editor : Robert Adhi Ksp

TOP STORIES

ANTARA - The Indonesian National News Agency

BIG HOLDS INTERNATIONAL WORKSHOP ON COASTAL SATELLITE ALTIMETRY.

ANTARA - The Indonesian National News Agency | November 14, 2012 | Copyright

Byline: Editor Antaranews.com

Bogor, W. Java, Nov 4 (ANTARA) - The Indonesian Geospatial Information Agency (BIG) held an international workshop on Coastal Satellite Altimetry in Bogor, West Java, on Wednesday.

"This workshop is part of a joint research project between BIG and Reconstruction of Sea Level Change in South Asia Using Satellite Altimetry and Tide Gauge Data (RESELECASEA)," BIG chief researcherParluhutan Manurung said here Wednesday.

Parluhutan explained the objective of RESELECASEA project is to reconstruct a map of sea level rise in Southeast Asia using satellite altimeter data and tidal observations.

It is also intended to improve researchers' competence in processing and using satellite altimeter data, he said.

"RESELECASEA project is funded by competitive research funding from the Asia Pacific Network for Global Change Research (APN) whosesecretariat is based in Japan," Parluhutan said.

He explained RESELECASEA project is carried out from 20 to 202. The project has managed to reconstruct sea-level changes not only on regional but also global scales.

This reconstruction process was for the first time carried out in the Southeast Asian waters.

"This reconstruction can give us a picture of sea level changes dating back to 900. We are currently trying to find a model to predict how sea level changes in the future will be," he said.

According to him, reconstruction of sea-level changes in the past is very important to improve researchers' understanding of the surface situation in the past as well as to lay a basis for the projection of sea level changes in the future.

The workshop was attended by about 00 participants consisting of researchers and institutions such as the Indonesian National Space and Aeronautics Institution (LAPAN), the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG), BIG andforeign participants including those from Italy, Colorado, and Vietnam.

The workshop was supported by Prof. Robert R Leben from the University of Colorado who has been working on the development of satellite altimeter at NASA and monitoring activities around the Gulf of Mexico, Dr.Stefano Vignudelli from Italy who is the editor ofCoastal Altimetry book and Dr.Jonson Lumban Gaol from the Department of Science and Marine Technology of the Bogor Institute of Agriculture (IPB).

The study results presented at the workshop emphasized the importance of monitoring sea level continuously in the long run.

Satellites that can monitor the entire sea surface in the long run are very important because data on the average sea level all the time is an indicator of climate change due to global warming, he said.

"Satellite altimetry is present and future technology. Since it was launched for the first time in 992 satellite altimetry has observed the entire ocean surface with relatively homogeneous and accurate quality," Parluhutan explained.

The data obtained from satellite altimetry is very significant for various scientific and practical purposes such as mapping, oceanography, geophysics, fisheries as well as climate change and sea level rise.

Currently, experts are focusing on improving the accuracy of the altimeter in coastal area due to its potential use in terms of scientific and practical purposes.

"This is one of the BIG's motivations to build satellite altimetry community experts through workshops, training and applied research activities," Parluhutan said.

The head of Indonesian Geospatial Information Agency Asep Karsidi said synergy is necessary to encourage the Indonesian government to build a satellites.

"BIG's task is to present the results of national and international researches in the field of satellite. There should be synergy with a number of parties in developing our satellite," he said.

Asep added, BIG which has changed its name from Bakorsutanal (National Coordinating Agency for Surveys and Mapping) expected to get involved in researches to develop a satellite in support of national development.***3***

(T.K-LWA/S02)

17 NOV 2012

PERUBAHAN IKLIM

Kenaikan Muka Laut 2,8 Milimeter Per Tahun

JAKARTA, KOMPAS — Penelitian perubahan permukaan laut di perairan Indonesia setahun terakhir menunjukkan kenaikan 2,8 milimeter per tahun. Di kawasan timur lebih tinggi dibanding barat. Pemantauan di tingkat global, kenaikan rata-rata muka laut 3 mm per tahun.

Demikian disampaikan Kepala Badan Informasi Geospasial (BIG) Asep Karsidi pada workshop "Reconstruction of Sea Level Change in South Asia Using Satellite Altimetry and Tide Gauge Data (Reselecasea)", di Bogor, Jawa Barat, Rabu (14/11).

Menurut Parluhutan Manurung dari BIG, pemimpin proyek Reselecasea, kenaikan rata-rata muka laut dunia 3 mm—berdasar pengamatan 1993-2010.

Adapun tingkat kenaikan muka laut di Asia Tenggara berdasar pemantauan satelit altimetri (2011-2012) bersifat temporal. Pada 1972-1999, muka laut Indonesia justru menurun dibandingkan penelitian 1959-1972.

Kenaikan muka laut di wilayah Indonesia juga tak merata. Menurut Robert R Leben dari University of Colorado, AS, kenaikan muka laut di kawasan timur relatif lebih tinggi daripada barat. Hal itu dipengaruhi arus angin dari Samudra Pasifik.

Pemantauan ketinggian air laut itu menggunakan satelit altimeter yang dikembangkan Leben. Turut terlibat penelitian itu, antara lain, Stefano Vignudelli dari Italia dan Jonson Lumban Gaol dari Departemen Ilmu dan Teknologi Kelautan IPB.

Proyek riset itu berhasil merekonstruksi perubahan permukaan laut, bukan hanya dalam liputan global, melainkan juga untuk kawasan laut Asia Tenggara.

Rekonstruksi itu menunjukkan perubahan hingga mundur ke tahun 1950. Kini diupayakan model proyeksi perubahan permukaan laut pada masa depan.

Pemantauan tanpa henti

Hasil studi yang disajikan pada workshop kali ini menekankan pentingnya pemantauan permukaan laut dalam jangka panjang dan terus-menerus tanpa henti. Itu dinilai sangat penting karena data permukaan laut rata-rata dari masa ke masa adalah indikator dari perubahan iklim.

Untuk pemantauan jangka panjang, Deputi Teknologi Wahana Dirgantara Lembaga Penerbangan dan Antariksa Nasional (Lapan) Soewarto Hardhienata mengatakan, pihaknya akan mendukung BIG membuat satelit altimetri untuk pemantauan kelautan.

Saat ini, Lapan menguasai teknologi pembuatan wahana satelit. Hingga 2014, Lapan akan meluncurkan dua satelit, menyusul satelit Lapan TUBsat yang mengorbit tahun 2007.

Sementara itu, lokakarya kali ini bagian dari kegiatan BIG dengan Asia-Pacific Network for Global Change Research yang mendanai proyek Reselecasea. Tujuannya ialah merekonstruksi peta kenaikan permukaan laut di Asia Tenggara menggunakan data satelit altimeter dan data hasil pengamatan pasang surut. Selain itu, meningkatkan kemampuan peneliti dalam pengolahan dan penggunaan data satelit altimeter. (YUN)

SP SUARA PEMBARUAN MEMIHAK KEBENARAN
Selamat datang Tamu | Login
Kamis, 13 Desember 2012
Cari artikel...
Pencarian Arsip
HOME POLITIK & HUKUM METROPOLITAN NASIONAL EKONOMI & BISNIS INTERNASIONAL OLAHRAGA HIBURAN KIPRAH GAYA HIDUP INOVASI
Harian Umum Sore. R E-PAPER | GALERI FOTO | KLASIFIKASI | Kunjungi kami di:

Permukaan Air Laut Indonesia Naik 2-8 mm per Tahun

Rabu, 14 November 2012 | 14:52


Ilustrasi air laut [google]

[BOGOR] Indikasi menguatnya perubahan iklim terlihat dalam berbagai fenomena alam. Kenaikan muka air laut salah satunya. Meski penelitian penyebab dominan masih terus diteliti, kenaikan muka air laut harus diwaspadai. Dalam kondisi global kenaikan muka air laut 3 milimeter (mm) per tahun, sedangkan di Indonesia mencapai 2-8 mm per tahun.

Untuk itulah Badan Informasi Geospasial (BIG) bersama Projek Riset Reconstruction of Sea Level Change in South Asia Using Satellite Altimetry and Tide Gauge Data (RESELECASEA) sejak tahun 2011 melakukan riset untuk merekonstruksi peta kenaikan permukaan laut dan pasang surut laut di Asia Tenggara dengan data satelit altimeter.

Kepala BIG Asep Karsidi mengatakan dari sisi fisik bumi mengalami pemanasan global yang semakin nyata. Terjadinya perubahan iklim ditandai semakin meningkatnya bencana meteorologi dan hidrologi.

"Tuntutan pemantauan kenaikan tinggi muka air laut di lokal (Indonesia) sangat penting dengan pemanfaatan altimetri. Sebab indikasinya wilayah timur Indonesia kenaikan muka lautnya lebih tinggi dibanding wilayah barat," katanya di sela workshop Coastal Satelite Altimetry di Bogor, Rabu (14/11).

Untuk mengetahui secara lebih cermat Indonesia membutuhkan kehadiran satelit altimetri. Asep pun berharap Lembaga Penerbangan dan Antariksa Nasional (Lapan) bisa mengembangkan satelit tersebut. Sebab kenaikan muka air laut membawa sejumlah implikasi seperti tenggelamnya wilayah daratan, ketahanan pangan karena terganggunya iklim dan banjir.

Deputi Bidang Kedirgantaraan Lapan Ing Soewarto menyatakan Indonesia berpotensi memiliki satelit altimetri. Lapan menurutnya sudah menguasai pembuatan satelit, hanya perlu melengkapi muatannya untuk monitoring altimetri.

"Lapan sejauh ini sudah menghasilkan satelit A1 untuk penerapan teknologi,Lapan A2 atau Lapan Orari, Lapan A3 atau Lapan IPB-Sat untuk ketahanan pangan dan penelitian daerah pesisir," ucapnya.

Deputi Bidang Informasi Geospasial Dasar BIG Poentodewo mengungkapkan dengan mengetahui data tentang laut, muncul sudut pandang dalam proses pembangunan yang bertitik pangkal pada laut tidak hanya daratan.

Ia mencontohkan fenomena banjir Jakarta bukan hanya masalah yang terjadi di belakang laut. "Perlu diingatkan bahwa pembangunan di sepanjang pesisir, bagaimana kebijakan pembangunan kawasan pantai semuanya terkait dengan penataan kawasan pesisir. Selama ini kita miskin data untuk itu. Oleh karena itu penelitian maritim ini penting," jelasnya. [R-15]

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Tanya Jawab

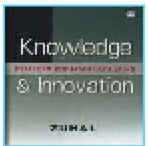
ATASI JURANG TEKNOLOGI DAN BISNIS DENGAN INKUBATOR
14/06/2011
Jurang antara Teknologi dan Bisnis akan semakin dalam jika tidak segera dicarikan solusinya. Diperlu [...]

SELENGKAPNYA

Lainnya

- Obesitas Pada Anak dan Air Putih
- Manfaat Minum Air Putih

Resensi



ORKESTRA INOVASI DAN KEKUATAN DAYA SAING
Judul : Knowledge and Innovation, Platform Kekuatan Daya Saing
Penulis : Zuhal
Penerbit: Gramedia Pustaka Utama
Tebal : x + 485 halaman
Cetakan: I, 2010

Kunci kemajuan suatu bangsa sejatiny [...]

SELENGKAPNYA

Artikel Lainnya

- Memahami Cuaca Antariksa

Advertorial

LOMBA PENULISAN IPTEK-HAKTEKNAS 2012
LATAR BELAKANG

Banyak negara mencapai kemajuan dan kemakmuran karena mengandalkan sumberdaya manusia yang kreatif dan inovatif untuk dapat meningkatkan daya saing negara dan mencapai kemandirian

Berita ini

Telah dibaca: 248

Satelit Altimetri Bisa Pantau Kenaikan Muka Air Laut

Ditulis oleh Alffens |

Penilaian Pengguna: / 0

Jelek Bagus Nilai

Tuntutan pemantauan kenaikan tinggi muka air laut di Indonesia sangat penting. Untuk mengetahui secara lebih cermat hal tersebut Indonesia membutuhkan kehadiran satelit altimetri.

Hal itu disampaikan Kepala Badan Informasi Geospasial, Asep Karsidi saat menghadiri Workshop yang diselenggarakan bersama BIG dengan Projek Riset Reconstruction of Sea Level Change in South Asia Using Satellite Altimetry and Tide Gauge Data (RESELECASEA).

Project RESELECASEA ini telah berhasil merekonstruksi perubahan permukaan laut bukan hanya dalam liputan global tetapi istimewanya untuk kawasan perairan laut di Asia Tenggara. Proses rekonstruksi ini adalah yang pertama kali dilakukan khusus untuk perairan laut di Asia Tenggara.

Rekonstruksi ini dapat menunjukkan gambaran perubahan masa lalu mundur hingga ke tahun 1900 dan sedang diupayakan model untuk memproyeksi bagaimana perubahan permukaan laut di masa depan. Kemampuan merekonstruksi perubahaan permukaan laut pada masa lalu sangat penting untuk meningkatkan pemahaman akan situasi permukaan pada masa lalu dan menjadi dasar untuk melakukan proyeksi di masa depan.

Asep Karsidi berharap Lembaga Penerbangan dan Antariksa Nasional (Lapan) bisa mengembangkan satelit tersebut. Sebab kenaikan muka air laut membawa sejumlah implikasi seperti tenggelamnya wilayah daratan, ketahanan pangan karena terganggunya iklim dan banjir.

Deputi Bidang Kedirgantaraan Lapan Ing Soewarto menyatakan Indonesia berpotensi memiliki satelit altimetri. Lapan menurutnya sudah menguasai pembuatan satelit, hanya perlu melengkapi muatannya untuk monitoring altimetri.

"Lapan sejauh ini sudah menghasilkan satelit A1 untuk penerapan teknologi,Lapan A2 atau Lapan Orari, Lapan A3 atau Lapan IPB-Sat untuk ketahanan pangan dan penelitian daerah pesisir," ucapnya.

Deputi Bidang Informasi Geospasial Dasar BIG Poentodewo mengungkapkan dengan mengetahui data tentang laut, muncul sudut pandang dalam proses pembangunan yang bertitik pangkal pada laut tidak hanya daratan.

Ia mencontohkan fenomena banjir Jakarta bukan hanya masalah yang terjadi di belakang laut. "Perlu diingatkan bahwa pembangunan di sepanjang pesisir, bagaimana kebijakan pembangunan kawasan pantai semuanya terkait dengan penataan kawasan pesisir. Selama ini kita miskin data untuk itu. Oleh karena itu penelitian maritim ini penting," jelasnya

Sementara itu dengan RESELECASEA yang mendapat pendanaan riset kompetitif dari Asia Pacific Network for Global Change Research (APN) di Tokyo ini bertujuan untuk merekontruksi peta kenaikan permukaan laut di Asia Tenggara dengan menggunakan data Satelit Altimeter dan data hasil pengamatan pasang surut dan meningkatkan kemampuan para peneliti Indonesia dalam pengolahan dan penggunaan data satelit altimeter.

Proyek RESELECASEA ini berlangsung dari 2011-2012, dengan Dr. Parluhutan Manurung dari BIG sebagai peneliti utama, mendapat dukungan dari Prof. Robert R Leben dari University of Colorado yang telah mengerjakan pengembangan satelit altimeter di NASA dan berbagai kegiatan pemantauan arus di sekitar Teluk Meksiko dan Dr. Stefano Vignudelli adalah editor buku Coastal Altimetry dari Italia dan Dr. Jonson Lumban Gaol dari Departemen Ilmu dan Teknologi Kelautan IPB

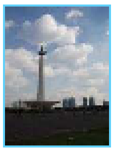
Komentar Terbaru

KLIBS Usung Anastesi Lokal unt...
dr. Wigid.. saya peserta seminar parenting di SD K... More...
30.10.11 08:59
By

Peluang Broadband Masih Terbuk...
Nice article. More...
21.06.11 16:11
By

Biogas dari Limbah Tahu
Mantaps... salut... sekalian mau bertanya.. mi... More...
26.05.11 09:27
By

Kolom



IMPLIKASI LINGKUNGAN AKIBAT PENGEMBANGAN JAKARTA
11/12/2009 |
Banjir musiman di Jakarta dapat diestimasikan terjadi pada setiap awal tahun dan akhir tahun. Banyak faktor yang melatarbelakangi terjadinya banjir di Jakarta, diantaranya karena semakin meluasnya wil [...]

SELENGKAPNYA

Artikel Lainnya

Info Produk

Angket

Artikel Apa Yang Anda Sukai?

- Pertanian dan Pangan
- Energi
- Transportasi
- TIK
- Kesehatan
- Hankam
- Bencana
- Tanya Jawab
- Kolom
- Resensi
- Advetorial
- Profil Peneliti

Pilih Hasil

Appendix 10: Glossary of Terms

Include list of acronyms and abbreviations

AVISO	Archiving, Validation, and Interpretation of Satellite Oceanographic
APN	Asia Pacific Network
BAKOSURTANAL	National Coordinating Agency for Survey and Mapping of Indonesia
BIG	Geospastial Indormation Agency of Indonesia, former name BAKOSURTANAL
CNR	Consiglio Nazionale delle Ricerche in Pisa
CSEOF	Cyclostationary Empirical Orthogonal Functions (CSEOF)
GDR	Geophyscal Data Record
IPB	Bogor Agricultural University IPB
IHO	International Hydrographic Organization
LV	loading vectors
NetCDF	Network Common Data Form
OCOG	offset centre of gravity
PODAAC	Physical Oceanography Distributed Active Archive Center
PORSEC	Pan Oceanic Remote Sensing Conference
PCTS	principal component time series
RESELECASEA	Reconstruction of Sea Level Change in Southeast Asia
SEAS	South East Asia Seas
SSH	Sea Surface Height
GDR	Geophyscal Data Records

Appendix 11: Presentations of Training and Workshop 2011

Appendix 12: Presentations of Training and Workshop 2012

Appendix 11

Presentations of

Training and Workshop 2011

About

The RESELECASE Project

APN

RESELECASEA

Reconstruction of Sea Level Change in Southeast Asia Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data

Dr. Parluhutan Manurung
National Coordinating Agency for Surveys and Mapping (Bakosurtanal) - INDONESIA

Manurung, P[1]; Vignudelli, S[2]; Leben, R R[3]; Lumbangaol, J[4]; Khafid, K[1]; Sofian, I[1]; Sinaga, R[5]; Phuoc Hoang Son, T[6]

[1]National Coordinating Agency for Surveys and Mapping of Indonesia (BAKOSURTANAL), INDONESIA; [2]Consiglio Nazionale delle Ricerche in Pisa, ITALY; [3]CCAR at the University of Colorado, UNITED STATES; [4]Bogor Agricultural University, INDONESIA; [5]Sinaga & Co, INDONESIA; [6]Nha Trang Oceanography Institute, VIETNAM

What is the reseach main objectives?

- Providing more accurate reconstructions of sea level changes in the region.
- Making local stakeholders aware of the importance of monitoring sea level changes in the region.

The research partners:

- An inter-diciplanary (geodesy, oceanography and remote sensing) collaborative efforts between institutions in Indonesia and Vietnam with international experts to provide know-how and guidance.
- Coordinating partner is BAKOSURTANAL with Dr. Parluhutan Manurung is the project coordinator.
- Brings together four partners:
  - University of Colorado - US (Prof. Robert Leben).
  - Consiglio Nazionale delle Ricerche – Italy (Dr. Stefano Vignudelli).
  - Bogor Agriculture Institute - Indonesia (Dr. Jonson Lumban Gaol).
  - Nha Trang Oceanography Institute – Vietnam (Dr. Tong Phuoc Hoang Son).
- Drawing developing countries into the project bring their local expertise (tidal modelling, in situ measurements for validation/calibration, data assimilation, etc.

Methodology:

- Collecting and compiling in situ sea level data and other relevant supporting geospatial data around Indonesia.
- Transferring know-how about open ocean and coastal altimetry processing.
- Generating an historical altimeter record at selected coastal locations in the Celebes Sea.
- Applying Cyclostationary Empirical Orthogonal Function (CSEOF) sea level reconstruction method to the coastal tide gauge measurements to extend the coastal sea level record back in time.
- Planning field verification of the CSEOF model in a sample area, Manado City, located in the Sulu Sea North Sulawesi Indonesia.
- Organizing a workshop inviting local scientists and government representatives.

Satelite Altimetry Tracks in SE Asia:

Tracks of Satellite Altimetry, consisting of GFO, Envisat, and T/P and Jason 1/2 in South East Asia.

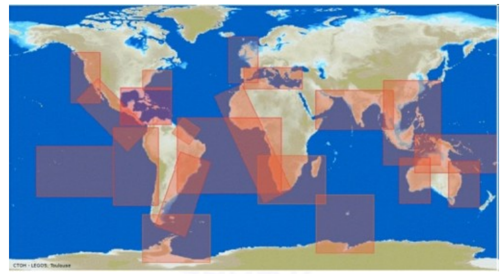
Testing Area surrounding Sulawesi Sea with the nearest Coastal Gauge Stations

What are the expected outcomes?

- Numerical reconstruction and maps of sea level change in the SE Asia Region based on CSEOF.
- In house software for CSEOF and know-how about coastal altimetry processing.
- Draft papers to be published in national and refereed international journals.
- Numerical model and documents which are accessible to government, public and research communities.

Activities	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Kick Off Meeting and Workshop													
Collecting & Quality Control Coastal Tide Gauge Data													
Collecting & Quality Control Satellite Altimetry dataset													
Preprocessing & Analysis Altimetry dataset													
First Report To APN													
Develop computer program and modelling													
Field Verification Result													
Writing paper for journal													
2nd Workshop on Final Result													
Final & Financial Report													

Regional Clusters for Retracking



Consiglio Nazionale delle Ricerche

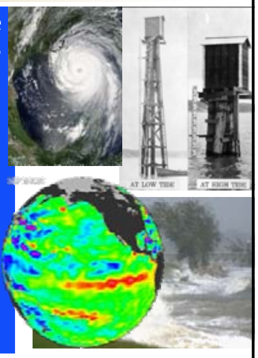
Sea Level Past, Present, and Future

Sea Level Past, Present, and Future

Bob Leben
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

What is Global Mean Sea Level?

- "Global Mean Sea Level" is the the average height of the oceans over the entire globe at a single point in time.
- Mean Sea Level at a specific location in the ocean may be higher or lower than the global mean because of differences in ocean temperature and other effects.
- Does not include ocean tides or storm surge.



A Brief History of Sea Level

- Over the last 500 million years sea level has ranged over hundreds of meters.
- In the last 500,000 years sea level has varied over a range of more than 120 meters.
- The most recent large change was an increase of almost 140 meters as the last ice age ended.
- Sea level began to rise again in the 19th century and accelerated again in the early 20th century.
- The modern satellite altimetry record (1993-present) shows a rate of sea level rise of about 3 mm/year.

Historical Sea Level Records

A number of observational sources can be used to estimate sea level over the historical record. Some examples are:

Geological

- Seismic stratiography, transgressive sequences, raised beaches, wave-cut shelves.

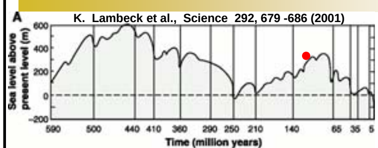
Biological

- Shells, tree stumps, coral reefs, salt marshes.

Man-made

- Ancient Roman *piscinae* or "fish pools", coastal wells, middens or "refuse heaps" such as a mound of shells.

The last 600,000,000 years…



- Temporal variation in sea level over the last 590 million years as inferred from seismic sequence stratigraphy. The higher frequency change reflects a combination of global and local signatures, but the major oscillations are primarily global in origin, associated with continental breakup and the formation of new ocean ridge systems.
- 94 million years ago sea level rise was affecting what would become Boulder, Colorado along the coast of the North American Inland Sea.

Boulder, Colorado

Why worry about sea level when you live over a mile high?

Signs of shifting climate in the western U.S. :

- rising temperatures
- earlier snowmelt
- northward-shifting winter storms
- increasing precipitation intensity and flooding
- record-setting drought
- plummeting Colorado River reservoir storage
- widespread vegetation mortality and more large wildfires

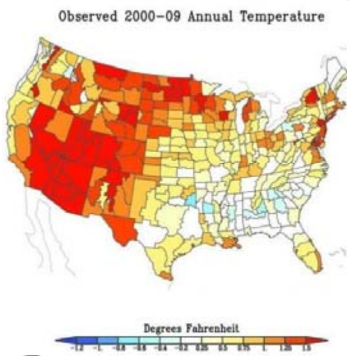
(Overpeck et al., 2010).

Sea level is a "lens" on climate!

Recent drops in water levels in major reservoirs fed by the Colorado River, such as Lake Mead, may be a sign of things to come as climate change takes hold in western North America.

In the American West there is a saying: "Whiskey is for drinking, water is for fighting!"

Western U.S. Warming

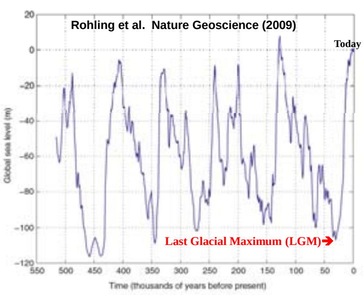


- Map of the observed difference between the average annual U.S. temperatures for this century (2000 to 2009) and those of the last century (1900 to 1999).

(Credit: NOAA)

The last 500,000 years…

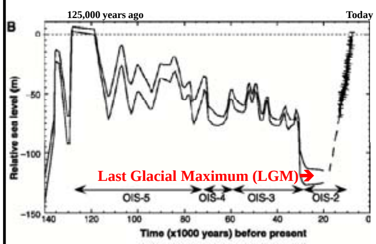
Red Sea planktonic foraminifera analyses



- This sea level estimate is based on stable oxygen isotope analyses of planktonic foraminifera and bulk sediments from the Red Sea.
- Over the glacial cycles of the last 500,000 years, sea level has oscillated by more than 100 meters as the great ice sheets, particularly those of northern Europe and North America, waxed and waned.

The last 140,000 years…

Coral Reef Estimates of Sea Level at Huon Peninsula, Papua New Guinea



K. Lambeck et al., Science 292, 679-686 (2001)

- Relative sea level for the past 140,000 years inferred from the height-age relationships of raised reefs and from submerged fossil corals for the past 13,000 years.
- The fluctuations are the result of the glacial cycle-induced changes in continental-based ice volumes.
- Upper and lower limits are shown for the pre-LGM part of the record (before about 25,000 years ago), and mean sea level estimates with error bars are shown for the post-LGM record.
- The LGM record is missing from Huon. The dashed lines for this period correspond to information from northwestern Australia. The timing and duration of the major oxygen isotope stages is shown.

Paleo Sea Level

The last time the Arctic was 3 to 5°C warmer than present, global sea level was ~6 meters higher than today.

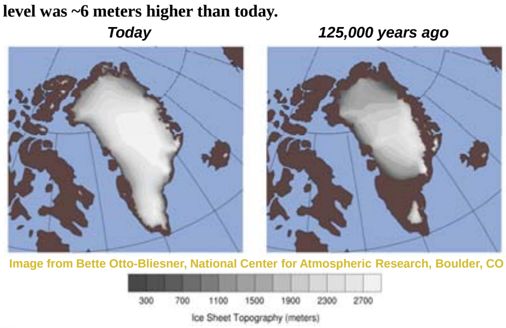
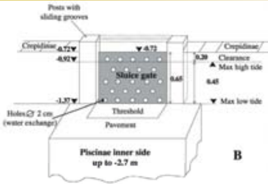


Image from Bette Otto-Bliesner, National Center for Atmospheric Research, Boulder, CO

Modern sea level record starts in Roman times….

Roman Piscinae in the Tyrrhenian Sea



Piscinae "Fishpool" Sea Leveling

Lambeck et al. (2004): "Sea level in Roman time in the Central Mediterranean and implications for recent change", Earth and Planetary Science Letters, 224, 563-575.

- Give a precise measure of local sea level in the central Mediterranean basin for the Roman period 2000 years ago as:

  -1.35 ± 0.07 m

- Part of this change is the result of ongoing glacio-hydro isostatic adjustment of the crust subsequent to the last deglaciation. When corrected for this, using geologically constrained model predictions, the change in eustatic sea level since the Roman Period is:

  -0.13 ± 0.09 m

- A comparison of nearby tide-gauge records with the model-predicted isostatic adjustment establishes that the onset of the modern sea-level rise occurred in recent time at ~100 ± 53 years before present.

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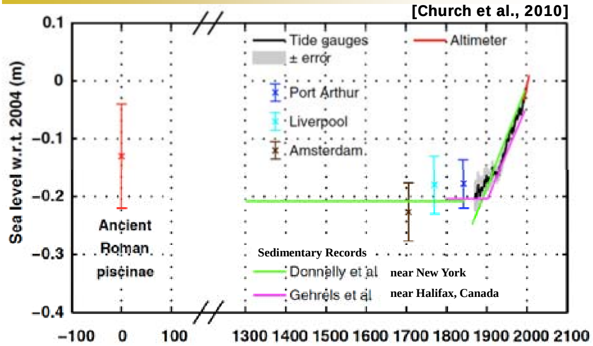
Last 2,000 years



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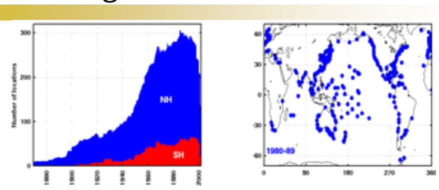
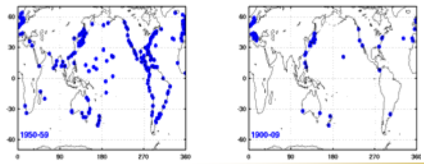
Tide Gauge Measurement Distribution



Church and White (2006)



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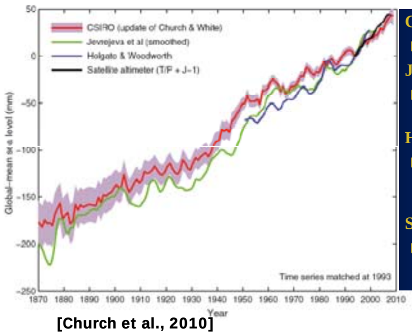
The last 140 years…tide gauges and satellites



- CSIRO
  - EOF reconstruction
- Jevrejeva et al.
  - Nonlinear trend analysis (MC-SSA).
- Holgate & Woodworth
  - Reintegrated global averages of regional mean trends.
- Satellite Altimetry
  - Annual mean values.

[Church et al., 2010]

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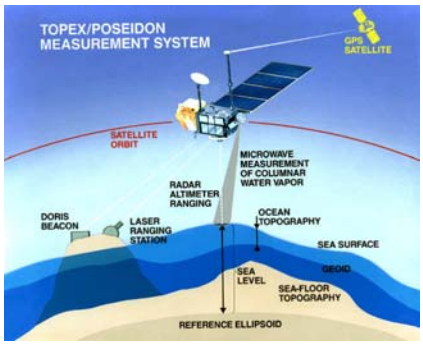
Schematic of Satellite Altimeter System



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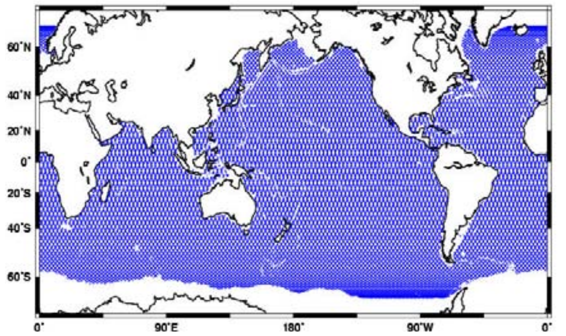
TOPEX/Poseidon, Jason-1&2 10-day Groundtrack



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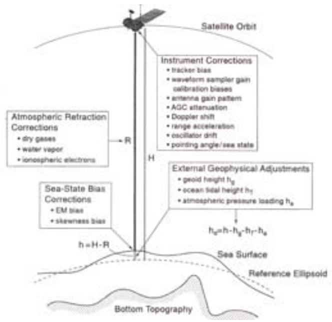
Schematic Summary of Corrections



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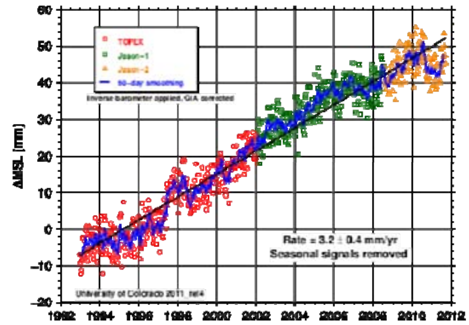
http://sealevel.colorado.edu



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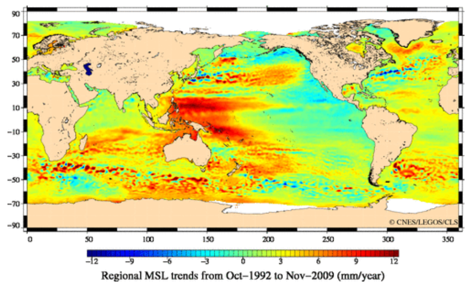
Spatial Variations in Sea Level Rise: 1993-2009



(available on http://www.aviso.oceanobs.com/msl/)

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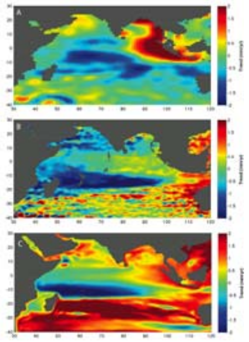
Regional sea level trends are also important…

- Trends from 1961-2001 for the Indian Ocean computed from **Church and White (2004) EOF reconstruction.**
- Trends from 1961-2008 for the Indian Ocean computed from **CSEOF reconstruction (Hamlington et al. 2011)**
- Spatial variation of trend for the Indian Ocean from 1961-2008 from **HYCOM Ocean Model Simulation(Han et al, 2010).**



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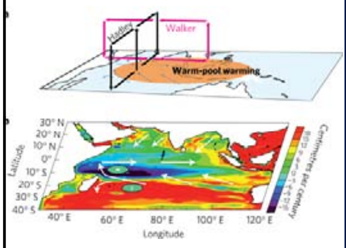
… especially when forced by the warming climate.



Han et al., 2010

Warm-pool warming enhances the Indian Ocean regional Hadley and Walker cells shown in (a).

The two enhanced cells combine to form a specific pattern of surface wind change shown by the surface arrows in (a) & (b).

These changes together with the vertical Ekman pumping velocity shown by green circles with a dot (upwelling) and x (downwelling) drive the respective falling and rising patterns of sea level.

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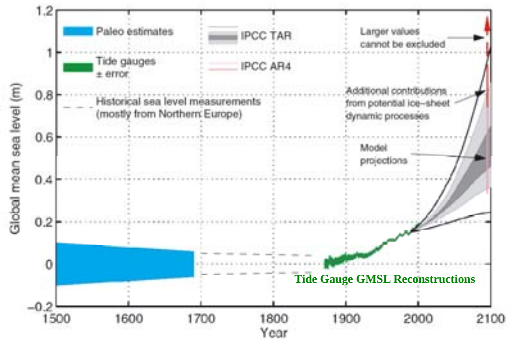
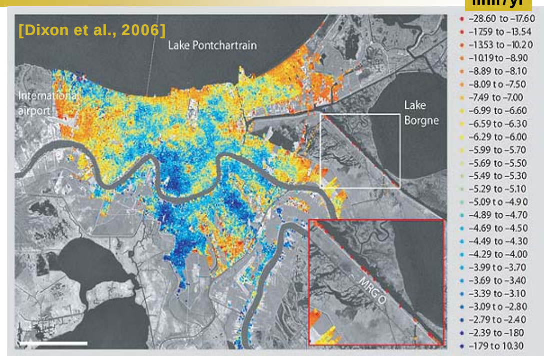
The next 100 years …



Land Movement Can Affect Sea Level Locally

InSAR Image of Subsidence in New Orleans



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1 Meter of Sea Level Rise – Louisana USA

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1-meter Sea Level Rise - Indonesia

Sea Level Rise of 1 Meter

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Summary

Observations of sea level change are consistent with how we expect sea level to respond in a warming climate.

- Sea level rose twice as fast in the last decade than over the last half of the 20th century.
- Presently, ocean warming, melting of mountain glaciers, and melting of the polar ice caps are contributing in roughly equal amounts to the observed rise. The large uncertainty in future sea level rise projections is due mainly to the uncertain contributions of Greenland and Antarctica, which appear to be accelerating.
- Many of the remaining questions about sea level rise can only be answered with continued satellite measurements and tide gauge measurements.

Combining the Indonesian Seas altimeter and tide gauge record is the focus of this workshop and our collaboration.

THANK YOU!!

Colorado Center for Astrodynamics Research
University of Colorado at Boulder
International Workshop On Coastal Altimetry
November 16&17, 2011 Bogor, Indonesia

Introduction to

Deep Water Satellite Altimetry

Introduction to
Deep Water Satellite Altimetry

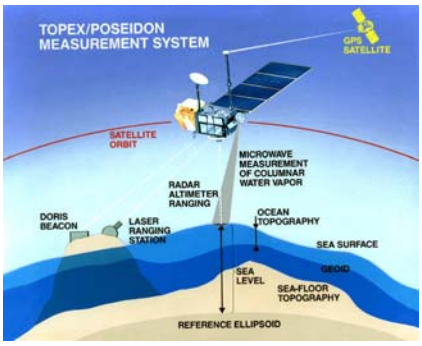
Bob Leben
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

What is an altimeter and radar altimetry?

Altimeter - An instrument that determines height above a reference level, commonly by measuring the change of atmospheric pressure, or by measuring vertical distance directly with a radar or laser system.

Radar Altimetry - The measuring of range from an aircraft or satellite to the sea surface using a short pulse of microwave radiation with known power toward the sea surface. The pulse interacts with the rough sea surface and part of the incident radiation reflects back to the altimeter. The techniques for determining the range to the ocean surface based on the travel time of such a microwave pulse is commonly referred to as altimetry.

Schematic of Satellite Altimeter System



Basic Concept of Satellite Altimetry

The measurement of sea surface height from space by a satellite borne altimeter is deceptively simple:

1. **Send a microwave pulse to the ocean surface and detect the reflected pulse, measuring the two-way travel time between sending and receiving the pulse.**
2. **Calculate the distance of the ocean surface from the satellite, the altimeter range, by multiplying the one-way travel by the speed of light. The one-way travel time is equal to 1⁄2 the two-way travel time.**
3. **Adjust range measurement to account for atmospheric, pulse reflection, instrument and external geophysical corrections to the path length.**
4. **Determine the ocean height by subtracting the range from the orbit height of the satellite.**

While measuring sea surface elevation from space is conceptually simple, satellite altimetry is in fact quite complex, requiring nearly 60 algorithms and a variety of external measurements to accurately determine the sea surface height elevation associated with dynamic ocean currents.

TOPEX Altimeter (ALT)

The ALT is a dual-frequency, nadir-looking, pulse-compression radar.
- **Range measurements are made at both Ku-band (13.6 Ghz) and C-band (5.3 Ghz) to eliminate the ionospheric electron range error.**

The ALT generates a linear-FM (chirp) pulse waveform with a 320 MHz bandwidth and a 102.4 microsecond duration, for both the Ku- and the C-band.
- **The pulse repetition frequency is approximately 4500 for the Ku-band and 1200 Hz for the C-band.**
- **The antenna, shared with the CNES solid-state altimeter (SSALT), is a 1.5 meter diameter parabolic reflector. The antenna beamwidth is approximately 1.1 degrees for Ku-band and 2.6 degrees for C-band.**

Measurement geometry

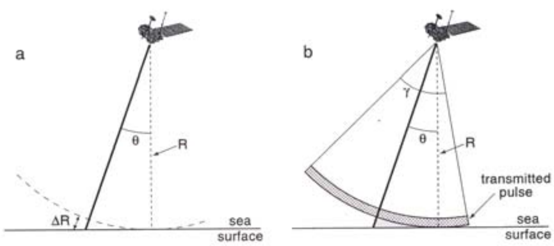
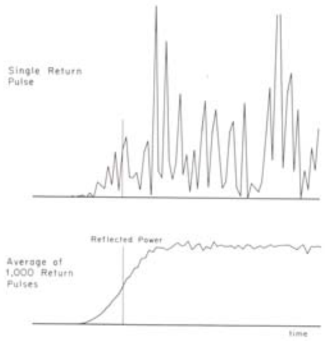
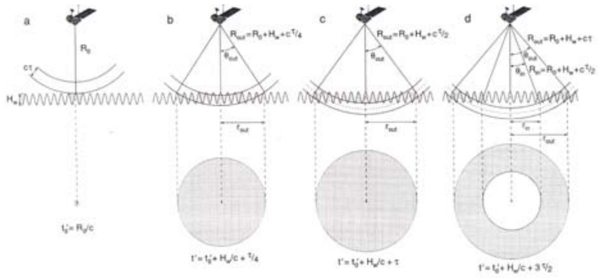


FIGURE 7 The measurement geometry for (a) a very narrow beamwidth-limited altimeter; and (b) a pulse-limited altimeter with a relatively large antenna beamwidth γ. In both cases, the boresight of the antenna views the sea surface at off-nadir angle θ from a height R above the sea surface.

Return pulse averaging



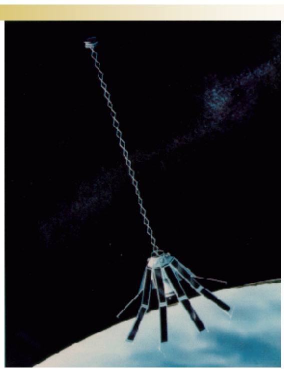
Measurement geometry



Ocean Satellite Altimeter Missions

Mission	Dates	Agency	Repeat Orbit
Skylab	1973	NASA	non-repeat
GEOS-3	1975-1978	NASA	non-repeat
SEASAT	1978	NASA	partial
GEOSAT	1985-1989	U.S. Navy	non-repeat, 17-day
ERS-1	1991-2000	ESA	3-day 35-day, 176-day
TOPEX/POSIEDON	1992-2006	NASA/CNES	10-day
ERS-2	1995-2011	ESA	35-day
GFO	1999-2008	U.S. Navy	17-day
Jason-1	2001-present	NASA/CNES	10-day
ENVISAT	2001-present	ESA	35-day
Jason-2/OSTM	2008-present	NASA/CNES	10-day

GEOSAT

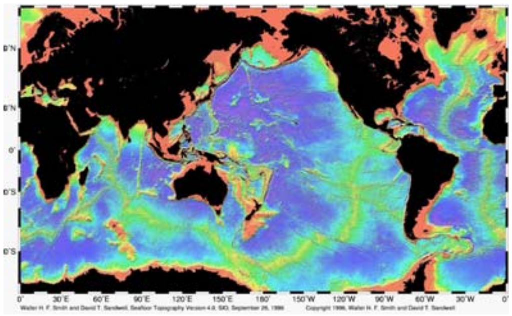


U.S. Navy's GEOSAT

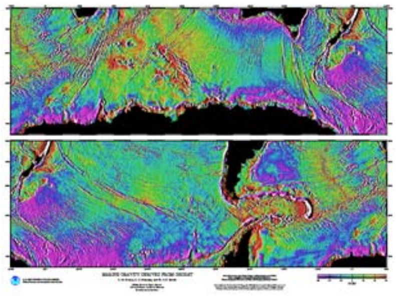
The U.S. Navy GEOdetic SATellite carried an altimeter that was capable of measuring the distance from the satellite to the ocean surface with a relative precision of about 5 cm.

- Primary mission phase, the Geodetic Mission, was dedicated to mapping the marine geoid at high spatial resolution. Data were originally classified. The data around Antarctica were declassified in 1990 and the entire data set in June, 1995.
- Launched on March 12, 1985.
- Near circular orbit, inclination 108°, period 101 min, and altitude 800 km.
- The Exact repeat mission phase began on November 8, 1986 after the satellite was maneuvered into a 17-day repeat orbit (actually 17.05 days) until the satellite ultimately failed in January 1990.
- Public release of the high resolution Geodetic data allowed the estimation of sea floor topography using satellite altimetry.

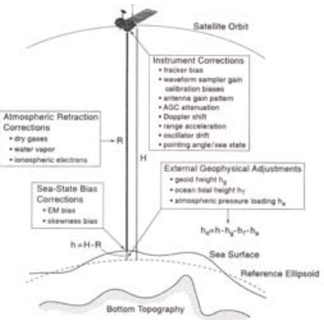
Sea Floor Topography



Marine Gravity



Schematic Summary of Corrections



Altimeters Range Corrections

Altimeter range corrections can be grouped as follows:

- Atmospheric Refraction Corrections
- Sea-State Bias Corrections
- External Geophysical Corrections
- Instrument Corrections

Atmospheric Range Corrections

The presence of dry gases, water vapor and free electrons in the atmosphere reduces the propagation speed of the radar pulse. These are the so-called atmospheric range corrections.

- Dry Gases
- Water Vapor
- Ionospheric Free Electrons

All of these corrections cause a delay in the returned signal and are often referred to as a *path delay*, acting to make the range measurement too long.

Atmospheric Range Corrections: Dry Gases

At microwave frequencies the troposphere is a non-dispersive medium, and the index of refraction is independent of frequency. For convenience the path delay is broken into a dry and wet component. The dry component reflects primarily the refractive effects of oxygen on the path delay.

A simplified expression for the dry troposphere range correction, which takes into account the variation in gravity with latitude, is given by the formula:

$$\Delta R\_dry \approx 0.2277*P(1 + 0.0026\cos(2\ latitude))$$

Where P is the sea level pressure in millibars and ΔR_dry is in cm.

This range correction averages 226 cm with variations of 2 cm. The uncertainty associated with errors in the pressure fields from numerical weather models is about 1 cm.

Atmospheric Range Corrections: Water Vapor

The atmospheric range correction associated with columnar water vapor is called the *wet troposphere* correction and reflects water vapor and cloud liquid water droplet contributions to atmospheric refraction.

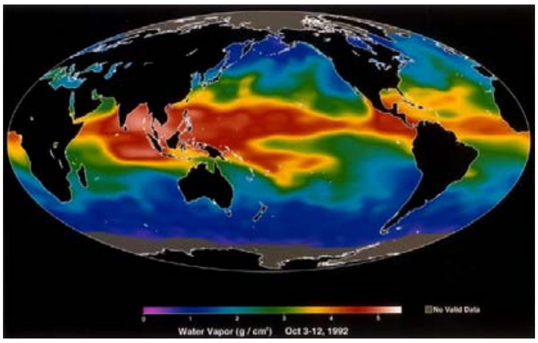
This effect is parameterized by empirical formula:

$$\Delta R\_wet \approx 1.6\ L$$

where L is the integrated columnar liquid water in gm/cm^2 and ΔR_wet has units of cm.

This range correction averages 10 cm at high latitudes to 24 cm in tropical regions. Time variations are about 5 cm. The uncertainties is about 1 cm when corrected using a three-frequency microwave radiometer.

TMR Water Vapor (g/cm2)



Microwave Radiometry

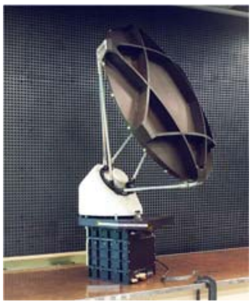
Modern altimeter rely on bore-sight radiometers to estimate the ΔR_wet.

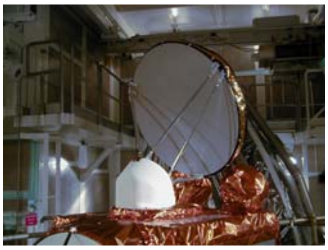
- Algorithms using three frequency (18, 21 and 37 GHz) brightness temperature trained on a large global database of radiosonde profiles to estimate ΔR_wet have accuracies of about 1 cm in rain free conditions
- Algorithms based on the two frequencies (23.8 and 36.5 GHz) used in the ERS radiometers have accuracies of about 2 cm rms.

Note: The ability to correct satellite altimeter data for water vapor attenuation requires coincident measurements from a passive microwave radiometer onboard the satellite because the columnar water vapor at any particular location varies with time.

This was an important lesson learned from GEOSAT.

Jason Microwave Radiometer (JMR)





Atmospheric Range Corrections: Ionospheric Free Electrons

Electrons liberated from atoms in the ionosphere by energetic solar radiation interact with microwaves to slow their propagation. Since the ionosphere is a dispersive medium, the refraction is a function of the frequency so that the free electron density can be calculated using the ranges measuremetns at different frequencies.

The ionosphere range correction is calculated from the total electron content unit (TECU) using the formula:

ΔR_iono = 0.22 TECU

where TECU is given in 10^16 electrons per meter^2 with ΔR_iono in cm.

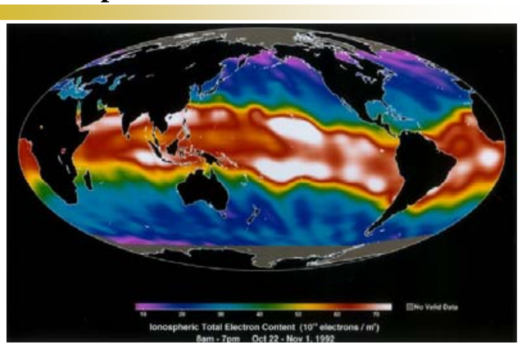
Like the wet troposphere correction, accurate measurements of TECU are required for accurate altimetry given the time and space scales of ionospheric variability

Scales of the Ionospheric Delay

The ionosphere exhibits spatial and temporal variations that are difficult to reproduce with numerical models. Observations show:

- Mean values of the ionospheric delay range from 12 cm near the equator to 6 cm at higher latitudes.
- Variations about the mean are as large as 5 cm near the equator and 2 cm at higher latitudes.
- Meridional gradients as large as 2 cm per 100 km can occur during mid to late afternoon at latitudes of 20° to 30° .
- Uncertainty in the measurements are about 1 cm after smoothing the ionospheric correction at length scales less than 100 km.

Ionospheric Total Electron Content



Sea State Bias Corrections

The sea state bias is made up of two components
- Electromagnetic (EM) Bias - the difference between mean sea level and the mean scattering surface.
- Skewness Bias - the difference between the mean scattering surface and the median scattering surface.

Recall that the returned signal measured by an altimeter is the pulse reflected from the small wave facets within the antenna footprint that are oriented perpendicular to the incident wave fronts.

The shape of the returned waveform is thus determined from the distribution of these scatterers rather than the distribution of the actual sea surface height.

The half power point on the leading edge of the returned wave form corresponds to the median scattering surface.

External Geophysical Corrections

- Geoid height - An accurate geoid is needed to calculate the total dynamic topography signal that includes both the mean ocean circulation and its variations. Early geoids have not been accurate enough for this application, however, by including gravity measurements form GRACE mission have reduced geoid errors at scales greater than 300 km so that scientifically useful information can be derived.
- Ocean and solid earth tidal height - Both ocean and solid earth tides are measured by the altimeter and are considered noise on the non-tidal dynamical signal. Existing models derived from T/P data are accurate to better than 2 cm rms in the deep ocean.

External Geophysical Corrections (cont.)

- Atmospheric pressure loading - This is simply the depression of the sea surface by the atmosphere pressure force on the ocean surface. Spatial and temporal variations of this force are compensated partially by variations in the surface elevation. To first order, the ocean response as an "inverse barometer", changing height by about one centimeter per milli bar of pressure change.

$$\Delta \text{ IB (cm)} \approx 0.995 \text{ (P-1013)}$$

where P is the sea level pressure and 1013 is the mean sea level pressure.

In reality, the ocean responds both statically and dynamically depending on the spatial and temporal scales of the forcing.

- Barotropic ocean signals, which are have significant power at periods shorter than 20 days and are aliased by altimetric sampling, is also an important external geophysical correction being studied. Barotropic ocean models forced with wind and pressure can be used to correct for barotropic variability altimetery measurements.

Instrument Corrections (some)

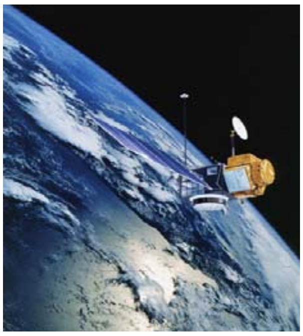
- Doppler shift - Doppler shifting of the transmitted chirp affects the range calculation. This is corrected using the range rate, the rate of change of the range. Range rate is calculated in ground processing by least squares fitting of the range data over about 3 seconds of TOPEX data.
- Range acceleration - The tracker algorithm is affected by the range acceleration. The range acceleration is calculated using the least squares employed for the range rate. Range rates can be as high as 10 meters per second^2 over ocean trenches.
- Oscillator drift - any drift in the frequency of the oscillator direct affects the range calculated by counting cycles of the on board oscillator. This is calibrated by timing of telemetry signals at a ground receiving station. The distinction between frequency and counts per second resulted in an error in the ground based software for TOPEX causing a significant drift and bias in the altimeter measurement.
- Pointing angle/sea state - the largest source of instrumental error is caused by of nadir pointing of the altimeter instrument. To varying degrees this affects the adaptive tracker unit (ATU) estimates of two-way travel time, the significant wave height and the sigma naught.

TOPEX/POSEIDON

TOPEX/POSEIDON

A joint NASA/CNES satellite altimeter mission launched on August 10, 1992.
- Carried two altimeters: the dual frequency TOPEX altimeter and the solid-state Poseidon altimeter, which shared a single antennae on the satellite.
- Highly successful primary and extended missions collected 364 10-day repeat cycles of data through 8/11/2002.
- TOPEX and Jason-1 flew in the same orbit (with Jason leading by 60 seconds) for the first 21 repeat cycles of the Jason mission to intercalibrate the satellites.
- Starting on August 15, 2002 T/P was maneuvered into an interleaved orbit for tandem sampling mission with Jason-1. The interleaved mission phase started on September 20, 2002.
- Decommissioned in January 2006.

What's wrong with this picture?



Current Satellite Altimetry Missions:

Operational Missions: Near real-time and archival data are available from the following ongoing missions:

- Jason-1
- Envisat
- OSTM/Jason-2

All of these data are currently being processed and archived at CU/CCAR.

http://eddy.colorado.edu/ccar/data_viewer/index

Data can also be acquired from NASA and CNES/AVISO.

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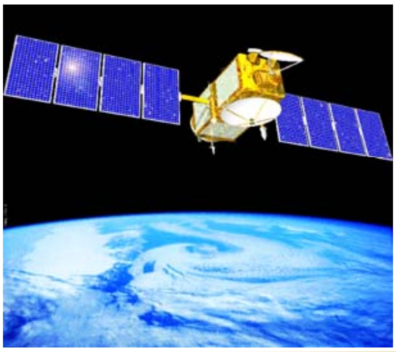
Jason-1



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Jason-1

Jason-1: A joint U.S./French NASA/CNES satellite altimeter mission.

- Jason-1 is a T/P "follow-on" and was placed in the T/P 10-day repeat orbit.
- Launched on December 7, 2001.
- Initial 6-month calibration phase, in which Jason-1 was on orbit 60 seconds behind T/P, was followed by a maneuver of T/P into a "tandem" interleaved 10-day repeat orbit to increase mesoscale sampling. T/P was placed into "interleaved" orbit on September 20, 2002.
- After calibration of Jason-2/OSTM, Jason-1 was placed into in the "interleaved" orbit where it is flying today.

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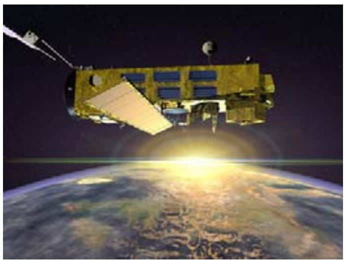
ENVISAT



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Active Missions: Envisat

Envisat: This is the European Space Agency (ESA) Environmental Satellite (Envsat) a follow-on to the ERS-1&2 altimeter missions.

- Launched March 1, 2002.
- Envisat replaced the ERS-2 satellite. Tandem mission plans are not clear, but CU/CCAR has existing processing capabilities to use data as soon as available, as was done during the ERS-1&2 tandem missions in 1995-1996.
- Calibration and validation was completed and the satellite became operational in January 2003.
- Placed in a 35-day repeat orbit, but recently moved in to a 30-day near repeat.

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OSTM/Jason-2

OSTM/Jason-2

Ocean Surface Topography Mission (OSTM)/Jason-2: A joint U.S./French NASA/CNES satellite altimeter mission.

- OSTM/Jason-2 is a T/P "follow-on" mission and was placed in the T/P 10-day repeat orbit.
- Launched on June 20, 2008.
- Initial 6-month calibration phase, in which Jason-2 was in orbit 58 seconds behind Jason-1, was followed by a maneuver of Jason-1 into the "tandem" interleaved 10-day repeat orbit to increase mesoscale sampling on 14 Feb 2009.

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Ocean Altimeter Mission Summary

Satellite	Agency	Mission period	Measurement precision (cm)	Orbit accuracy (cm)	Repeat period (days)
Skylab	NASA	May 1973–February 1974	100	>1000	
GEOS-3 (Geodetic Earth Orbiting Satellite 3)	NASA	9 April 1975–December 1978	25	~500	
SEASAT	NASA	28 June 1978–October 1978	5	~100 (20)	17.05 3
Geosat (Geodetic Satellite)	U.S. Navy	12 March 1985–December 1989	4	30–50 (10–20)	~23.07 17.05
ERS-1 (Earth Remote Sensing Satellite 1)	ESA	17 July 1991–May 1996	3	8–15 (<5)	3,35,168
TOPEX/Poseidon (TOPography Experiment)	NASA/ CNES	10 August 1992–January 2006	1.7	2–3	9.9156
ERS-2 (Earth Remote Sensing Satellite 2)	ESA	21 Apr 1995–July 2011	3	7–8 (< 5)	35
GFO-1 (Geosat Follow-On 1)	U.S. Navy	10 February 1998–December 2008		10 (5)	17.05
JASON-1 (T/P Follow-On)	NASA/ CNES	7 December 2001–present	1.5	1 (goal)	9.9156
ENVISAT (ENVIronmental SATellite)	ESA	2 March 2002–present		1 (goal)	35
OSTM/Jason-2	NASA/ CNES	20 June 2008–present	1	1 (goal)	9.9156

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Exact Repeat Sampling

The ground track spacing at any latitude between individual ascending and descending passes is:

Spacing(degrees) = 360/N

where N is the number of orbital revolutions in the exact repeat.

- **For T/P, Jason-1, OSTM/Jason-2 this spacing is 360/127 or about 2.83° .**
- **For Geosat/GFO this spacing is 360/244 or about 1.48° .**
- **For ERS/Envisat this spacing is 360/501 or about 0.72° .**

The spatial sampling is directly a function of the repeat period because the ground speed of sampling along track varies only slightly with altitude.

The distance between ground tracks also varies with increasing latitude because of the circumference of lines of latitude decreases as a function of the cosine of the latitude.

Exact repeat orbits are used to reduce errors in referencing sea surface height measurement to a mean sea surface.

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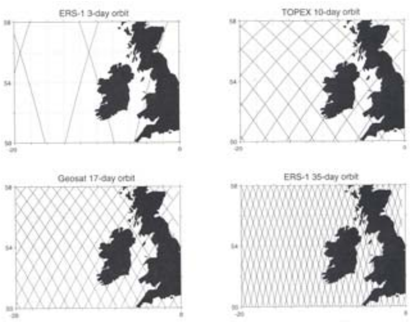
Example Repeat Ground Tracks



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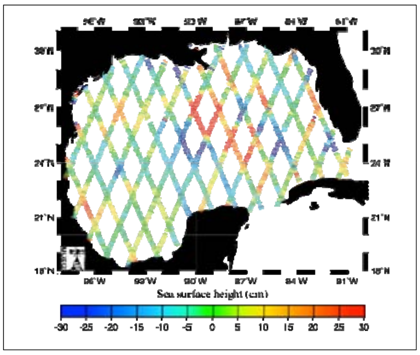
GFO Along-Track Mar 3 - 21, 2001



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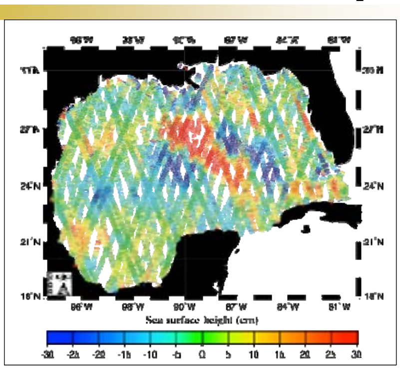
TOPEX/ERS-2/GFO Mar 1 2001 - Apr 1 2001:



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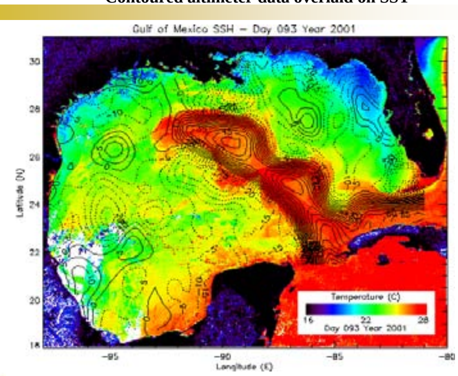
Sample Altimeter Data Product

Contoured altimeter data overlaid on SST



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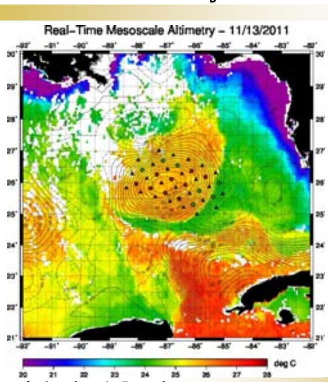
SSH Contour Overlay on SST Image



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Online References

CNES Radar Altimetry Toolbox

- http://www.altimetry.info/

WOCE/NASA Altimeter Algorithm Workshop

- http://oceanesip.jpl.nasa.gov/sealevel/wocealt87.pdf

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Satellite Altimetry Applications:

Ocean Monitoring and Marine Industry

Satellite Altimetry Applications: Ocean Monitoring and Marine Industry

Bob Leben
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

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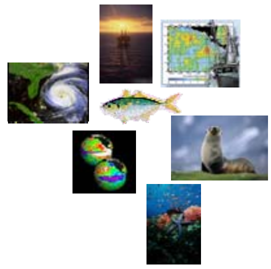
Climate



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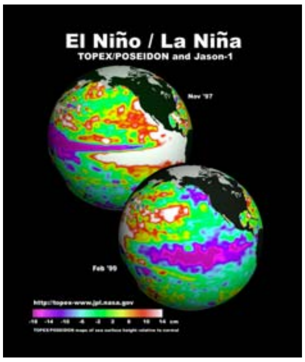
El Niño and La Niña forecasting & monitoring



- TOPEX/Poseidon and Jason provide important extended time series monitoring of El Niño and La Niña events
- NOAA's long term climate forecasts, based in part on ocean altimeter data, include flood control, agricultural strategy, water and energy use planning
- Worldwide damage from the 1997-1998 El Niño probably exceeded $20 billion*. Reliable predictions could help minimize economic impacts.
- Media outlets use the data to explain weather and climate to the public
- TOPEX/Poseidon and Jason data are recognizable to more than a billion people worldwide

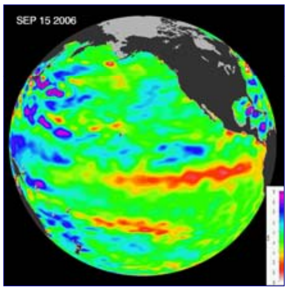
Images produced by Dr. Victor Zlotnicki, Dr. Lee -Lueng Fu and Akiko Hayashi, of the Oceans Research Element at NASA's Jet Propulsion Laboratory.

*D. Anderson, European Center for Medium-Range Weather Forecast

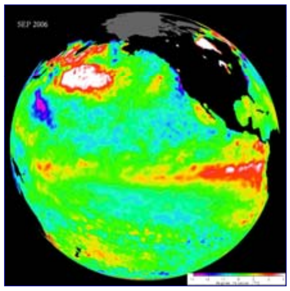
2006 El Niño

A mild El Niño formed in the eastern tropical Pacific in September 2006. Sea level anomalies of 15 cm from Jason-1 and temperature anomalies of 2 deg C from MODIS were observed.

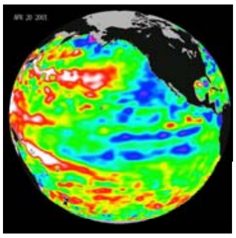
Jason sea surface height



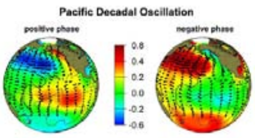
MODIS sea surface temperature

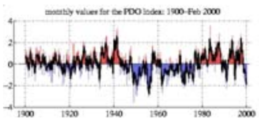


Pacific decadal oscillation (PDO)



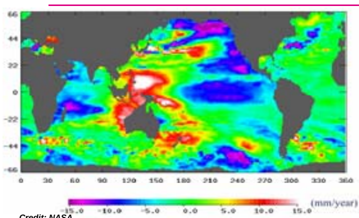
- In this April 2001 image, the Pacific Decadal Oscillation pattern had persisted for three years
- Warm water (high sea levels in red and white)
- Cooler water (lower sea level in blue)



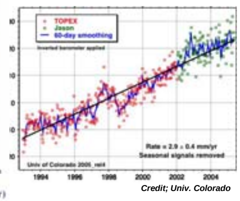


PDO images are courtesy of Nathan Mantua & Steven Hare, University of Washington, Units are degrees Celsius

Global mean sea level rise



Credit; NASA



Credit; Univ. Colorado

This global map of the trend of sea surface height (SSH) is estimated from the combined data from TOPEX/POSEIDON and Jason-1 from 1993 through 2004. Complex patterns of spatial variability are clearly shown. In the North Pacific the pattern of variability is similar to that of the Pacific Decadal Oscillation, in part caused by wind-driven long-period Rossby waves. The SSH trends in the North Atlantic are caused by a slowdown of the circulation of the subpolar gyre of the North Atlantic Ocean, leading to a decrease of the northward heat transport of the ocean.

In the South Atlantic and South Pacific, the marked striations are roughly consistent with the characteristics of Rossby wave fronts, reflecting a possible role of Rossby waves in the decadal change of ocean circulation. In the Southern Ocean the spatial pattern shows the characteristics of a wavenumber-2 Antarctic Circumpolar Wave, with two minima centered at longitudes of 30°-60° and 210°-240°. These waves travel eastward around Antarctica in 8 to 9 years.

The decadal trend of SSH in the Indian Ocean suggests that there is a decrease in the northward geostrophic flow of the upper ocean and hence a reduction of the ventilation of the tropical Indian Ocean by the cold water from the South Indian Ocean, responsible for a long-term warming of the upper Indian Ocean.

Hurricane Katrina Heats up in the Gulf

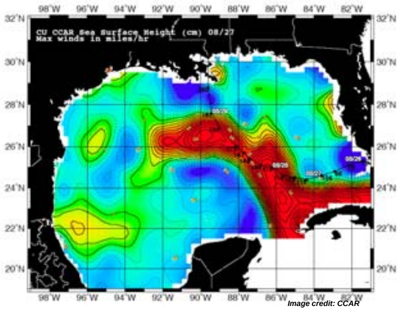


Image credit: CCAR

SSH highs at the center of the Loop Current reached 50-70cm in this image from August 27, 2005. Wind speeds of Hurricane Katrina, indicated in black along the path of the storm, reached highs of 173 mph.

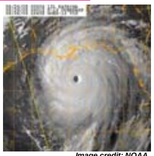
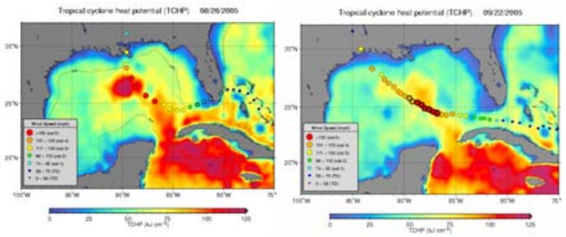


Image credit: NOAA

Maximum wind speeds of Hurricane Katrina increased dramatically as that storm passed over the warm waters of the Loop Current in the Gulf of Mexico in late August 2005. The storm evolved quickly from a category 3 to category 5 event in a matter of 9 hours as it drew heat from the Loop Current and a large warm core eddy evident in the sea surface height derived from merged TOPEX/Poseidon, Jason-1, GFO, and Envisat altimeter data processed by the Univ. of Colorado's CCAR group.

(R. Leben, G. Born)

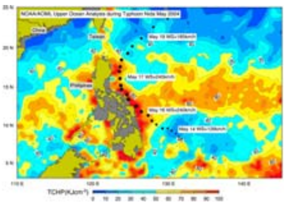
Packing Heat in the Gulf



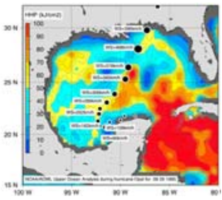
(G. Goni and J. Trinanes, NOAA/AOML)

Tropical Cyclone Heat Potential (TCHP) fields are derived from altimetry data for hurricanes Katrina (left) and Rita (right) in 2005. The path of each hurricane is indicated with circles, their size and color representing intensity (see legend), as the storms made their way across the Gulf of Mexico. Both hurricanes rapidly intensified to category 5 as they passed over the Loop Current and a warm ring, then diminished to category 4 and category 3, respectively, by the time they traveled over cooler waters outside the warm ring. NOAA's Atlantic Oceanographic and Meteorological Laboratory uses blended satellite altimetry data, including those from NASA's TOPEX/Poseidon and Jason-1 missions, to estimate TCHP (a measure of the oceanic heat content from the sea surface to the depth of the 26°C isotherm) in the Gulf of Mexico in near-real time. High values of TCHP may be linked to hurricane intensification. These fields are critical to scientists and forecasters in better understanding the link between the ocean and the intensification of hurricanes. See http://www.aoml.noaa.gov/phod/cyclone/data/ for more information.

Hurricane monitoring and forecasting



Typhoon Nida intensified from category 2 to category 4 in 10 hours when it crossed a region of high TC Heat Potential.

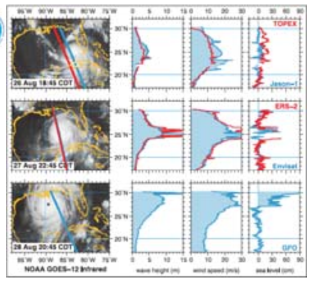


Hurricane Opal intensified from category 1 to category 4 while traveling over warm features in the Gulf of Mexico.

(Goni, others)

Ocean altimeter data is used for long term seasonal forecasts of the numbers and strengths of hurricanes expected in a given hurricane season, as well as short term forecasts of the strength of individual hurricanes. These images from the U.S. Naval Research Laboratory illustrate altimetry combined with sea surface temperature data and a two-layer model to show ocean heat potential. Ocean altimetry data is routinely used by the National Hurricane Center for improved hurricane intensity forecasts. This research demonstrates that storms and hurricanes may intensify when they travel over warm ocean features. Tropical Cyclone Heat Potential maps are derived from sea height anomaly and sea surface temperature fields. These fields are produced in near-real time in all seven basins where TCs occur and are distributed daily on the web (http://www.aoml.noaa.gov/phod/cyclone/data/).

Hurricane storm surge seen with altimetry



Credit: NOAA

The left column shows a comparison of GOES 12 infrared images and altimeter data collected by (top) Jason 1 and TOPEX, (middle) Envisat and ERS-2, and (bottom) GFO during near-coincident overflights of Hurricane Katrina on 26, 27, and 28 August 2005. The three columns on the right show the altimeter measurements of wave height, wind speed, and sea level anomaly, respectively, as a function of latitude along the altimeter tracks shown on the infrared images.

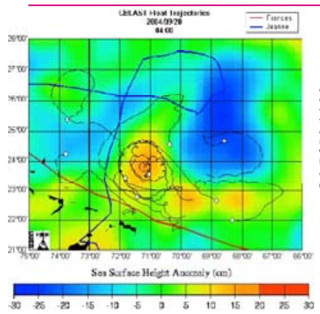
(R. Scharroo, W. Smith, J. Lillibridge)

For the first time, a hurricane storm surge has been observed by an ocean altimeter. The panels here depict significant wave height, wind speed and the residual sea level anomaly during Hurricane Katrina in late August 2005. The bottom rightmost panel from the Geosat Follow-On (GFO) altimeter shows sea level windward of the hurricane eye rising toward the shoreline and reaching 90 cm at the coast. This, apparently, is the wind driven storm surge.

Satellite altimeters play an important role in forecasting ocean conditions that can intensify a tropical storm and can observe the storm conditions at the sea surface. Altimeter data also indicate that Katrina intensified over areas of anomalously high dynamic topography rather than areas of unusually warm surface waters.

(Eos, Vol. 86, No. 40, 4 October 2005)

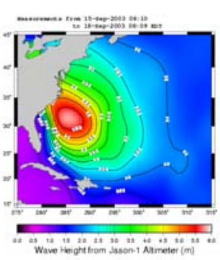
CBLAST: Hurricane research with altimetry



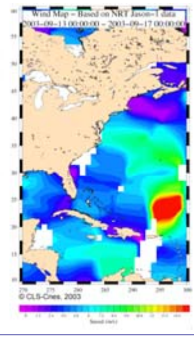
CBLAST float trajectories are shown overlaid on CCAR SSH anomaly. The white crosses show the final float positions on the date and time noted. Nine floats were deployed ahead of hurricane Frances in an effort to sample properties in the surface layer in near-real time. Sea surface height anomaly images were downloaded during the sampling period. Investigators were able to see the correspondence of their trajectories with sea surface elevation.
(Credits Scripps)

Scripps Institution of Oceanography investigators have been using the CCAR near real-time altimetry to monitor ocean circulation features during deployment of CBLAST floats during the recent hurricane season. CBLAST floats are used to study the upper ocean mixed layer. The primary goal is to improve our understanding of air-sea surface flux processes in high winds, specifically in the complex conditions of tropical hurricanes where swell, sea spray and secondary boundary layer circulations play a role. The ultimate goal and prime motivation for this work is to parameterize these new observations and improve the accuracy of hurricane intensity prediction.
http://www.sdcoos.ucsd.edu/data/floats2004/

Jason-1 Sees Isabel

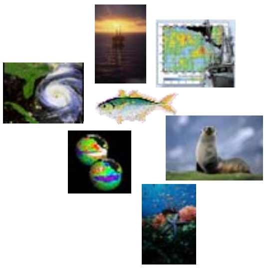


Jason significant wave height data during Hurricane Isabel, September 2003.

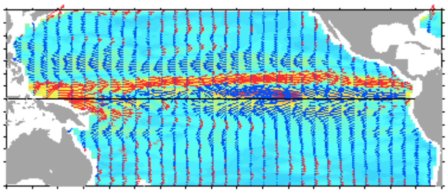


Wind data from Jason NRT data during Hurricane Isabel, September 2003.

Marine Industry



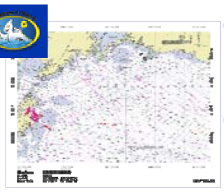
Ocean Surface Current Analysis - Real time (OSCAR)



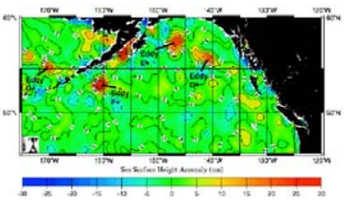
(Cheney, Mitchum, Lagerloef, Bonjean, others)

Ocean Surface Current Analysis - Real time (OSCAR) is a pilot processing system and data center providing operational ocean surface velocity fields from satellite altimeter and vector wind data. Surface currents are computed from satellite altimeter and vector wind data using methods developed during the Topex/Poseidon mission. OSCAR is a transition to operational oceanographic applications using Jason altimeter data. The regional focus is the tropical Pacific, where the value for a variety of users is demonstrated, specifically for fisheries management and recruitment, monitoring debris drift, larvae drift, oil spills, fronts and eddies, as well as on-going large scale ENSO monitoring, NOAA's CoastWatch, and climate diagnostics and prediction programs. Other potential uses include search and rescue, naval and maritime operations.

GhostNet Project: Derelict fish net detection

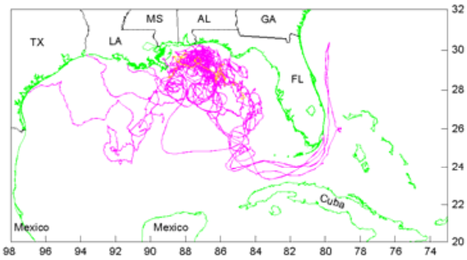


Flight track and debris sightings



Lost or abandoned fishing nets threaten fish, birds, sea turtles, and marine mammals in the open ocean. When entangled in coral reefs, these nets can also damage the reef environment. The GhostNet project (an industry, Government, and academia partnership) utilizes circulation models, drifting buoys, satellite imagery, and airborne surveys with remote sensing instruments in the detection of derelict nets at sea. These components were employed for the detection of marine debris during a 14-day aircraft survey of the Gulf of Alaska. Altimeter data from CCAR at the University of Colorado was among the suite of data used to locate convergent areas where nets were likely to collect. An aircraft survey with visible and IR cameras and a LIDAR instrument located debris in the targeted locations.

Simulations of oil-spill trajectories: Gulf of Mexico



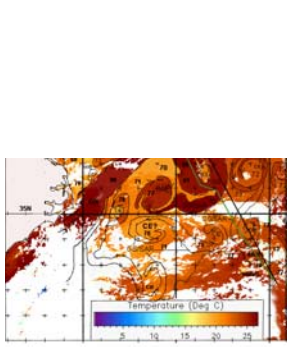
Trajectories of oil-spill simulating drifters deployed in the Gulf of Mexico in Nov. 1998 were tracked by the Service ARGOS system for 30 days for the U.S. Minerals Management Service (MMS); some drifters persisted in transmitting longer. Comparisons were then made against computer-model-generated oil-spill simulations using, in part, an ocean current field produced by the Princeton Regional Ocean Forecast System (PROFS) employing data assimilation of CCAR's blended altimeter data products which include TP and Jason data.

Offshore oilfield operational support: Gulf of Mexico

Data User: Capt. Karl Greig, captain of a large anchor handling tug boat owned by Edison Chouest Offshore, a petroleum industry service company, uses NRT Jason data from CCAR to optimize routes while towing semi-submersible drilling rigs used in deepwater oil and gas exploration between lease blocks.
Example Operation: Moving a rig from Mississippi Canyon block 68 to Mustang Island block 68, a total of 425 nautical miles. Typical towing speeds are 3 to 4 knots so avoiding and/or using eddy currents significantly reduces transit times, in this case by over 50 hours.
Altimeter Product Used: Overlays of geostrophic velocity vector on colored magnitudes values accessed on CCAR website by satellite phone.
Estimated Savings: $650,000 in rig downtime and towing costs for one event.

Colorado Center for Astrodynamics Research
University of Colorado at Boulder
International Workshop On Coastal Altimetry
November 16&17, 2011 Bogor, Indonesia

Jenifer Clark: Gulfstream



Data User: Jenifer Clark, professional satellite oceanographer.
Application: Provides realtime ocean charts for general marine consulting using infrared, satellite altimetry, and surface isotherm data. Oceanographic analyses are produced and available for the Gulf Stream area and all major global currents.
Operation: Using near real-time altimeter data with sea surface temperature imagery to evaluate currents affecting offshore operations. Waypoints are also provided for taking advantage of favorable currents and for avoiding unfavorable ones.
Altimeter Product Used: Near-real time data SSH and geostrophic velocity data viewers.

Colorado Center for Astrodynamics Research
University of Colorado at Boulder
International Workshop On Coastal Altimetry
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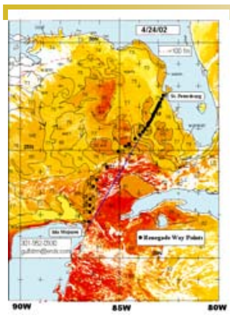
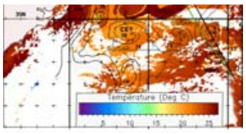
Jenifer Clark: Sport sailing





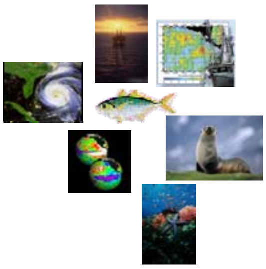
Example optimized routes for sport sailing

Private companies like Jenifer Clark's Gulfstream make charts of sea surface height. Eddies and swift moving currents are identified and mapped to increase safety and economic return for recreational boating, transatlantic ship routing, cable laying and oil exploration.

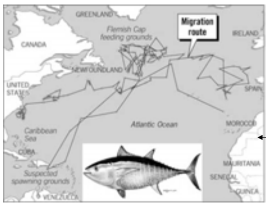
Jenifer Clark: Deep sea recovery

Jenifer Clark assisted Phoenix International Corp. in their recovery of the Navy Helicopter CH-46 near the Gulf Stream in 10,000 ft deep water off of the Virginia coast in June 2002.

Marine Research



Southern Bluefin Tuna Tagging



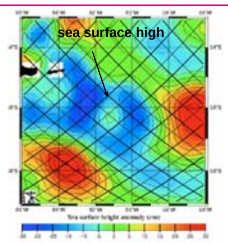
The migration route of one Bluefin Tuna over a two year period.

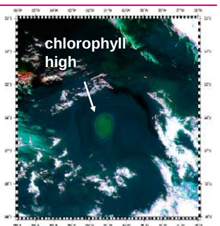
Source: Stanford University

Tagging a Southern Bluefin Tuna

Since May 2005 the University of Colorado's CCAR group has been supporting a Bluefin Tuna tagging program run by the New Zealand Government's Ministry of Fisheries by providing a custom, high resolution subset of the CCAR mesoscale SSH data product. The near real-time altimeter data aids the shipboard tag and release program in locating Bluefin Tuna habitats. This program is part of New Zealand's international obligation as a member nation of the Convention for the Conservation of Southern Bluefin Tuna (CCSBT). The "archival" tags are placed inside the belly of the captured fish through a small incision. While active, the computer chip records the fish's global movement, water temperature range, depth of water traveled in and, when recaptured, its growth rate. The tags are satellite monitored and will help to provide a much better picture of the behavior and migration patterns of these fish. As the tagging program moves to new areas CCAR will update the regional data subset. Altimeter data will also be used throughout the study to better understand the relationship between sea surface height and the distribution and migration of the Bluefin Tuna. For more information see; http://www.ccsbt.org/docs/research.html, http://www.tunaresearch.org/tagagiant/technology.html, http://www.marine.csiro.au/LeafletsFolder/31sbt/31sbt.html

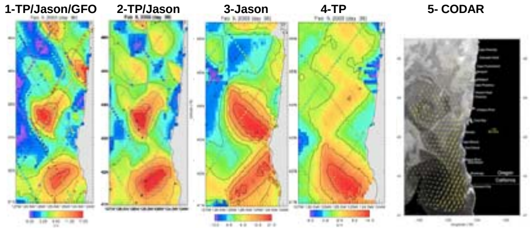
Real-time Tandem Mission SSH + SeaWifs





A combination of altimetry and SeaWIFS ocean color imagery (right) shows the evolution of a small anticyclonic eddy in the Drake Passage that formed on the continental slope of the Patagonia shelf just to the southwest of Cape Horn. The feature is about 50 km in diameter and is a 20 cm positive SSH anomaly relative to the surrounding waters. The interleaved TOPEX/POSEIDON (left, thin lines) and Jason (thick lines) resolves this fine scale structure. There is remarkable correspondence between the two remote sensing data products, in terms of the location, size and sense of rotation of this eddy. The tandem mission data effectively resolves these small, high latitude features, which otherwise would have been beyond the resolution of either altimeter alone. In this case, it is the interleaved tracks of TOPEX/POSEIDON that makes resolution of the fine-scale eddy possible.

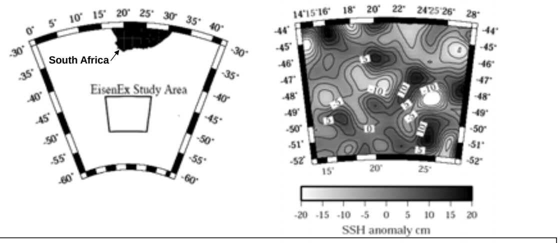
Tandem Mission Data; Mesoscale Circulation in the California Current



(Strub)

Altimeter data and coastal radar surface velocity fields collected at Oregon State University's College of Oceanic and Atmospheric Sciences (COAS) quantify and explain changes in mesoscale circulation in the California Current off Oregon. Increased resolution from the Tandem Mission (panels 1 & 2) provides the ability to monitor the development of eddies off Oregon. Coverage by the individual altimeters (panels 3 and 4) distorts the SSH fields. These panels resolve anticyclonic eddies - one off Oregon between 43N and 44N and another between 41N and 42N. Overlaying the CODAR velocity field on a surface temperature field from the AVHRR sensor (panel 5) confirms the location of these eddies. The anticyclonic eddy between 41N and 42N draws warmer water from the south into its clockwise circulation, forming a sharp boundary between the warm water in the eddy and the cooler water surrounding the eddy.

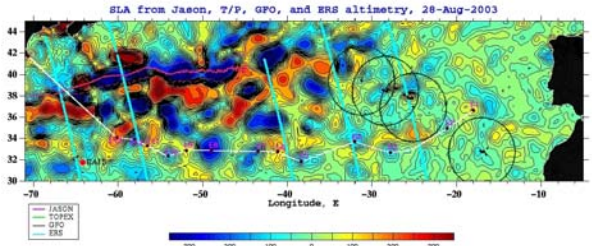
Iron enrichment for biogeochemistry studies



EisenEx is a mesoscale iron enrichment experiment conducted by a German research institute* in a Southern ocean eddy. The eddy, defined with altimeter data, can be seen in the right figure at 21 E 48 S. This and similar experiments are designed to study iron fertilization and its impact on the exchange of carbon between the ocean and air over the Antarctic Circumpolar Current. Over the past decade, scientists have been looking at the ocean iron cycle in more detail to better understand the link between the trace element iron in the ocean and carbon uptake. CCAR mesoscale altimetry has been used in four of nine fertilization experiments to date with near realtime data sent directly to the ship (Polarstern, in this case) during the research cruise. Summaries of these programs can be found at http://www.bbm.me.uk/FeFert/index.htm.

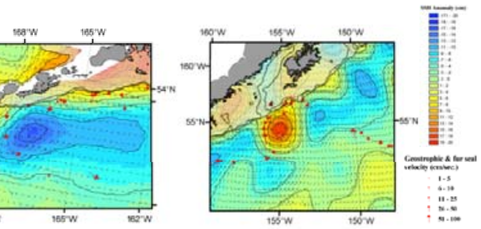
*Forschungsbereich Marine Biogeochemie Chemische Ozeanographie at the Leibniz-Institut für Meereswissenschaften in Kiel

Biologic sampling in eddies



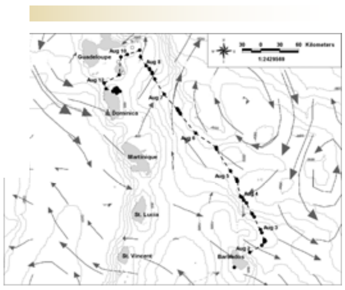
Valery Krosnyrev of Wood's Hole Oceanographic Institution (WHOI) is using along track data from Jason, T/P, GFO and ERS-2 to interpolate mesoscale feature maps that are used to vector R/V Knorr through cyclonic eddies on a transatlantic transect that is in progress. The white line shows the path of the ship. The pink line is the mean Gulf Stream current. The research is biologic in nature.

Stellar sea lion research



NOAAs National Marine Mammals Laboratory tracks Stellar sea lions in the North Pacific Ocean using blended altimeter data, including TOPEX/Poseidon and Jason OSDRs (SSH and current velocity vectors) from the University of Colorado's CCAR group. The data indicates that the sea lions travel 100's of miles across the North Pacific from shore to feed around the edges of ocean eddies. The figure on the left shows a mesoscale cold-core eddy near the Aleutian Islands, and the figure on the right indicates a cold-core eddy spun off the Alaska Stream. Each image is one tagged animal, with red vectors show heading and mean speed on a given day.

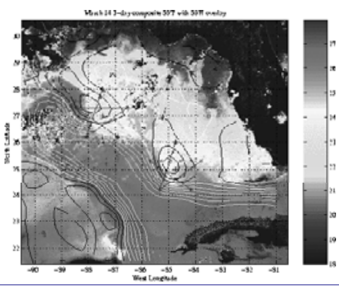
Satellite-tracked Sea Turtle migratory patterns



•Seaturtle.org uses CCAR near-real time mesoscale geostrophic velocity anomaly fields
•Study aid on migratory routes of hawksbill turtles in relation to surface eddy fields in near real-time

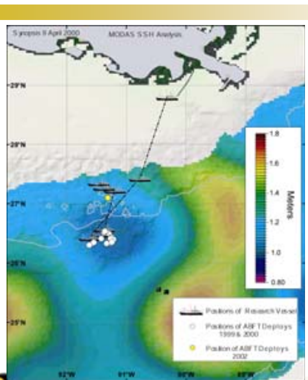
•Plan is to incorporate the data into graphical interfaces hosted on their web site
•Shown is a migration route from Barbados to Dominica overlaid on coincident geostrophic velocity streamline vectors.

Cetacean surveys in the Gulf of Mexico



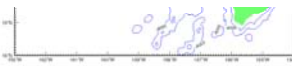
The MMS and the NOAA National Marine Fisheries Service (NMFS) conducted studies on sperm whales and deepwater acoustics in the Gulf of Mexico. The CCAR/TAMU cooperation provided NRT analyses of SST overlaid with SSH provided by CCAR using data from TP and ERS-2 altimeters. The example shown above gives suggested locations for XBT surveys of two cyclonic features in which a NOAA Ship searched for sperm whales, between March and April 2001. This application of remote sensing provided a "route map" for marine mammal biologists working aboard the vessel to locate cyclones (biological "oases") and anticyclones (biological "deserts").

Tuna tagging

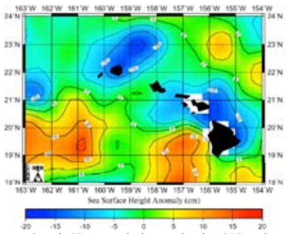


Researchers from the Monterrey Bay Aquarium tag tuna using Navy MODAS data assimilation and TP sea surface height analyses

Sediment transport research



The study region is centered on station 2 (Aloha).

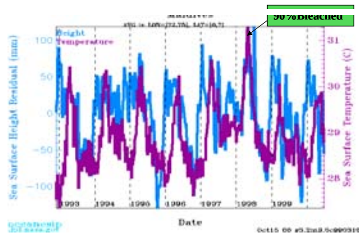


Sample SSH anomaly data product in HOTS study region.

Erik Fields, a computing and network technologist working for Professor David Siegel at the University of California Santa Barbara, is using along track Jason data from the CCAR Along-track Data Host (http://www-ccar.colorado.edu/~realtime/global_realtime/alongtrack.html) to make Objective Analysis (OA) maps of sea surface height anomaly at sea. The OA maps will be used with hydrographic surveys and acoustic Doppler current profilers to predict the path of neutrally buoyant sediment traps deployed as part of the VERTIGO sediment transport experiment. This experiment is described at the web page: http://www.whoi.edu/science/MCG/vertigo. The cruise worked in the vicinity of the Hawaii Ocean Time-Series (HOTS) Aloha station for several weeks for this study.

Coral bleaching and climate change

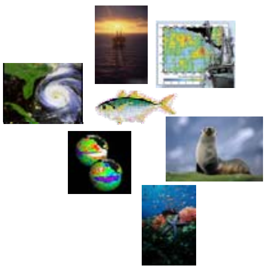
- TOPEX/Poseidon and Jason altimeter sea level and NOAA AVHRR sea surface temperature data monitor and assess global coral reef environments.
- High and low tropical sea levels and ocean temperatures caused by the '97 to '98 El Niño/ La Niña "bleached" 25% of all coral reefs.



Biodiversity - Coral ecosystems are our oceans "rainforests"

Maldive Islands, Central Indian Ocean, NASA Landsat 7 image

Land Operations



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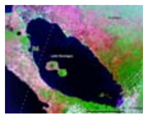
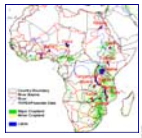
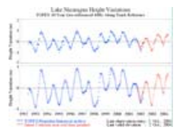
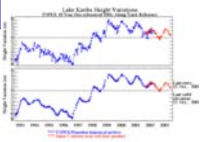
Near real-time measurement of inland waters





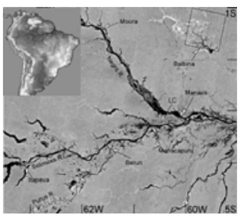




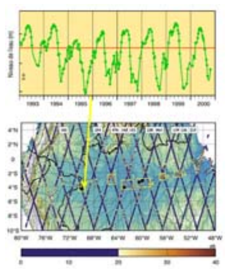
(Birkett, others)

Satellite radar altimeters are used to monitor the variation of surface water height of large inland water bodies. Using near-real time Jason data, a time series of surface water height variations is constructed. A semi-automated data ingestion/analysis system delivers time series products to a website for public access and to serve the USDA/FAS for its flood/drought investigations. This project is the first of its kind to utilize near-real time altimeter data over inland water in such an operational manner. Users: Primarily the US Dept. of Agriculture, Foreign Agriculture Service, PECAD division (Production Estimation and Crop Assessment Division), http://www.fas.usda.gov/pecad.

Amazon River level variation



Radar mapping of the Amazon basin (credit D. Alsdorf, UCLA)

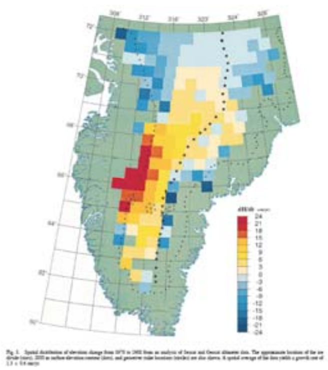


Water level variations since 1993 on the upper part of the Amazon, over the Topex/Poseidon ground track #102 (upper). Yellow and red indicate flooded regions, where the altimeter radar beam is well reflected (lower). (Credits Legos)

(Cazanave, et al)

Satellite altimetry is used to measure river level variations in areas historically difficult to reach due to large distances, limited access, and low population density (and therefore limited infrastructure) as the Amazon river basin in Brazil.

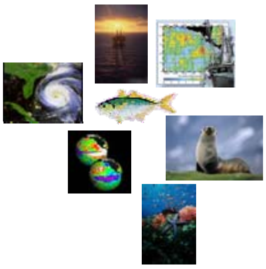
Greenland ice sheet elevation changes



Another example of land applications of ocean altimeter data is its use to measure surface elevation change on the southern Greenland ice sheet. In a study funded by NASA's Polar Program, the ESE, and JPL*, researchers found that the average elevation change above 2000 m elevation from 1978 to 1988 was not significant, contrary to reports that positive ice sheet growth rates suggest increased precipitation due to warmer polar climate.

*Davis, C., Kluever, C., Haines, B., Perez, C., and Yoon, Y., Improved elevation-change measurement of the Southern Greenland Ice Sheet from satellite radar altimetry, IEEE transactions on Geoscience and Remote Sensing, Vol. 38, No. 3, May 2000

Education

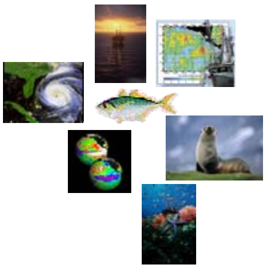


Altimetry in the classroom

In addition to the scientific and operational uses of the data, altimeter missions have provided product content and programs for both formal and informal educational settings. The educational community has embraced the unique concepts highlighted by altimeter missions like TOPEX/Poseidon and Jason-1 as a resource for teaching basic ocean awareness and ocean science to students from grade school through college and to all ages and backgrounds of the general public. The partnership between NASA/JPL and CNES/AVISO in collaboration with classrooms, schools, and informal education facilities has made it possible to widen the reach of activities and become a resource for science team member participation. Available products and activities include classroom visits, posters, CDs, web sites, online activities, literature, school programs, exhibit materials and more.

http://sealevel.jpl.nasa.gov

NRT Data Resources



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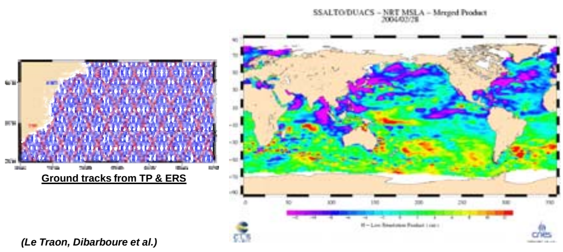
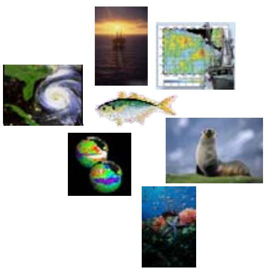
Ssalto/Duacs NRT operational oceanography



(Le Traon, Dibarboure et al.)

The CNES/CLS Ssalto/Duacs (Developing Use of Altimetry for Climate Studies) multi-altimeter processing system provides operational oceanography and climate forecasting centers with high quality near-real time altimeter data to improve climate simulations and, more specifically, seasonal climate forecasts. The NRT and historical products developed and refined with Duacs are widely used in the scientific community covering a large spectrum of operational oceanography needs, from mesoscale to climate applications. The data is used in particular for the Mercator project (http://www.mercator-ocean.fr), the French contribution to GODAE, using IGDR data from all available altimeters.

Other Applications



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Other users/applications

- Insurance Claims Adjustors
- Marine Architects
- Fisheries Managers
- Commercial Fishermen
- Search and Rescue
- Ocean Circulation Nowcasts/Forecasts/Hindcasts
- Forensic Oceanographers

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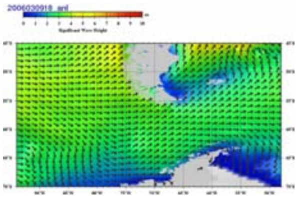
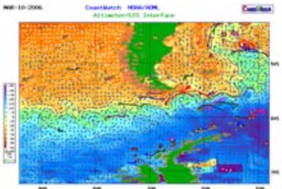
Volvo Ocean Race Support



Significant wave height and wind direction from NOAA WaveWatch III Model.



Geostrophic currents and drift trajectories

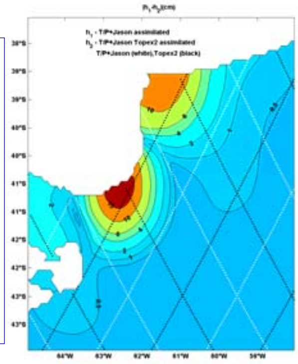
NOAA-AOML provided near-real time surface currents from altimetry, SSTs, and surface winds to 2006 Volvo Ocean Race teams. VOR, held every 4 years, covered 31,000 nautical miles in 9 legs, starting in Vigo, Spain in Nov. 2005 and finishing in Goteborg, Sweden in Jun. 2006. A dedicated AOML web page displayed data distributed to the sailboats (*http://www.aoml.noaa.gov/phod/VOR/*). Racing teams used this information to negotiate (un)favorable currents or winds during the race. This collaboration in turn provided feedback on data products, as well as atmospheric and sailboat drift data to NOAA from the teams, helping with validation efforts.

G.Goni, NOAA

Patagonian Coastal Shelf Tides

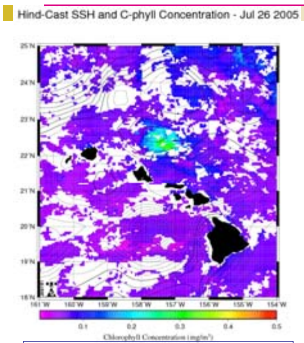
Tandem Mission data provides critical information required to resolve tides on the continental shelves, where the tidal range is generally larger and wavelengths are shorter than in the open ocean. In this example off the Patagonian shelf, complex shallow water tidal wave systems produce some of the world's largest tidal amplitudes.

The figure illustrates the impact of including the Tandem Mission data in a hydrodynamic assimilation of the M2 tides. The colors indicate the magnitude of the difference between a model based on assimilating T/P or Jason alone (ground tracks denoted by white lines), and a model assimilating the combined Tandem Mission dataset, including data along the interleaved tracks of the Tandem Mission (denoted by black lines).



G. Egbert, OSU

Ocean color & SSH view ocean eddies



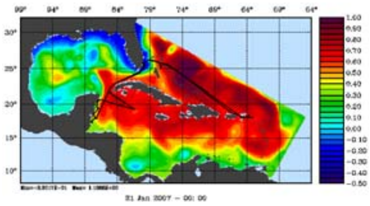
Hindcast SSH anomaly contours overlaid on chlorophyll concentration derived from 7-day composite of MODIS ocean color imagery north of the Hawaiian Islands. Image shows an anticyclonic eddy with high chlorophyll concentration. Graphic generated from CCAR online data visualization tool.

Allison Fong of the Univ. Hawaii at Manoa studies the spatial and temporal abundances of nitrogen-fixing bacteria that may play an important role in open-ocean biogeochemical cycling, using data from the HOT program[1]. In July 2005, the project sampled a region of enhanced chlorophyll north of Oahu. Satellite-derived ocean-color (MODIS), and sea surface height data (Topex/Poseidon) from the Univ. Colorado Center for Astrodynamics Research (CCAR) near-real time (NRT) web site indicated the feature was coincident with the decay of an anti-cyclonic eddy. The CCAR NRT and hind-cast data allowed tracking and sampling of the feature for both biogeochemical and biological parameters. The images were used to track the progression of this and similar eddies, providing compelling evidence suggesting increased productivity due to these mesoscale features.

[1]Hawaii Ocean Time-series (HOT) program

A. Fong, U. Hawaii

Intra-Americas Sea Trials



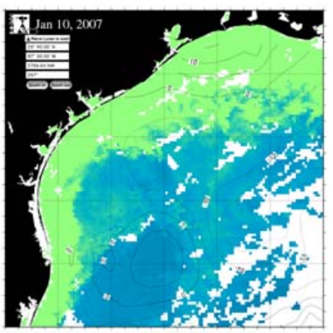
Sea surface height forecast for 21 Jan 2007 from the ROMS modeling system which is run in real-time on board the Royal Caribbean International vessel Explorer of the Seas. The black line shows the vessel's cruise path. See http://marine.rutgers.edu/po/ias/

University of California, Santa Cruz researchers are assimilating CCAR NRT sea surface height data into a Regional Ocean Modeling System (ROMS). ROMS is used for data assimilation and ocean prediction in the Intra-Americas Sea (IAS) with particular emphasis on the Caribbean Sea. In partnership with the University of Miami, NOAA, NSF and the Royal Caribbean Cruise Line, the cruise ship, *Explorer of the Seas*, has been equipped with oceanic and atmospheric sensors providing continuous observation along two cruise tracks that circumnavigate the Caribbean Sea once every two weeks. The objectives and scientific goals of the program are:

- To develop a real-time data assimilation and prediction system for the IAS based on a continuous upper ocean monitoring system;
- To demonstrate, as a proof of concept, the utility of a real-time data assimilation and prediction system in a real-time, sea-going environment, and to demonstrate the value of collecting routine ocean observations from specially equipped ocean vessels, in this case cruise liners;
- To develop much needed experience in both the assimilation of disparate ocean data and the prediction of ocean circulation using regional ocean models.

B. Powell, A. Moore, UC Santa Cruz

Hilton's Realtime Navigator

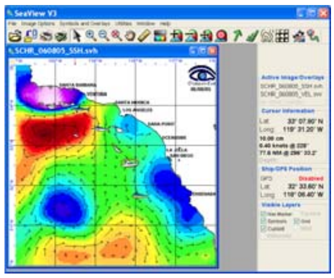


CCAR sea surface height contours and ocean color overlay hosted on the Realtime-Navigator website.

- Private company provides fishing charts and atlas
- Clients: Large game (marlin, tuna) fisherman
- Offshore Gulf of Mexico
- Altimeter and ocean color data maps provided via CCAR web site
- CCAR produces daily sea surface height (from Jason-1, GFO, and Envisat) and chlorophyll concentration maps (MODIS) for 10 regions in the Gulf and along the Atlantic Coast.

http://www.hiltonsoffshore.com/

Ocean Imaging for Fishing



A SeaView screen shot of a Southern California coastal image showing SSH anomaly and ocean current analyses updated 5-7 times per week. Symbols used to manage fishing strategy are also shown on the image.

Ocean Imaging Corporation (OI) has supplied ready-to-use oceanographic analysis products to commercial and recreational fishing fleets worldwide since 1983. OI provides 500-meter ocean color, plankton and altimeter derived sea surface height anomaly imagery (SSH) and ocean current products to clients worldwide. OI research investigated the correlation of albacore tuna catch data to SSH anomaly patterns and geostrophic near-surface flow. Significant correlations were found between albacore location and 'catchability' and the altimeter-derived data. Operational products are distributed to vessels at sea in near real time via the SeaView data retrieval and visualization system.

The data are pre-processed by CCAR and provided on a daily basis in an ASCII format listing the lat/long, SSH anomaly (cm) and the U/V components of geostrophic surface flow. The data are then processed at OI to generate SeaView-compatible SSH anomaly analyses and ocean current vector overlays. The data are posted to FTP and web servers within 30 minutes of retrieving the 'raw' data from CCAR allowing 24/7 access to the final products by OI customers via internet connection. The majority of end-users download the products directly to their onboard PC while out at sea either using cellular or satellite telephone.

http://www.oceani.com

Satellite Applications:

Climate Monitoring

Satellite Applications: Climate Monitoring

Bob Leben
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

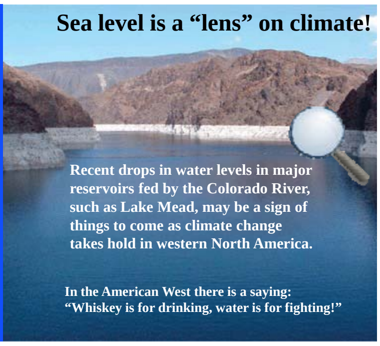
Boulder, Colorado

Why worry about sea level when you live over a mile high?

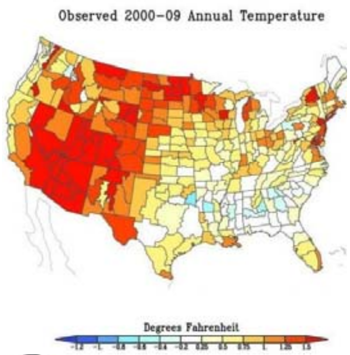
Signs of shifting climate in the western U.S. :

- rising temperatures
- earlier snowmelt
- northward-shifting winter storms
- increasing precipitation intensity and flooding
- record-setting drought
- plummeting Colorado River reservoir storage
- widespread vegetation mortality and more large wildfires

(Overpeck et al., 2010).



Western U.S. Warming

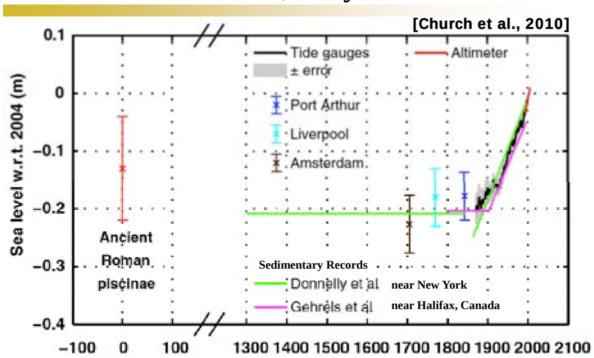


- Map of the observed difference between the average annual U.S. temperatures for this century (2000 to 2009) and those of the last century (1900 to 1999).

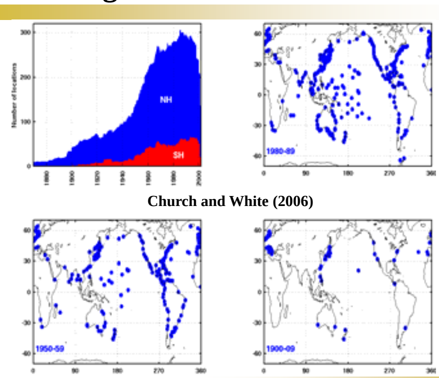
(Credit: NOAA)

Last 2,000 years

[Church et al., 2010]

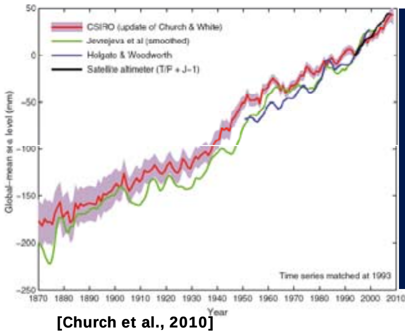


Tide Gauge Measurement Distribution



Church and White (2006)

The last 140 years…



CSIRO
- EOF reconstruction

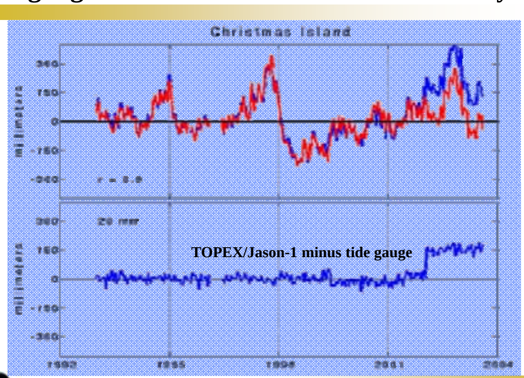
Jevrejeva et al.
- Nonlinear trend analysis (MC-SSA).

Holgate & Woodworth
- Reintegrated global averages of regional mean trends.

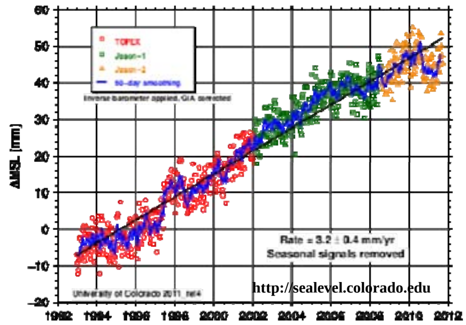
Satellite Altimetry
- Annual mean values.

[Church et al., 2010]

Tide gauges are used to monitor the satellite system



Inter-calibrated Satellite GMSL

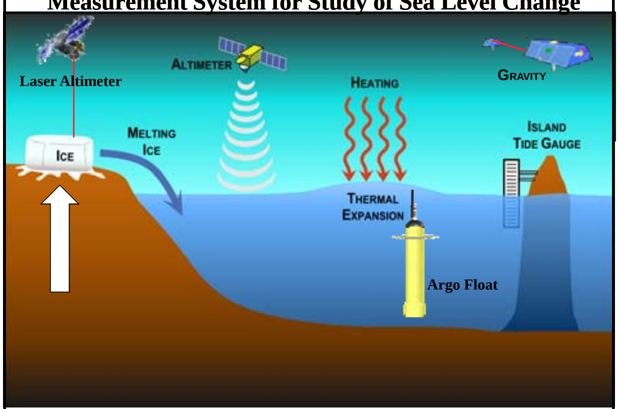


Causes of Sea Level Change

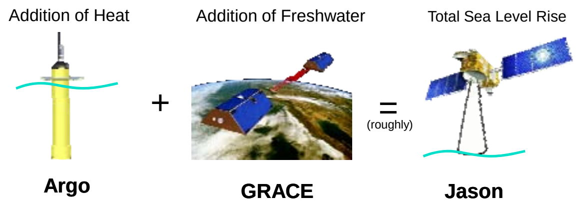
- **Thermal Expansion (~ 1 meter potential)**
- **Water Exchange with Continents (potential)**
  - Greenland Ice (7 meters)
  - Antarctic Ice (60 meters)
  - Mountain Glaciers (0.7 meter)
  - Terrestrial Water Storage Variations (< 0.5 meter)
  - Other (halosteric, etc.)

$$\Delta SL_{Total} = \Delta SL_{Thermosteric} + \Delta SL_{Greenland} + \Delta SL_{Antarctica} + \Delta SL_{Glaciers} + \Delta SL_{Storage} + \Delta SL_{Other}$$

Measurement System for Study of Sea Level Change

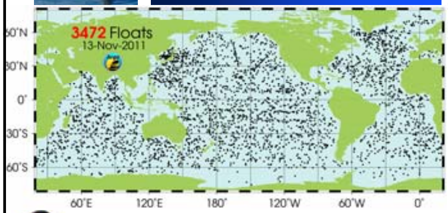


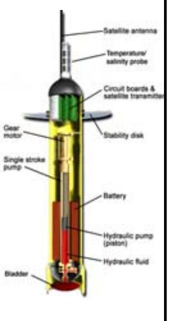
Closing the Sea Level Budget



The Argo Array

Floats cycle to 2000m depth every 10 days, with 4-5 year lifetimes for individual instruments, and provide temperature/salinity (T/S) profiles and velocity measurements. All Argo data are publically available in near real-time.





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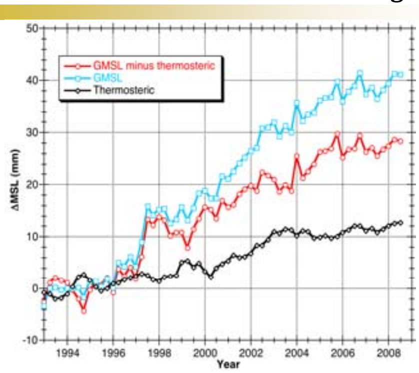
Thermosteric Sea Level Change



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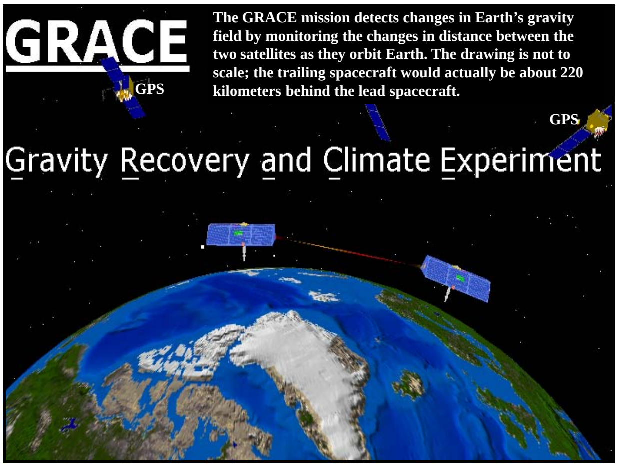
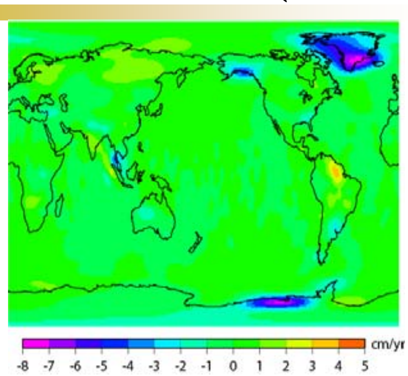


GRACE Secular Trends (2002-2009)



GIA Model Removed

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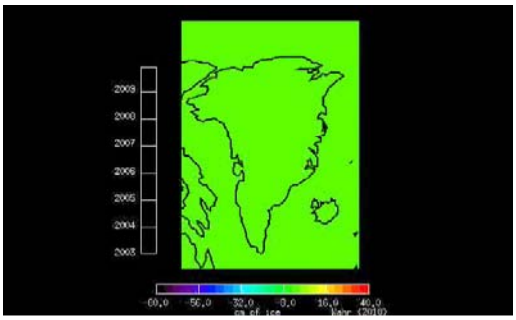
Greenland Mass Change from GRACE



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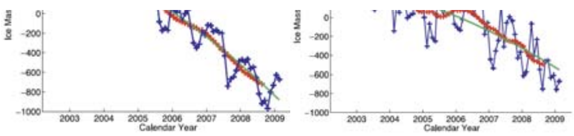
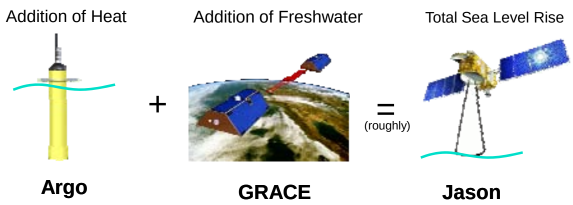
Greenland and Antarctic



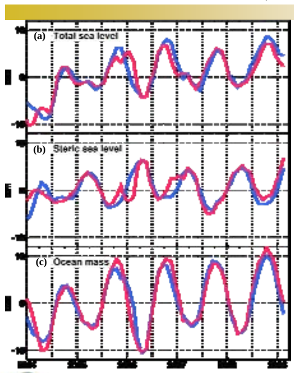
Greenland Ice Sheet **Antarctic Ice Sheet**

Source: Velicogna, I. *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.

Closing the Sea Level Budget



Closure of Grace, Argo, and Altimetry



Blue lines are the observed:

(a) Total sea level from Jason-1

(b) Steric sea level from Argo

(c) Ocean mass from GRACE

The red lines are inferred from the equation below using the complementary observations.

$$\Delta SL_{Total} = \Delta SL_{Thermosteric} + \Delta SL_{Mass}$$

[Leuliette and Miller, 2008]

Current Sea Level Budget

Thermal Expansion: ~ 1 mm/year

\+ **Mountain Glaciers: ~ 1.2 mm/year**

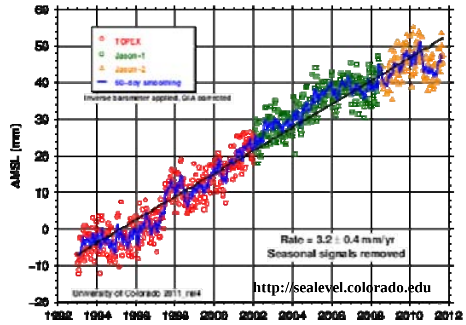
\+ **Greenland Ice Melt: ~ 0.6 mm/year**

\+ **Antarctic Ice Melt: ~ 0.5 mm/year**

Land Water Storage: ?

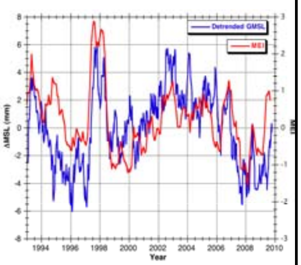
= **Total: 3.3 mm/year**

Intercalibrated Altimetric GMSL



Detrended GMSL vs. Multivariate ENSO Index(MEI)

After the linear trend and seasonal cycle are removed from the GMSL time series, much of the GMSL signal is explained by the El Niño Southern Oscillation (ENSO) climate signal.



For information on the MEI see: http://ww.esrl.noaa.gov/psd/mei/

Sea Level Reconstruction

The study of sea level can be extended before the period from 1993 to 2009 using reconstruction techniques.

- Tide gauges have a long record, but the spatial distribution is poor.
  - Most tide gauges are located around heavily populated areas in North America, Europe and Eastern Asia.
  - Relatively few tide gauges extend back into the 19th century.
  - Most gauges are coastal.
- Satellite altimetry provides near-global coverage, but the record is short and does little to answer the question of how the current state of the ocean compares to previous ocean states.
  - Modern satellite altimetry records extends back to only 1993.
- As a result of the shortcomings of the tide gauge and altimetry records, combining the two datasets is an active research area.
- Combining the near-global coverage of satellite altimetry data with the long record length of the tide gauge data is called **"Sea Level Reconstruction"**.

Using Sea Level Reconstruction to Study Trends and Climate

Sea Level Reconstruction:

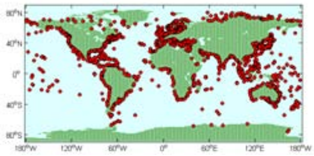
- **Combines near global coverage of satellite altimetry data with the long record of the tide gauge measurements to reconstruct maps of sea level at times before satellite sampling.**
- **Allows analysis and reconstruction of sea level trends and climate signals over long time periods.**

As an example, we will show the reconstruction of ENSO climate signals from 1950-2009 using tide gauge data and satellite altimetry.

Tide Gauge Measurements

- Tide gauges have provided sea level measurements for 200 years.
  - Long record, but the spatial distribution is poor.
  - Most tide gauges are located around heavily populated areas in North America, Europe and Eastern Asia (northern hemisphere).
- Permanent Service for Mean Sea Level (PSMSL) collects and edits data from over 2000 tide gauges.
  - Only 1200 of the available tide gauges have been included in the Revised Local Reference (RLR) dataset.
  - After a recent update, PSMSL record covers the time period from 1807 to 2011.

San Francisco tide gauge, (1856-present)



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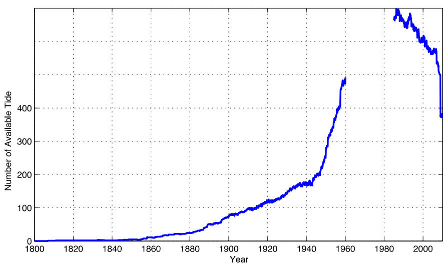
Measuring Sea Level: Past and Present

- Number of available tide gauges in the PSMSL RLR dataset over the period from 1807 to 2010.



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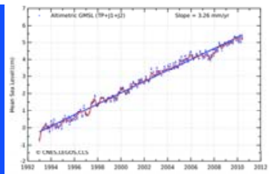
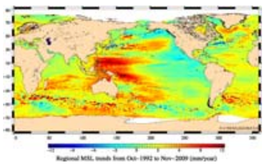
What are sea level reconstructions?

- Satellite altimetry has provided accurate measurements of sea level with near-global coverage.
  - Modern satellite altimetry records extends back only two decades.
    - TOPEX/Poseidon: 1993-2005
    - Jason-1: 2001-Present
    - Jason-2: 2008-Present
  - Led to first definitive estimates of global mean sea level (GMSL).
  - Regional distribution of sea level rise can also be estimated.





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Previous Reconstructions

- Sea level reconstructions stemmed from SST reconstruction techniques (Smith et al., 1996; Kaplan et al., 1998; 2002).
- Chambers et al. (2002) was the first to perform an EOF based sea level reconstruction.
  - Computed EOF basis functions from 7 years of altimetry data.
  - Removed trends and focused on capturing inter-annual-scale signals like ENSO.
- Church and White et al. (2004) provide the only publicly available reconstructed sea level dataset covering the period from 1950 to 2001.
  - Also used EOFs to form the basis of their reconstruction with annual cycle removed.
  - Included trends in their reconstruction and provided a method for reconstructing global mean sea level.
- These reconstructions are sensitive to several different parameters, including: 1) choice of basis function, 2) choice of weighting, 3) tide gauge editing, 4) method for accounting for GMSL.
- By addressing each of these areas, we can attempt to improve on past sea level reconstructions.

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Basis Functions: CSEOF vs. EOFs

- Most SST and sea level reconstructions have relied on EOFs as basis functions.
  - Techniques like EOF analysis do not accommodate time-dependent spatial patterns and, therefore, enforce stationarity.
  - EOFs are prone to mode mixing, particularly with regards to the annual signal.
- To address this and other problems, Kim et al. (1996; 2001) introduced the concept of **cyclostationary empirical orthogonal function (CSEOF) analysis**.
  - CSEOF analysis has been shown to extract the annual and ENSO signals from the satellite altimetry data (Hamlington et al., 2010; 2011).
  - By using CSEOFs in place of EOFs, an alternative and improved reconstruction could be computed.

EOF and CSEOF analysis and reconstruction software will be demonstrated in the training

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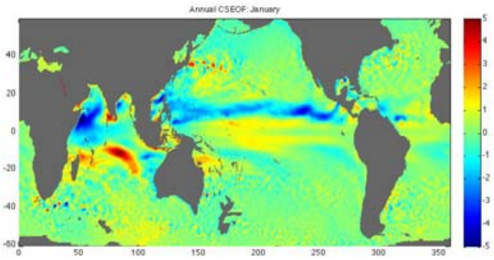
CSEOF : Annual Signal



- Performing a CSEOF decomposition of AVISO satellite altimetry data with a nested period of one year gives the annual cycle as the first mode and ENSO as the second mode.

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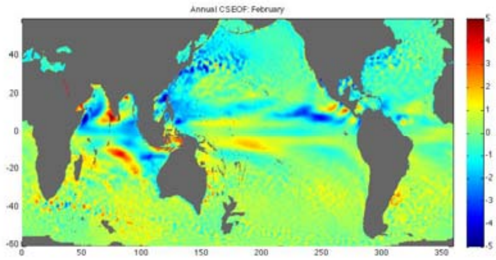
CSEOF: Annual Signal



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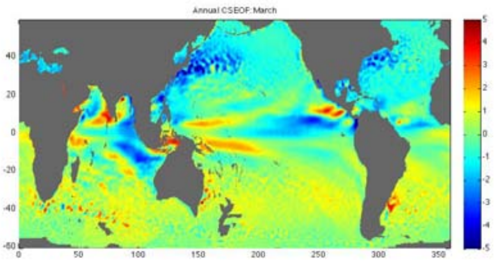

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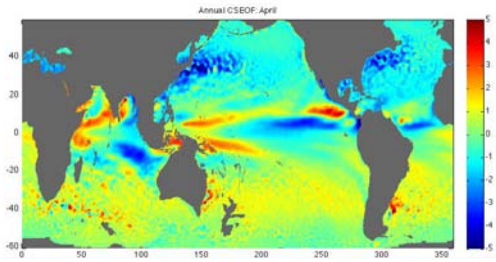

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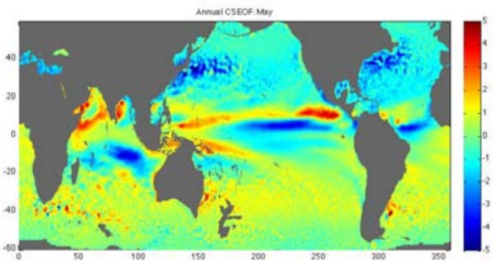

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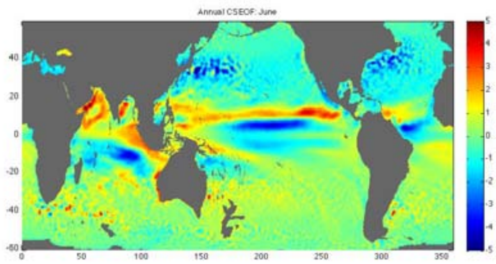

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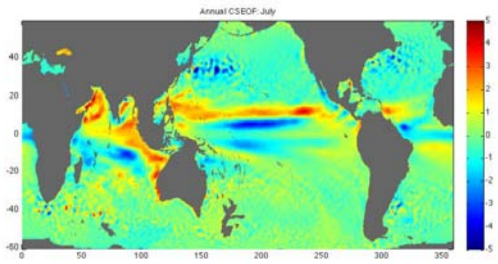

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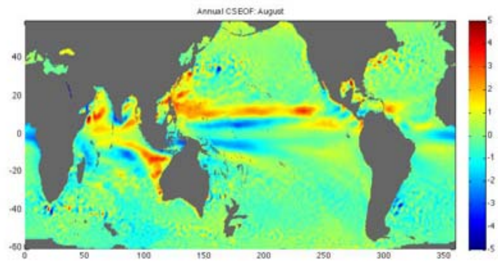

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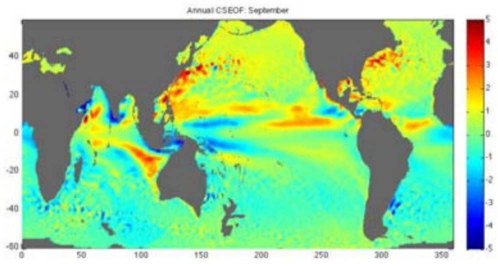

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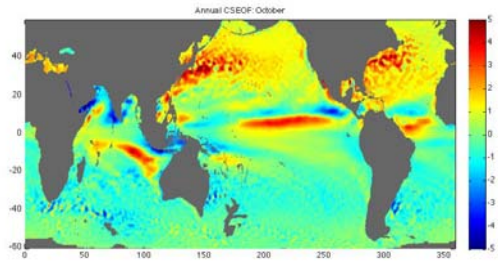

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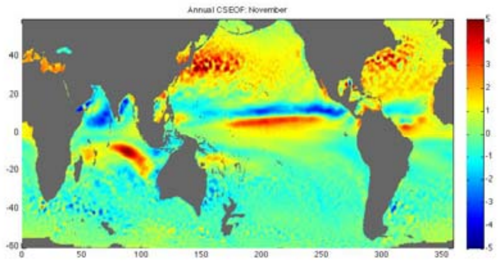

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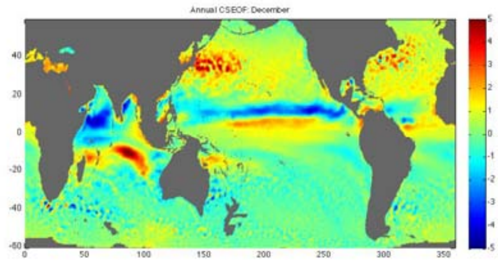
CSEOF: Annual Signal



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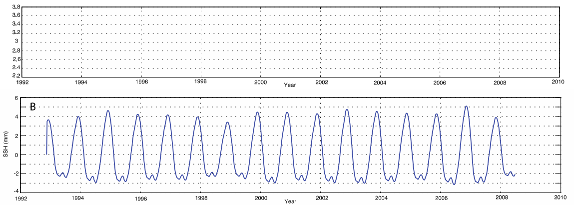
CSEOF: Annual Signal

- The amplitude modulation of the annual cycle is represented by the PC time series (Fig. A). By combining the LVs and PC time series, we can compute the contribution of the annual cycle to GMSL (Fig. B).



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CSEOF Analysis: ENSO

- ENSO is another example of a signal that fluctuates in time at longer timescales than its well-defined period.
  - Includes biennial and lower frequency components.
  - CSEOF analysis has been shown to extract the ENSO using a one-year nested period. (Jin et al., 1996; Kim and Chung, 2001; Trenberth et al., 2005; Hamlington et al., 2010; Hamlington et al., 2011).
  - Second mode from satellite altimetry describes the Eastern Pacific El Niño, while the third mode represents the Central Pacific El Niño.

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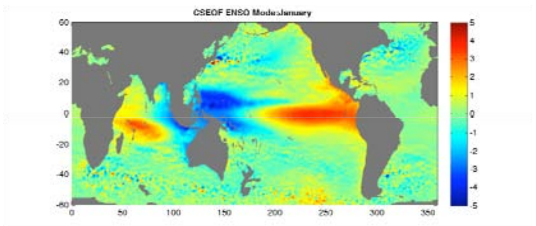
CSEOF Analysis: ENSO



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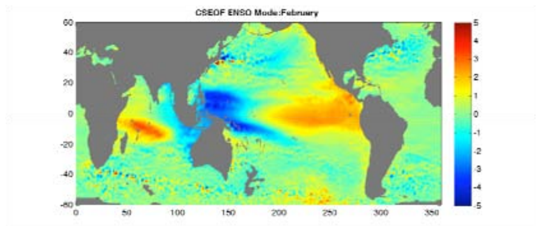
CSEOF Analysis: ENSO



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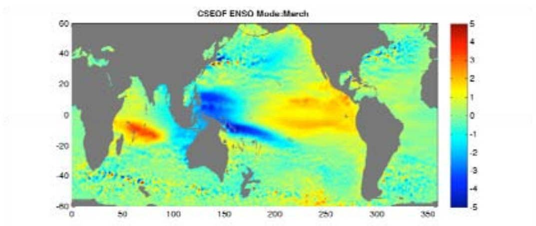

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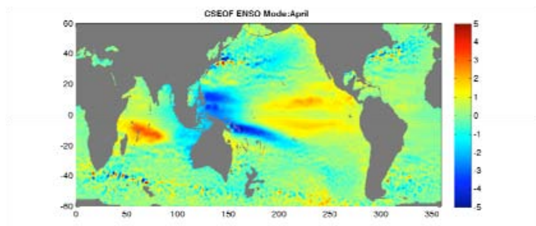

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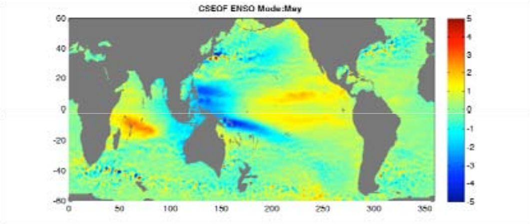

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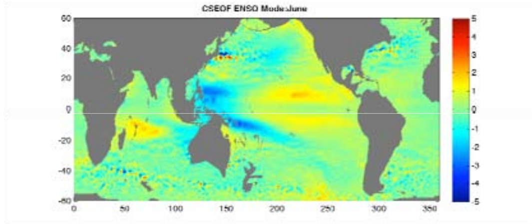

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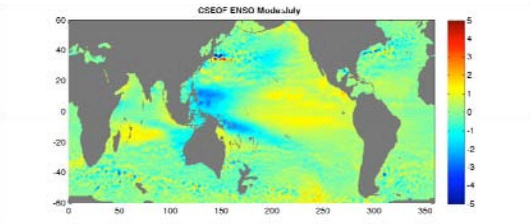

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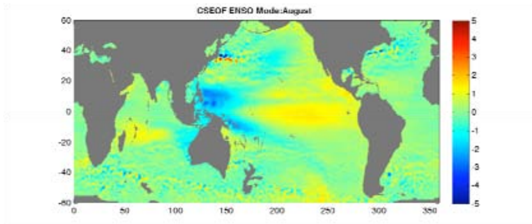

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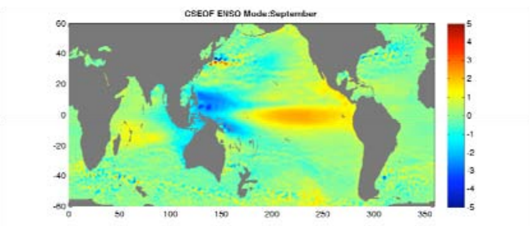

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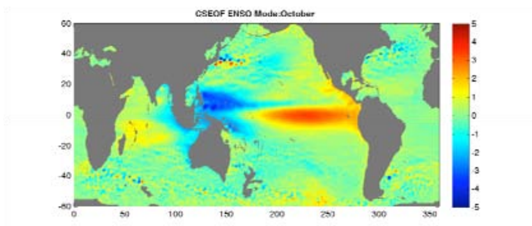

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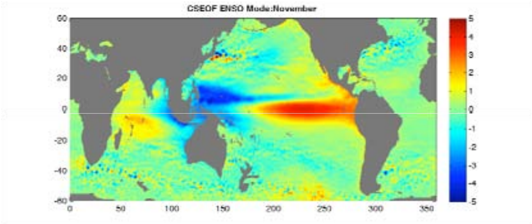

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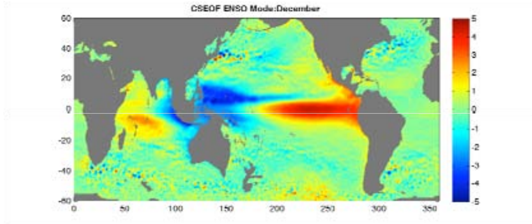
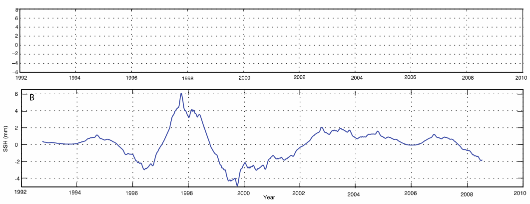
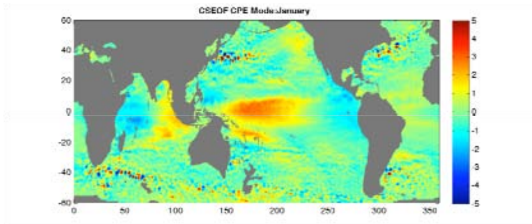


CSEOF Analysis: ENSO

- The amplitude modulation of ENSO is represented by the PC time series (Fig. A). By combining the LVs and PC time series, we can compute the contribution of ENSO to GMSL (Fig. B). Correlation between the Multivariate ENSO Index (MEI) and PC time series is 0.95.



CSEOF Analysis: CP ENSO



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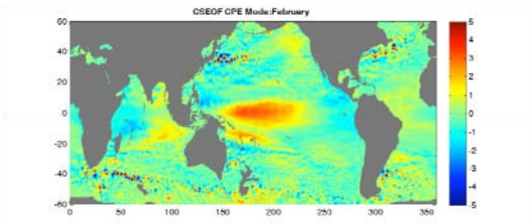

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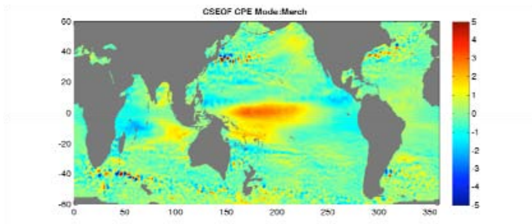

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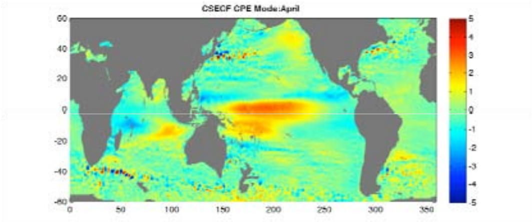

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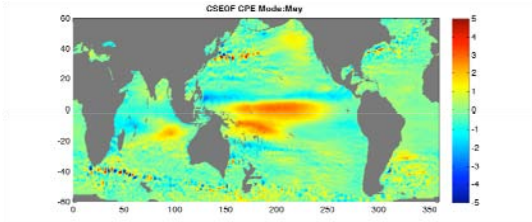

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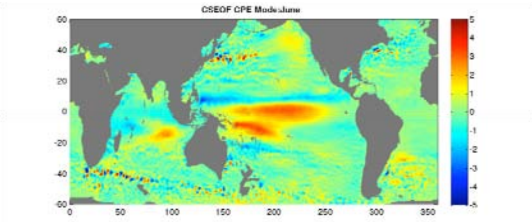

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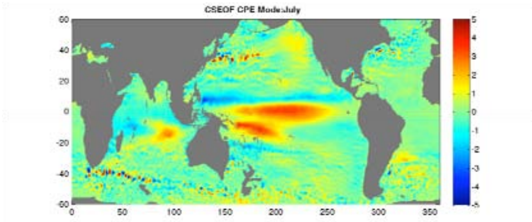

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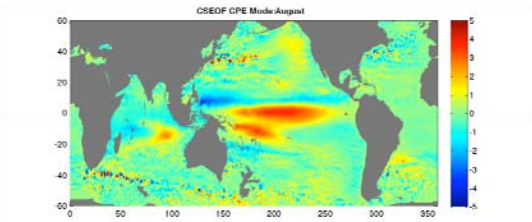

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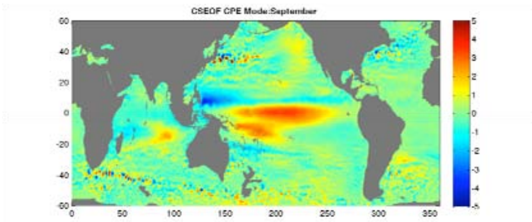

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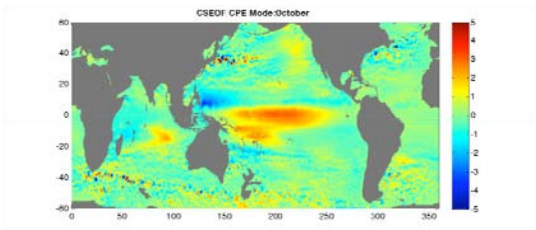

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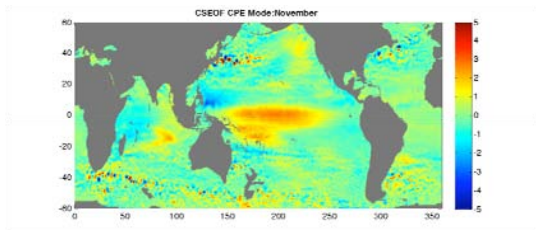
CSEOF Analysis: CP ENSO



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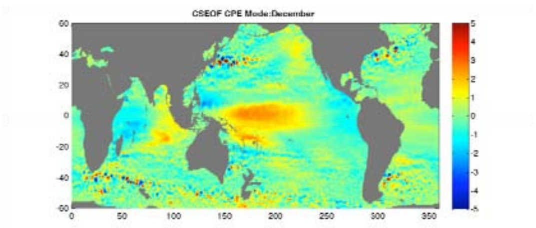

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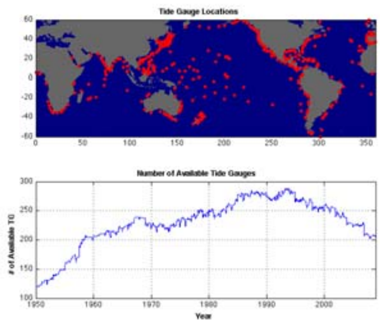
CSEOF Reconstruction Results



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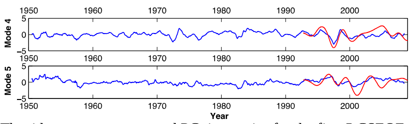

- The tide gauge reconstructed PC time series for the first 5 CSEOF modes are shown overlaid with the original altimeter-derived PC time series. The quality of the reconstruction is shown by the agreement between the two.

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CSEOF Reconstruction Results: Climate Indices

- CSEOF reconstruction provides SSH-based indices describing well-known climate signals.
  - These indices can be linked to major patterns of climate variability and provide a useful tool to monitor climate change.
- Indices computed strictly from the SSH reconstruction can be used to compare to the indices derived from SST reconstructions.
  - SST reconstructions extend back to the 19th century.
  - SSH reconstruction can be computed back to the first date that tide gauge data is available.
  - Could have advantages over SST computed indices because of limited sea surface temperature sampling during some time periods such as World War I & II (Giese et al., 2010).

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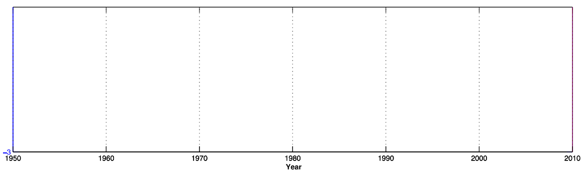
CSEOF Reconstruction Results: EP El Niño



- **The Eastern Pacific El Niño is described by CSEOF mode 2** in both the satellite altimetry and reconstructed sea level.
- The correlation between the Multivariate ENSO Index (MEI; Wolter and Timlin, 1998) and the reconstructed EP El Niño amplitude is **0.91** over the period from 1950 to 2010.

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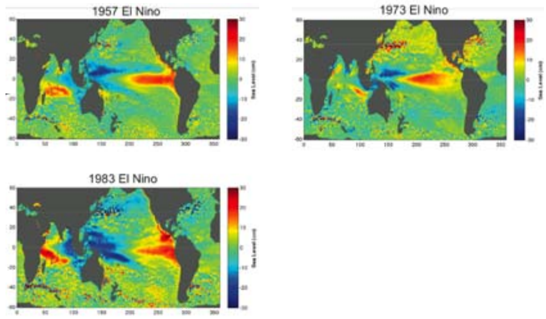
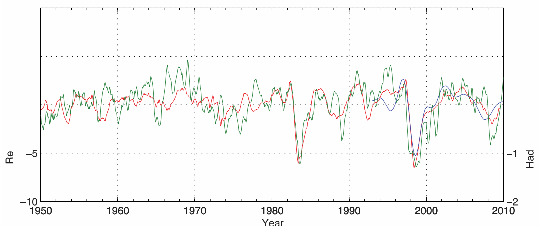
CSEOF Reconstruction Results: ENSO



Colorado Center for Astrodynamics Research
University of Colorado at Boulder

International Workshop On Coastal Altimetry
November 16&17, 2011 Bogor, Indonesia

CSEOF Reconstruction Results: CP El Niño



The Central Pacific El Niño or El Niño Modoki Index (EMI) computed from the reconstructed SSH (red), specifically the third mode of the reconstruction. The EMI computed from the Hadley reconstructed SST dataset is also shown, with a correlation of 0.61 between the two over the period from 1950 to 2010.

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Summary

- **Satellite observations are able to close the sea level budget.**
- **Many of the remaining questions about sea level rise can only be answered with continued satellite measurements into the future, which are in jeopardy.**
- **Sea level reconstructions are viable technique for extending the sea level and climate data record further back in time to complement the ongoing satellite record.**
- **Validation and analysis of sea level reconstructions and climate signals in coastal areas, such as the Indonesian Seas, is an important research topic.**
- **Understanding past, present, and possible future climate and sea level change requires accurate long-term records.**

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Future Satellite Altimetry Mission

Future Satellite Altimetry Missions

Presented by
Stefano Vignudelli
Consiglio Nazionale delle Ricerche, Italy
vignudelli@pi.ibf.cnr.it

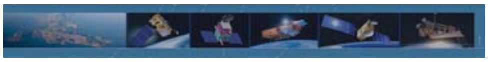
With invaluable help (and material) from
COASTALT Project

S. Vignudelli, A. Scozzari (CNR, Italy)
P. Cipollini, C. Gommenginger, H. Snaith, S. Gleason, G. Quartly, L. West (NOCS, UK)
Henrique Coelho (Hidromod, Portugal)
J. Fernandes, L. Bastos, C. Lázaro, A. Nunes. N. Pires, I. Araujo (U Porto, Portugal)
M. Bos (CIIMAR, Portugal)
S. Barbosa (U Lisbona, Portugal)
Jesus Gómez-Enri (U Cádiz, Spain)
C. Martin-Puig, M. Caparrini, L. Moreno (Starlab, Spain)
P. Woodworth, J. Wolf (POL, UK)
S. Dinardo, B. M. Lucas (SERCo/ESRIN, Italy)
J. Benveniste (ESA/ESRIN, Italy)

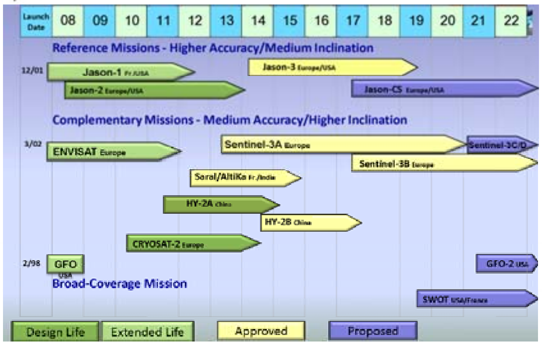
particular thanks also go to the Coastal Altimetry Community

Outline of my talk

- The era of modern altimetry
  - Status of missions
- A look at future with an eye to the coastal zone
  - Jason-3
  - CryoSat-2 (in operation)
  - Sentinel-3
  - HY-2
  - AltiKa
  - Constellations of altimeters
  - SWOT
- Summary



Global Altimeter Missions: now and then



Courtesy by P . Counet, Eumetsat

Jason-3

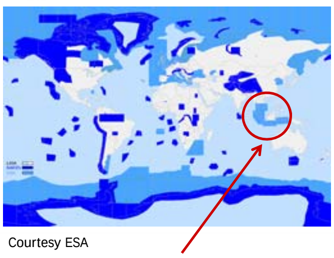
- Jason-3 is a follow-up of Jason-2
- To continue the climatic core record started on 1992 with TOPEX/Poseidon (more than 20 yrs at present)
- Jason-3 development underway, tentative launch to April 2014
- Expected capabilities in the coastal zone will be similar or even better than Jason-2

CryoSat-2

- Designed to measure ice thickness, but collects data in some selected oceanic regions
- Launched 8 April 2010
- Carries aboard the SAR/Interferometric Radar Altimeter (SIRAL)
- It uses a new Synthetic Aperture Radar (SAR) Technique which gives 250 m along-track resolution, much higher than conventional altimeters (ERS-2/Envisat RA-2) -
- SAR mode provides high res data over ocean, inland water and coastal zone

http://www.esa.int/esaLP/LPcryosat.html

CryoSat-2



Courtesy ESA

- Preliminary results showed at 5th Coastal Altimetry Workshop, San Diego
- Cryosat already performs equally well to conventional altimeters even without some of the corrections (Scharroo, Altimetrics)
- Cryosat waveforms are well behaved all the wave all the way to the coast. (Dinardo, ESA)
- Possibility of Fast Delivery Cryosat "SGDR" quality data (Smith, NOAA).

Indonesia is one of the regions selected to collect high resolution data in SAR mode

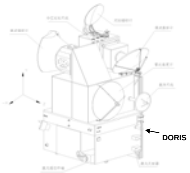
Sentinel-3A/B (EU/US)

- This is part of the proposed Sentinel constellation series being pursued by ESA under the Global Monitoring for Environment and Security (GMES) Program (European Union)
- will carry a new generation Altimeter (SRAL), similar to CryoSat-2
- Much much better capabilities in the Coastal Zone if compared to Envisat

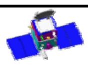
http://www.esa.int/esaLP/SEMZHM0DU8E_LPgmes_0.html

HY-2A

- Chinese Mission with CNES (France) contribution (orbit estimations)
  - HaiYang means 'ocean' in Chinese
- Successful launch on August 16th.
  - Doris powered on August 31st
  - since then orbit ephemeris are produced and distributed
- Carries Dual-frequency altimeter Ku/C
- Actual quality level of data still unknown
- Data policy (not confirmed yet but hopefully open)



ALTIKA



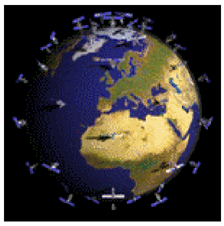
- Cooperative framework : CNES/ISRO
- Altimetric Gap filler between Envisat & Sentinel-3
- Research oriented mission
- New, higher frequency, greater performance
- Potential new applications on ice, land, coastal areas
- ...but with a consolidated architecture : conventional altimeter
- Tentative launch date : early 2012
- Payload AltiKa: Ka-band altimeter (higher accuracy, no need for a 2nd frequency) + Dual-frequency radiometer (sharing the same antenna)
- POD: DORIS/LASER
- Orbit: same as ENVISAT (sun-synchronous, 35-day cycle)

Coastal relevance?
- Smaller (along-track) footprint than Ku-band RAs
- Longer repeat orbit
- Better SSH precision
- Soon to be operational

http://smsc.cnes.fr/SARAL/

Constellations of altimeters

- 66 Iridium satellites would provide truly global coverage ideal for the earth observation sensors SWOT means Surface Water & Ocean Topography
- Iridium-NEXT telecommunication constellation renewed, starting from 2015
- They can take payloads of opportunity
- Altimetry is a very good candidate
- Some advantages would be cost efficiency, temporal sampling, near real time, etc.
- But it will always provide measurements on a fixed ground track pattern



SWOT – A revolution

- SWOT means Surface Water & Ocean Topography
- Combining research needs associated to hydrology and oceanography
- From a fixed pattern (1D along track) to images (pixels)
- Mapping of water level for rivers, lakes, and oceans (including coasts)
- Principle : Wide-Swath Interferometric, Ka-band altimeter

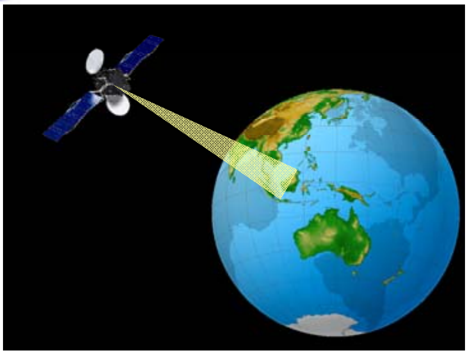
http://swot.jpl.nasa.gov/

Summary

Coastal Altimetry: great benefits from future missions

- Jason-3 will permit to continue the climatic record started on 1992 – this is very important for sea level rise studies
- A single radar altimeter provides sparse coverage as data is only available on the fixed pattern of satellite nadir tracks.
- A constellation of altimeters flying at same time will increase coverage
- Progress in technology will provide better capabilities in the Coastal Zone
  - CryoSat-2 and Sentinel-3 (SAR mode)
  - AltiKa
- Launched SWOT will provide complete Earth surface coverage
- The free availability of radar altimeter datasets makes multi-temporal data analysis as described here practical and affordable.

Thank you for your attention!



Reconstructing Sea Level Using CSEOFs

Reconstructing Sea Level Using CSEOFs

B.D. Hamlington, R.R. Leben
Colorado Center for Astrodynamics Research
University of Colorado, Boulder

K.-Y. Kim
Seoul National University

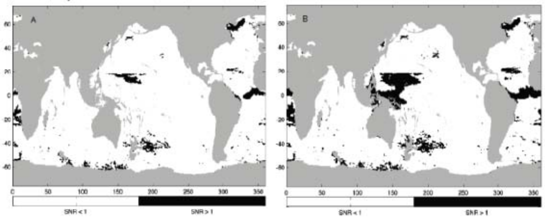
Using CSEOF Analysis to Improve Estimates of the Spatial Variations of Sea Level Trends

Improving Regional Sea Level Trend Estimates: 1993-2009

- By removing the CSEOFs representing the modulated annual cycle (MAC) and ENSO signals from the satellite altimetry data prior to computing the trend, the SNR and standard error of the trend estimate can be improved.
  - Identifying signals not associated with the trend in sea level but are physically interpretable allows us to remove them from the data.
- Compare two methods of computing regional trends:
  1. Fit annual signal, semi-annual signal and trend simultaneously using least squares.
  2. Remove MAC and ENSO CSEOFs from data then compute trend using least squares.
- The remaining signal once the explainable signals are removed is considered to be background noise.
- Power associated with both the linear trend and background noise is estimated by integrating the squared time series for each.
- SNR values are computed by dividing the linear trend power by the background noise power.

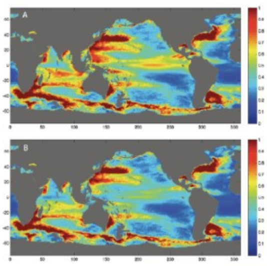
Improving Regional Sea Level Trend Estimates: 1993-2009

- Map of SNR between the linear trend and background noise. A) SNR computed solely using least squares, B) SNR from least squares incorporating CSEOF analysis.



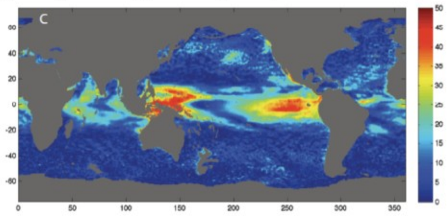
Improving Regional Sea Level Trend Estimates: 1993-2009

- Maps of standard error on the estimated linear trend computed from A) a simple least squares approach and B) least squares incorporating CSEOF analysis to estimate and remove MAC and ENSO signals. Standard error estimates are shown in units of mm/yr.



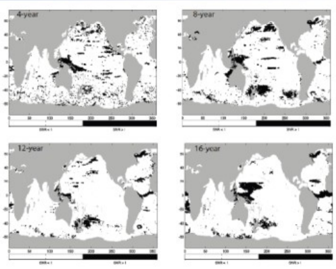
Improving Regional Sea Level Trend Estimates: 1993-2009

- Percentage reduction in the standard error when comparing simple least squares approach to approach using least squares and CSEOF analysis.



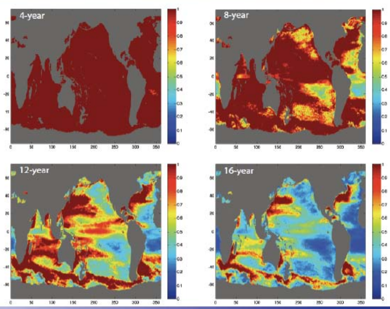
Improving Regional Sea Level Trend Estimates: 1993-2009

- Maps of SNR computed using varying lengths of original time series. Percentages of areas with SNR greater than one are 10.4%, 10.5%, 6.8% and 9.9% respectively.



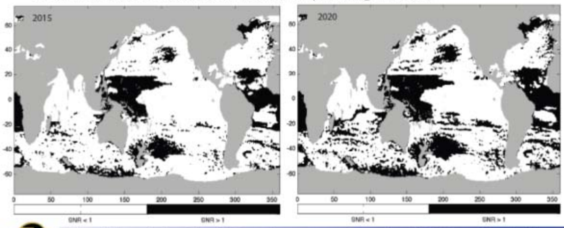
Improving Regional Sea Level Trend Estimates: 1993-2009

- Maps of standard error on the estimated linear trend computed using varying lengths of original time series. Standard error is in units of mm/yr.



Improving Regional Sea Level Trend Estimates: 1993-2009

- SNR maps are created by projecting results to the years 2015 and 2020. The linear portion of the trend is assumed to be stationary and the power associated with the background variability of the signal increases linearly with time. In 2015, the percentage of area with SNR > 1 is 22.4%, while in 2020, the percentage is 32.7%.



Improving Regional Sea Level Trend Estimates: 1993-2009

- The SNR between the secular trend and background noise can be improved by separating the non-secular background variability from the secular trend.
  - Leads to a significant reduction in formal estimates of the standard error on the linear trend computed using least squares.
  - CSEOF analysis is uniquely suited to extracting this background variability.
  - The standard error in the least-squares estimate of the linear trend is reduced across 97.1% of the globe when incorporating CSEOFs.
- Even when including the CSEOF analysis, less than 10% of the ocean has SNR > 1.
  - By varying length of time series, we can see how CSEOF analysis and the SNR changes over time.
  - With longer time series, it is possible another CSEOF will be physically explainable and thus can be removed from data to improve SNR and standard error.
- If another mode is not physically interpretable, only 22.4% of globe will have SNR > 1 in 2015, and 32.7% will have SNR > 1 in 2020.

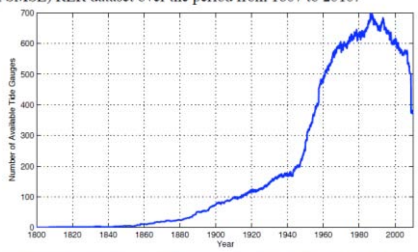
CSEOF Sea Level Reconstruction

What is a 'Sea Level Reconstruction'?

- Creating a sea level climate data record with sufficient duration, consistency and quality that can be used to accurately determine climate variability and change is a challenge.
  - **Tide Gauges**: Long record, but sparsely distributed.
  - **Satellite Altimetry**: Short record, but near-global coverage.
- Sea level is reconstructed by fitting altimetry-derived basis functions to tide gauge data.
  - [e.g. Chambers et al. (2002), Church and White et al. (2004), Ray and Douglas (2011) Hamlington et al. (2011), Meyssignac et al. (2011;2012)].
  - In past sea level and sea surface temperature (SST) reconstructions, generally empirical orthogonal functions (EOFs) have been used as the basis for the reconstruction.
- Here, we refer to a sea level reconstruction as a dataset with spatial coverage of satellite altimetry and length of tide gauge record.

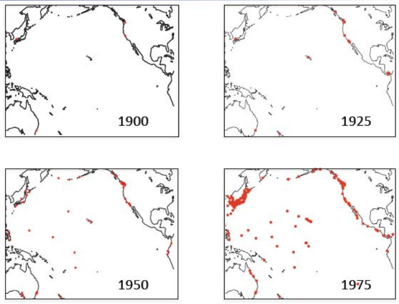
Tide Gauge Availability

- Number of available tide gauges in the Permanent Service for Mean Sea Level (PSMSL) RLR dataset over the period from 1807 to 2010.



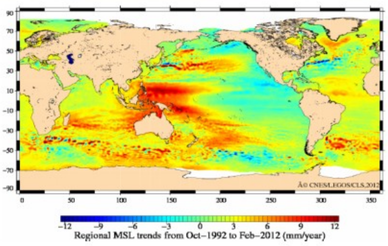
Tide Gauge Availability

- Number of available tide gauges in Permanent Service for Mean Sea Level (PSMSL) RLR dataset between 1900 and 1975.



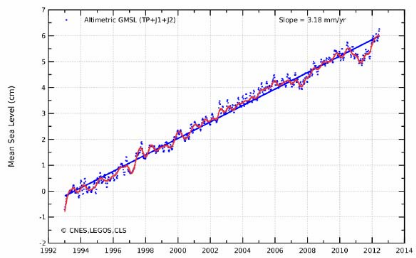
Satellite Altimetry – Regional Trends

- Regional sea level trends computed from the AVISO satellite altimetry dataset from 1992 to 2012.



Satellite Altimetry – Global Mean Sea Level

- Global mean sea level (GMSL) time series computed from the AVISO satellite altimetry dataset.

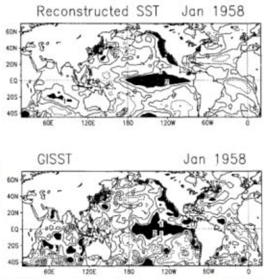


Past Sea Level Reconstructions

- Reconstruction techniques first developed for use with SST.
  - Smith et al. (1996), Kaplan et al. (1998, 2000).
  - Reconstructions extended back into the 19th century.
- Methods were extended to sea level in the last decade.
  - Smith et al. (2000), Chambers et al. (2002).
- Church et al. (2004) performed the most comprehensive reconstruction of sea level and released a dataset covering the period from 1950 to 2001.
  - Reconstruction was updated in Church et al. (2006), and Church et al. (2011).
- Several other papers on reconstructions have since been released.
  - e.g. Berge-Nguyen et al., (2008) Meyssignac et al. (2011, 2012a), Christiansen et al. (2011), Ray and Douglas (2011).

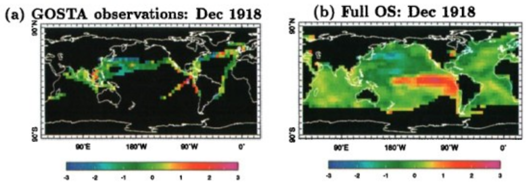
Smith et al. (1996): "Reconstruction of historical sea surface temperatures using empirical orthogonal functions"

- Smith first introduced the idea of reconstructing sea surface temperature by fitting empirical orthogonal functions (EOFs) to *in situ* measurements.
  - Reconstructed SST from 1950 to 1993.
  - Reconstruction was computed using a least-squares fit of EOF basis function to historical SST measurements.
  - EOFs were computed from an OI analysis of combined satellite and *in situ* measurements from 1982 to 1993.
  - By truncating the number of EOFs used in the reconstruction, it was found that smoother maps were produced when compared to simply averaging *in situ observations*.



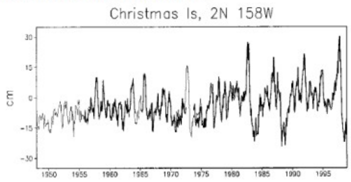
Kaplan et al. (1998): "Analyses of global sea surface temperature 1856–1991"

- *Kaplan et al.* (1998) built on the technique of Smith to reconstruct sea level back to 1856.
  - Used the truncation of the EOFs as well as the error of the historical measurements to perform a weighted least-squares procedure.



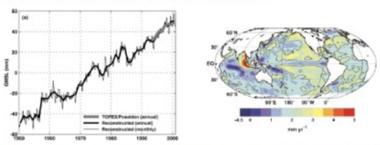
Smith (2000): "Tropical Pacific Sea Level Variations (1948–98)"

- *Smith* (2000) extended his SST reconstruction technique to reconstruct sea level from 1948-1998.
  - First published paper on performing sea level reconstructions.
  - Fit satellite altimetry-derived EOF basis functions to tide gauge data.
  - Only reconstructed sea level in the tropical Pacific.



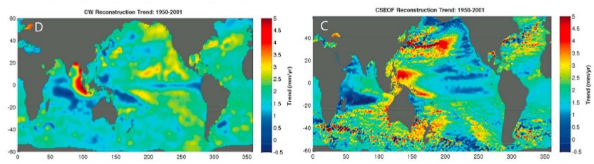
Church and White et al. (2004): "Estimates of the Regional Distribution of Sea Level Rise over the 1950–2000 Period "

- *Church and White et al.* (2004) used the method of *Kaplan et al.* (1998; 2000) to reconstruct sea level from 1950 to 2000.
  - Again, fit satellite altimetry derived basis functions to tide-gauge measurements.
  - First to account for global mean sea level (GMSL) in reconstruction by introducing a constant EOF basis function (mode of ones) and fitting to differenced tide gauge data to account for lack of global tide gauge datum level.
  - First reconstructed sea level dataset to be made publicly available.



Hamlington et al. (2011) "Reconstructing Sea Level Using Cyclostationary Empirical Orthogonal Functions"

- Using CSEOFs instead of EOFs as the basis for the reconstruction, we found that the reconstruction of climate variability could be improved.
- Hamlington et al. (2011) showed results for a CSEOF sea level reconstruction from 1950 to 2010.
  - Demonstrated reconstruction of ENSO from 1950 to 2010.
  - Reconstruction is publicly available through NASA JPL/PO.DAAC.



EOF Reconstruction Procedure

- Process of solving for the amplitudes of each basis function amounts to a weighted least squares problem (fitting satellite altimetry basis functions to tide gauge data):

- Reconstructed sea level fields (for an EOF reconstruction) are given by:

$$H(r,t) = \sum V_n(r)\alpha_n(t)$$

where V are the LVs and α(t) is the time series of the amplitude of the LV (reconstructed PC time series).

- Chambers et al. (2002) compute the amplitude by minimizing

$$S(\alpha) = (V\alpha - H^0)^T(V\alpha - H^0)$$

CSEOF Reconstruction Procedure

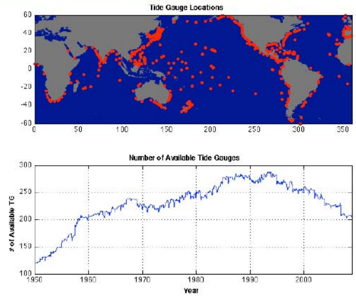
- CSEOF reconstruction technique follows the reconstruction methodology with the significant difference that we use CSEOFs instead of EOFs.
  - All LVs in the nest period are fit simultaneously and the computed reconstructed amplitude is then assigned to the center of the nested period (before fitting, weekly values were interpolated from the monthly tide gauge records).
  - This windowing process leads to the loss of six months of data at either end of the time series.
- The following sea level reconstruction results are obtained using a set of tide gauges similar to that of Church and White et al. (2004).
  - 409 tide gauges in our reconstruction vs. 426 in CW reconstruction.

Why use CSEOFs instead of EOFs?

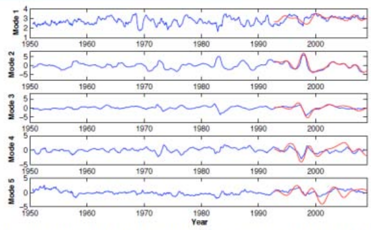
- The motivation for using CSEOFs in place of traditional EOFs as the basis functions for the reconstruction is fourfold:
  1. EOFs are not a good basis for signals in the ocean and are unable to explain the temporal evolution of spatial variability.
  2. CSEOFs account for both the high and low frequency components of the annual cycle in a single mode and do not require the removal of the annual signals from both the altimetry and tide gauge records prior to reconstruction.
  3. Specific signals, such as those relating to the modulated annual cycle and ENSO, can be reconstructed individually with little mixing of variability between modes.
  4. The reconstruction procedure using CSEOFs inherently smoothes the reconstruction, allowing for the use of fewer tide gauges to obtain a meaningful result.

CSEOF Reconstruction Results (Hamlington, *JGR*, 2012)

- The following results were published in *Journal of Geophysical Research*.
- They represent the first attempt at reconstructing sea level using CSEOFs.



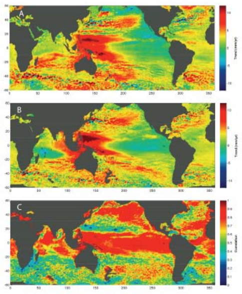
CSEOF Reconstruction Results



- The tide gauge reconstructed PC time series for the first 5 CSEOF modes are shown overlaid with the original altimeter-derived PC time series. The quality of the reconstruction is shown by the agreement between the two.

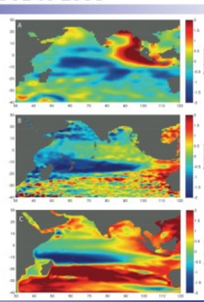
AVISO vs. CSEOF: 1993 to 2009

Regional sea level trends from 1993 to 2009 computed from the AVISO satellite altimetry data (A) and from the CSEOF reconstruction (B). The spatial variation of correlation between the AVISO and CSEOF reconstruction data over the same time period is also shown (C).



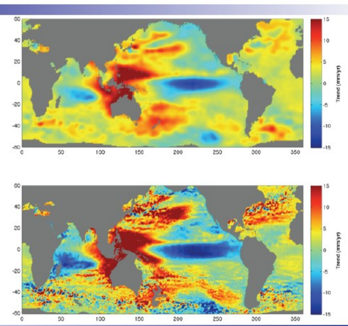
HYCOM Model vs. CSEOF Reconstruction: Regional Trends 1961 to 2008

- Trends from 1961-2001 for the Indian Ocean computed from **CW EOF reconstruction.**
- Trends from 1961-2008 for the Indian Ocean computed from **CSEOF reconstruction.**
- Spatial variation of trend for the Indian Ocean from 1961-2008 for **HYCOM SLA (Han et al, 2010).**



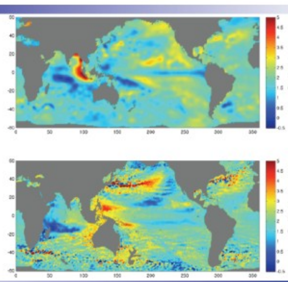
CW vs. CSEOF Reconstruction: Regional Trends 1993 to 2001

- Spatial variation of trend from 1993-2001 computed from **Church and White et al (2004)** (mm/yr).
- Spatial variation of trend from 1993-2001 computed from **CSEOF reconstruction** (mm/yr).



CW vs. CSEOF Reconstruction: Regional Trends 1950 to 2001

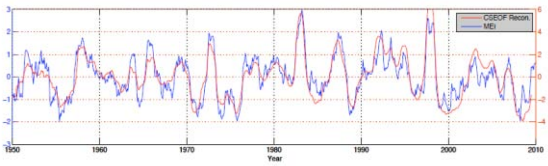
- Spatial variation of trend from 1950-2001 computed from **Church and White et al (2004)** (mm/yr).
- Spatial variation of trend from 1950-2001 computed from **CSEOF reconstruction** (mm/yr).



CSEOF Reconstruction Results: Climate Indices

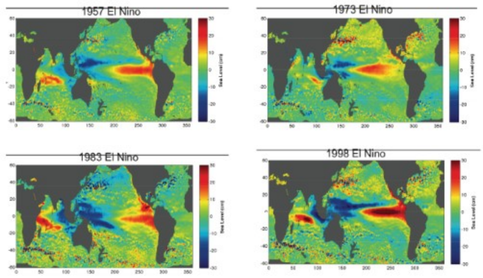
- CSEOF reconstruction provides SSH-based indices describing well-known climate signals.
  - These indices can be linked to major patterns of climate variability and provide a quick and easy way to talk to the general public about climate change.
- Indices computed strictly from the SSH reconstruction can be used to compare to the indices derived from SST reconstructions.
  - SST reconstructions extend back to the 19th century.
  - SSH reconstruction can be computed back to the first date that tide gauge data is available.
  - Could have advantages over SST computed indices (Giese et al., 2010).

CSEOF Reconstruction Results: EP El Niño

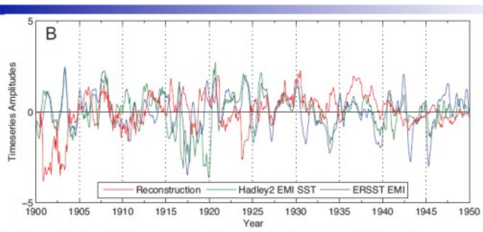


- The Eastern Pacific El Niño is described by CSEOF mode 2 in both the satellite altimetry and reconstructed sea level.
- The correlation between the Multivariate ENSO Index (MEI; Wolter and Timlin, 1998) and the reconstructed EP El Niño amplitude is 0.91 over the period from 1950 to 2010.

CSEOF Reconstruction Results: ENSO

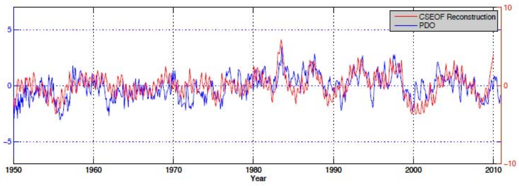


CSEOF Reconstruction Results: CP El Niño



The Central Pacific El Niño or El Niño Modoki Index EMI computed from the reconstructed SSH (red), specifically the third mode of the reconstruction. The EMI computed from the ERSST dataset is also shown, with a correlation of 0.61 between the two over the period from 1950 to 2010.

CSEOF Reconstruction Results: PDO



The Pacific Decadal Oscillation (PDO) index is computed from the CSEOF reconstruction (red) and from the SST measurements (http://jisao.washington.edu/pdo/).

CSEOF Reconstruction: GMSL

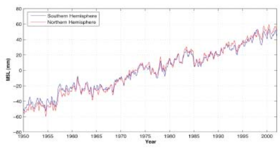
- There is great interest in global mean sea level and it must therefore be accounted for in sea level reconstructions.
  - No basis function from altimetry can describe the change in mean sea level over the reconstructed time period.
- To account for GMSL in their reconstruction, Church and White et al. (2004) introduced a spatially uniform basis function, effectively computing a weighted (using the instrument and truncation errors) mean of the tide gauges.
  - To account for differences in local datum at different tide gauge locations, CW use first differences of tide gauge data.
    - Difficult to do with CSEOFs as a result of temporal dependence of LVs.

$$\frac{dH(r,t)}{dt} = \frac{d\alpha(t)}{dt}V(r) \qquad \frac{dH(r,t)}{dt} = \alpha(t)\frac{dV(r,t)}{dt} + \frac{d\alpha(t)}{dt}V(r,t)$$

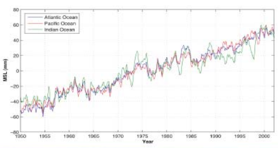
  - As a result of the constant basis function, same mean time series is added to every point across the globe.

CSEOF Reconstruction: GMSL

Mean sea level computed for the southern and northern hemispheres from the sea level reconstruction of Church et al. (2004) over the period from 1950 to 2001.



Mean sea level computed for the Atlantic (Blue), Pacific (Red) and Indian (Green) Oceans from the sea level reconstruction of Church et al. (2004) over the period from 1950 to 2001.



CSEOF Reconstruction: GMSL

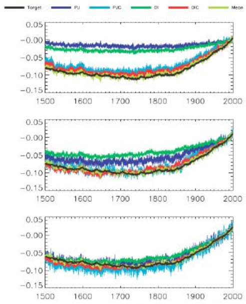
- Christiansen et al. (2010) determined that a spatially uniform mode is absolutely necessary to capture GMSL unless the "calibration" period is close to the length of the actual reconstruction.
    - Worked with pseudo-tide gauges that did not have differences in local datum.
    - Determined more tide gauges and longer calibration period lead to better reconstructions.
    - Results show that GMSL captured by the uniform basis function is similar to a weighted mean of the tide gauges.

CSEOF Reconstruction: GMSL

Results shown by Christiansen et al. (2010) relating length of calibration period to ability to reconstruct GMSL.

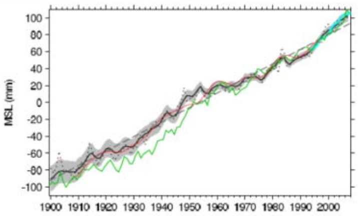
Target → Actual mean sea level
PJ → Chambers et al. (2002)
PJC → PJ with constant basis function
OI → Kaplan et al. (1998)
OIC → Church and White et al. (2004)
Mean → Mean of pseudo-TG data

Conclusions: 1) Until calibration period is long enough to obtain basis function related to mean sea level change, constant basis function must be introduced; 2) Mean of tide gauges is very similar to GMSL computed by other methods.



CSEOF Reconstruction: GMSL

- Ray and Douglas (2011) introduced a technique that estimates a consistent reference level for all tide gauges, thus eliminating the need to work with differenced tide gauge data.
- Very expensive computationally and only really practical with a small number of tide gauges.
- Reconstructed GMSL (solid black line) is very similar to mean of tide gauges (dotted black line).



Ray and Douglas (2011)

CSEOF Reconstruction: GMSL

- Rather than introduce another basis function, GMSL can be calculated separately from the reconstruction of the actual CSEOF modes.
- The following procedure is used to estimate GMSL, including the secular trend.
    1. The full CSEOF reconstruction is computed and then subsampled at each of the tide gauge locations.
    2. Time series from (1) are differenced for each TG location, ensemble averaged at each point in time, and then re-integrated → time series contains ENSO and any other signals the reconstruction captures.
    3. The raw TG data is also differenced, averaged using latitude-band weighting, and then re-integrated to form a GMSL time series associated with the original TG data → time series contains ENSO and any other signals the contained in the TG data.
    4. The time series computed in part (2) is subtracted from the time series computed in part (3) to form an estimate of the GMSL time series with all reconstructed signals removed, including the MAC and ENSO, thus correcting for any trend resulting from the spatial subsampling of signals captured by the reconstruction.

CSEOF Reconstruction: GMSL

$$Trend_{TG} = \overline{TG_{raw}} - \overline{Recon_{TG}}$$

$\overline{TG_{raw}}$ - Mean time series of tide gauge data.

$\overline{Recon_{TG}}$ - Mean time series of reconstruction subsampled at the tide gauge data

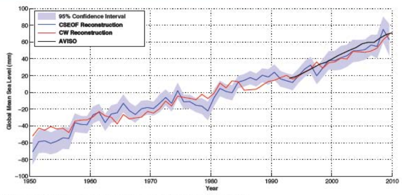
$Trend_{TG}$ - Secular trend time series without any of the signals captured by the reconstruction (eg. Annual cycle, ENSO)

- GMSL can then be computed by averaging over the whole reconstructed data set and adding in the secular trend computed above:

$$GMSL = \overline{Recon} + Trend_{TG}$$

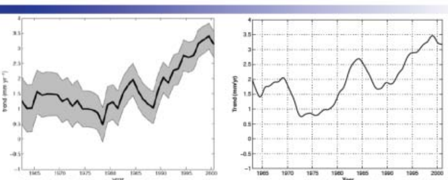
CSEOF Reconstruction: GMSL

A comparison of GMSL derived from satellite altimetry (1993-present; black) from the CSEOF reconstruction (blue) and from the CW EOF reconstruction (red).



- Trend in GMSL from 1950 to 2009 is estimated to be 1.97 mm/yr.
- Trend in GMSL from 1993 to 2009 is 3.22 mm/yr.
- Error is estimated through Monte Carlo simulations in which 70% of tide gauges are selected and used in the reconstruction. 100 trials are conducted → GMSL 1950 to 2009 = 1.95 ± 0.4 mm/yr, GMSL 1993 to 2009 = 3.52 ± 0.6 mm/yr.

CSEOF Reconstruction: 15-year trends



- As a check of the reconstruction, we can compare 15-year trends computed from the reconstructed GMSL (right) to the 15-year trends computed by Merrifield et al. (2010) (left).
    - Relatively **good agreement after 1980**, however generally **trends are higher before 1980** in the reconstructed GMSL.
    - Differences result from a combination of tide gauge dataset (**400+ vs. 120+ tide gauges**) used for the computation and the reconstruction correction for sampling bias.

CSEOF Reconstruction: Tide Gauges

To test sensitivity of the reconstruction to tide gauge editing, seven different tide gauge data sets were created using different editing criteria and a reconstruction was performed with each one.

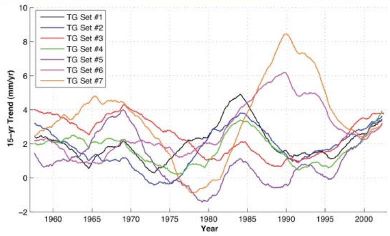
#	Tide Gauge Set	Number of Tide Gauges	Editing Criteria
1	All PSMSL Gauges	1179	GIA Corrected, IB correction Applied
2	Church et al. (2004)	508	GIA Corrected, IB correction Applied, see Church et al. (2004)
3	Merrifield et al. (2009)	122	GIA Corrected, IB correction Applied, see Merrifield et al. (2009)
4	Ray and Douglas (2011)	89	GIA Corrected, IB correction Applied, see Ray and Douglas (2011)
5	40-year minimum	289	GIA Corrected, IB correction Applied, all TGs with < 40 year record length removed
6	5-degree box	268	GIA Corrected, IB correction Applied, longest record in every 5-degree box retained
7	10-degree box	143	GIA Corrected, IB correction Applied, longest record in every 10-degree box retained

CSEOF Reconstruction: Tide Gauges

Reconstruction results from 7 different TG datasets.

TG Set	Trend 1993-2009 (mm/yr)	Trend 1950-2009 (mm/yr)	MEI Correlation	EMI Correlation
1	3.19	1.92	0.92	0.68
2	3.22	1.97	0.91	0.65
3	3.84	2.15	0.86	0.57
4	3.34	1.73	0.85	0.51
5	3.04	1.65	0.80	0.41
6	2.92	2.29	0.82	0.54
7	2.98	1.69	0.83	0.50

CSEOF Reconstruction: Tide Gauges



15-year trends over the period from 1950 to 2010 for each of the seven tide gauge datasets considered. Latitude-band weighting is used for computing the trends.

CSEOF MATLAB Codes Readme

Indonesia MATLAB Codes

1. Tide Gauge Comparison

Indonesia_recontg_comparison.m

If plot_opt is set to zero, the output will be a file named tgcomp.mat with the reconstructed data (recon_data) and tide gauge data (tg_data) at the latitude and longitude locations of the available tide gauges in the region of interest.

If plot_opt is set to one, the output will be a series of plots comparing the reconstruction to the tide gauge data in addition to the file tgcomp.mat as described above. To advance the plots, hit any key on the keyboard. The plots will have the name of the tide gauge and the location of the tide gauge in the title.

The code uses the sub-sampled reconstructed data in the cseof_recon_data.mat file. The specified region is from -10 to 24 latitude, and 100 to 127 longitude.

tg_comp.m

This code should not be changed, since the only reconstructed data we provide is in cseof_recon_data.mat.

2. EOF Reconstruction Codes

Eof_run.m

This is the main file for running the EOF reconstruction. The first thing that the user will specify is the region of interest in lines 17 through 20.

The function data_form reads in the Aviso data and sub-samples to the region of interest. The output is data_eof.mat, which will contain the Aviso data in the region of interest. The directory names need to be changed according to the location of the Aviso netcdf files. Once this function has been run once and assuming the user has not changed the region of interest, line 23 of eof_run.m should be commented out, and line 26 of eof_run.m should be uncommented.

The user may want to change whether to detrend or subtract a mean and the percent variance to keep. The greater the percent variance, the longer the code will take to run.

The function eigenx should not take long to run, so there is no need to comment it out.

When performing the reconstruction, the user should specify the locations of the synthetic tide gauge data. The lat-lon points must be within the region of interest, and can be input as individual points or a range (ie. tg_lon = [110:115]).

The reconstructed PC time series are located in the variable recon_amps and can be compared to the EOF PC time series in the variable pcts.

The fully reconstructed data is named recon_data. Neither the reconstructed PC time series nor the reconstructed data are saved in a .mat file.

Eigenx.m
Eof_recon.m
Reform.m
These codes do not need to be changed.

3. CSEOF Reconstruction Codes

This is the main file for running the CSEOF reconstruction. The first thing that the user will specify is the region of interest in lines 27 through 30.

The function data_form reads in the Aviso data and sub-samples to the region of interest. The output is data_cseof.mat, which will contain the Aviso data in the region of interest. The directory names need to be changed according to the location of the Aviso netcdf files. Once this function has been run once and assuming the user has not changed the region of interest, line 33 of eof_run.m should be commented out, and line 36 of eof_run.m should be uncommented.

The user may want to change whether to detrend or subtract a mean and the percent variance to keep. The greater the percent variance, the longer the code will take to run.

The call to function eigenx should not be commented out since it returns the data with bathymetry editing applied. To save time/space, this is not saved and must be returned by eigenx for the rest of the code to function correctly.

Once the cseof function (line 78), it can be commented out assuming the region of interest has not changed and the period of the nested cycle (line 70) has not been changed.

To recombine the PC time series and LVs, lines 85 and 86 should be uncommented. The range of modes to keep should be specified. To just return the ENSO related variability, for instance, the range will be set as 2:2.

When performing the reconstruction, the user should specify the locations of the synthetic tide gauge data. The lat-lon points must be within the region of interest, and can be input as individual points or a range (ie. tg_lon = [110:115]). The number of locations must be smaller or equal to the number of modes being used to reconstruct (line 96).

The reconstructed PC time series are located in the variable recon_amps and can be compared to the EOF PC time series in the variable pcts1.

The fully reconstructed data is named recon_data. Neither the reconstructed PC time series nor the reconstructed data are saved in a .mat file.

Cseof_reform.m
Cseof_reform_recon.m
Cseof.m
Recast.m
These codes do not need to be changed.

Coastal Altimetry -A Review

Coastal Altimetry – A Review

Presented by

Stefano Vignudelli
Consiglio Nazionale delle Ricerche, Italy
vignudelli@pi.ibf.cnr.it

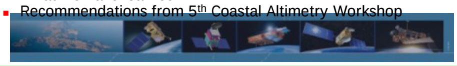
With invaluable help (and material) from
COASTALT Project

S. Vignudelli, A. Scozzari (CNR, Italy)
P. Cipollini, C. Gommenginger, H. Snaith, S. Gleason, G. Quartly, L. West (NOCS, UK)
Henrique Coelho (Hidromod, Portugal)
J. Fernandes, L. Bastos, C. Lázaro, A. Nunes. N. Pires, I. Araujo (U Porto, Portugal)
M. Bos (CIIMAR, Portugal)
S. Barbosa (U Lisbona, Portugal)
Jesus Gómez-Enri (U Cádiz, Spain)
C. Martin-Puig, M. Caparrini, L. Moreno (Starlab, Spain)
P. Woodworth, J. Wolf (POL, UK)
S. Dinardo, B. M. Lucas (SERCo/ESRIN, Italy)
J. Benveniste (ESA/ESRIN, Italy)

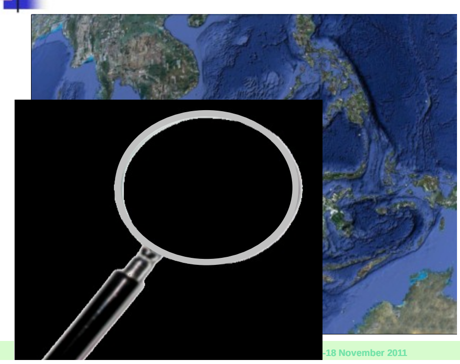
particular thanks also go to the Coastal Altimetry Community

Outline of my talk

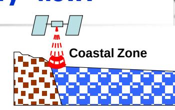
- Introducing Coastal Altimetry
  - Closer to coasts – why
  - A look back – key milestones
  - A lively community
- Coastal Altimetry in action
  - A little on fundamentals of satellite radar altimetry
  - What the re-analysis tells us
  - More, better and closer to coasts – how
  - Error budget
- Moving from research to routine use
  - Coastal altimetry products
  - Showcase of emerging applications
  - Benefits for Indonesia
- A summary
  - What we have learned
  - Recommendations from 5th Coastal Altimetry Workshop



The "Google Earth" effect: from global to local



Why "Coastal Altimetry" now?



- **Coastal Zone uncharted domain**
  - ~20 yrs multi-mission archive
- **Coastal Zone of strategic importance**
  - most people live there
  - source of food and raw materials
  - vital link to transport and trade
  - host valuable habitats and landscape
  - favored destination for leisure

Key impacts are where policy decisions are usually made

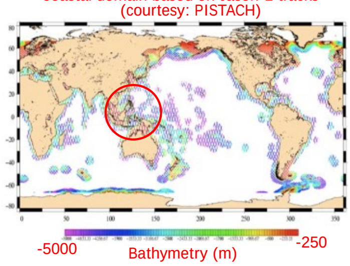
- **There is much interest in bringing altimetry to the coastline**
  - Not only for using in synergy with modelling tools and other data sources,
  - but also to understand the error budget in global sea level rise when altimeters are tied to coastal tide gauges for calibration.
- **A hope at horizon: progresses in technology**
  - New techniques (Delay-Doppler, Interferometry, Reflectometry)
  - New concepts (Constellations)

New missions (AltiKa, CryoSat-2, Sentinel-3, SWOT) will have much greater coastal capabilities

What do we mean by "Coastal Altimetry" ?

- We define **coastal altimetry** as altimetry over that ocean domain close to land where standard processing is problematic (information is somehow hidden)
- These data are normally **flagged as 'bad'** in official products for a number of reasons
  - non-standard waveforms,
  - inaccurate corrections, etc.

Coastal domain based on Jason-1 tracks (courtesy: PISTACH)



These data can – and should - be recovered!

Coastal Altimetry – a bit of history

- **Some seminal papers**
  - Manzella et al. 1997 - custom wet tropospheric correction
  - Crout 1998 - could recover data when coastal topography is flat
  - Anzenhofer et al. 1999 – retracking waveforms
  - Vignudelli et al. 2000 - Signal recovered consistent with in situ data

ALBICOCCA
France-Italy-UK 2001/04
Feasibility

ALTICORE-EU
EU/INTAS 2006/08
Capacity building

MAP/XTRACK/MARINA
CNES/LEGOS/CTOH
Integrated approach

ALTICORE-India
ALTICORE-Africa

PRODUCT DEVELOPMENT STUDIES INCLUDING RETRACKING

PISTACH
CNES 2007-present
For Jason-2

COASTALT
ESA 2008-present
For Envisat

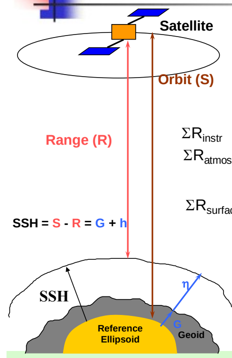
…plus several OSTST Projects funded by NASA and CNES

Coastal Altimetry – at centre of the community

Regular workshops (Silver Spring 2008, Pisa 2008, Frascati 2009, Porto 2010, San Diego 2011) – see at www.coastalt.eu)

Springer book just published (see TOC at http://www.springer.com)

Recap – how satellite altimetry works



SSH = S - R_{corr}

Range (R) must be corrected for various effects, with equation of form:

$R_{corr} = R_{altimeter} + \Sigma R_{instr} + \Sigma R_{atmos} + \Sigma R_{surface}$

ΣR_{instr} Instrument dependent (e.g. USO, Doppler)

ΣR_{atmos} Atmospheric path corrections given by:

$\Sigma R_{atmos} = R_{iono} + R_{wet\ tropospheric} + R_{dry\ tropospheric}$

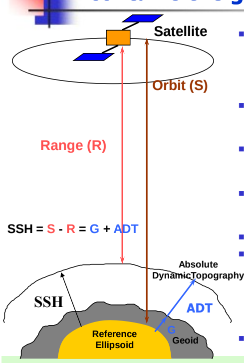
$\Sigma R_{surface}$ Surface dependent given by:

$\Sigma R_{surface} = R_{SSB}$ Sea Surface Bias

Some applications require correction of high-frequency signals (tides, wind and air pressure)

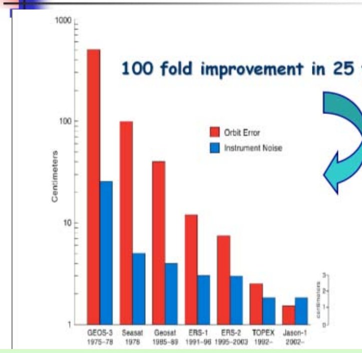
$\Sigma R_{surface} = R_{SSB} + R_{tides} + R_{wind\text{-}pressure}$

But the Sea Surface Height (SSH) contains the geoid signal!!



- SSH is composed of a variable oceanic part, the Absolute Dynamic Topography (ADT), and of a geophysical constant the Geoid. These latter deals with the position of the ocean at rest.
- Its small scales are not known with enough accuracy to permit the separation of the two components of the SSH.
- Consequently, SSH is decomposed into a Mean Sea Surface (MSS) and a Sea Level Anomaly (SLA)
- SLA which takes into account the variation of height around the MSS due to the variability of the ocean currents:
- *SSH =MSS + SLA =G+ADT*
- The MSS contains then both the Geoid and the permanent part of the ADT called the Mean Dynamic Topography (MDT) which deals with the stationary part of the ocean currents. Its knowledge permits to bypass the Geoid to study the ADT of the ocean:
- *ADT = MDT + SLA*

History of satellite altimetry accuracy in open ocean



Courtesy by L.L. Fu, NASA

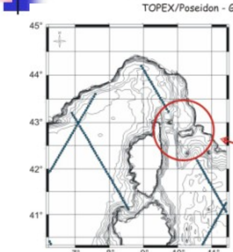
TOPEX Latest Error Budget

for 1-Hz measurement - from Chelton et al 2001

Source	Error
Instrument Noise	1.7cm
Ionosphere	0.5cm
EM Bias	2.0cm
Skewness	1.2cm
Dry Troposphere	0.7cm
Wet Troposphere	1.1cm
Orbit	2.5cm
Total	4.1cm

One picture is worth 1000 words - Starting point … really no data ?

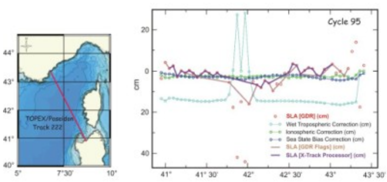
TOPEX/Poseidon - Ground Track Reference Mask



Standard Product

From this…

Beyond flags: new editing strategy



Circles: uncorrected sea level anomalies (SLA) and original corrections from the AVISO Geophysical Data Records (GDR).

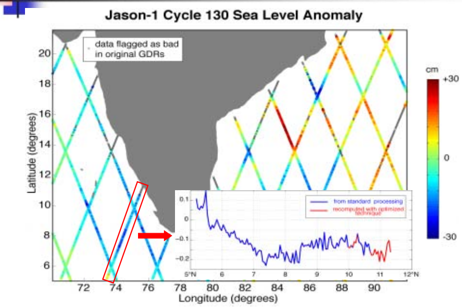
Brown line: SLA after application of the standard corrections from the GDR.

Purple line: the new SLA profile computed

- Screening profiles rather than single values
- Reconstructing /extrapolating profiles where possible

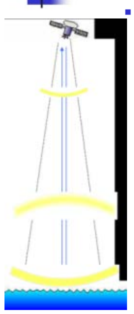
Much more data on average than using standard editing

Lesson learned I - Reprocessing standard along-track products

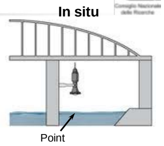


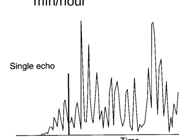
A significant part of data is recoverable just de-flagging, filtering, editing, re-interpolation of corrections

Recap - What are we measuring?



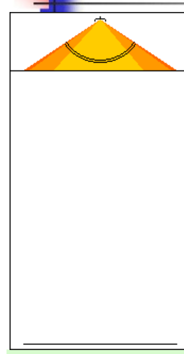
- The altimeter system is just a more complicated radar tide gauge mounted on satellite
  - Need of additional data (e.g. orbits and corrections)
  - But more uses (waves, winds, currents, bathymetry in addition to sea level)
  - Averages over footprints vs point-wise
  - Sampling of order of days vs min/hour



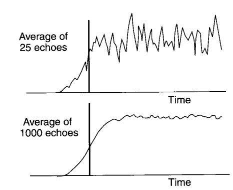


- It sends a microwave pulse towards the ocean surface, f = 13.5 Ghz
- Each individual return signal or echo (known as **waveforms**) is very noisy
- This is a result of random distribution of the ocean wave facets at any instant

Averaging many successive pulses can reduce noise



Source: ESA

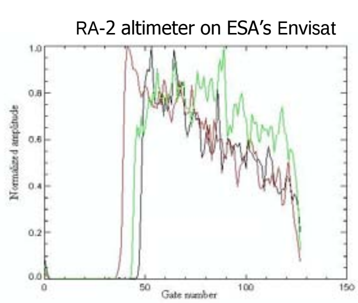


- Envisat is averaging 100 echoes on board
- then trasmitted on ground over 1/18 second of flight
- This means measurements every 350 m along track
- However, data are furtherly averaged on ground over 1 second of flight
- This means measurements every 7 km along track

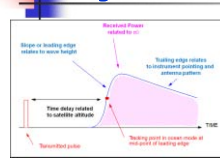
7 km is the standard resolution for use in open ocean

Real radar return signals (waveforms) in open ocean

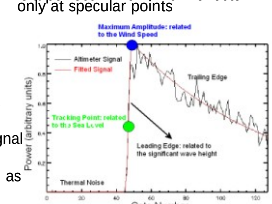
RA-2 altimeter on ESA's Envisat



How can we turn 'return radar signal' into useful data



- The shape of the waveform can be described analytically through the Brown model) over the ocean
- But it assumes that the sea surface is a perfect mirror which reflects only at specular points



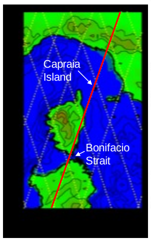
- We use a procedure called retracking to fit the Brown model (red line) to the waveform (black line)
- Then we can estimate the time required for two-way travel of signal (2T)
- The time is then converted to a measurement of distance, known as **range**
- h = T/c (c = 3 x 10^8 m/s)

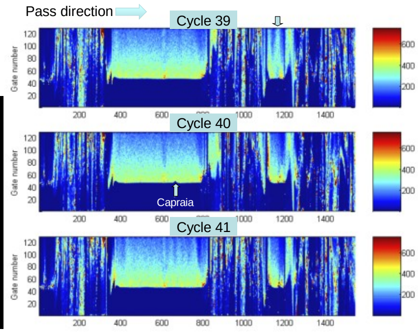
but what happens when satellite approaches coasts ?

Gomez-Enri J., Vignudelli S., et al., Bringing satellite radar altimetry closer to shore, In SPIE (Society of Photo-Optical Instrumentation Engineers), 2009

This is to illustrate how complicated the waveforms get

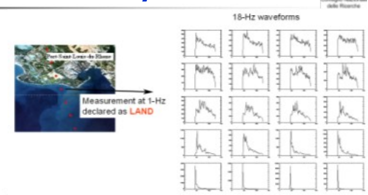
ENVISAT **pass 294** (descending)



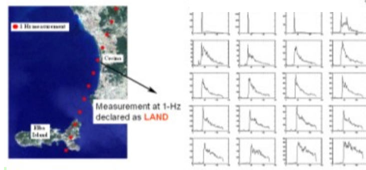


But if we zoom locally ....

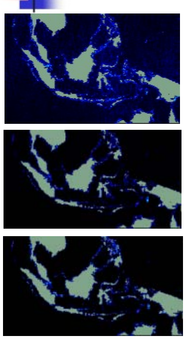
Envisat Ascending Track



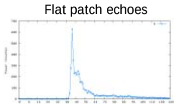
Envisat Descending Track



Indonesia is a challenging area

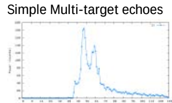


Flat patch echoes



Calm water in coastal regions or with the presence of small islands.

Simple Multi-target echoes



Multiple brightly surfaces reflecting within the altimeter footprint.

Complex Multi-target echoes

Combination of ocean component and rough terrain.

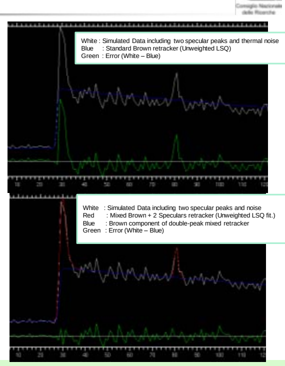
Courtesy by P. Berry, DMU

Lesson learned II – Re-thinking retracking

- We learnt that retracking waveforms in the coastal zone is challenging work
  - How close to the coast? – depends on how much high ground can affect tracking window too much
  - 90% of waveforms are Brown-like seaward of 10 km from the coast.
  - Standard (Brown model) retracking should be adequate seaward of 20 km from the coast.
- Identification of some retrackers better performing at the coast
  - e.g. RED3 in PISTACH Project
  - but BAG/ BAGP are even more promising (PISTACH)
- Use better waveform models, accounting for change of shape in coastal environment
  - e.g. scattering from non-linear surfaces.
  - e.g. by including the effect of white caps
  - e.g. by mixing different models – Brown, Specular and Mixed (COASTALT)
- Use innovative techniques
  - Denoised estimations with Singular Value Decomposition(PISTACH)
  - Cleaning waveforms (COASTALT)
  - Avoid treating each waveform in isolation but using info from adjacent ones – 2D Hyperbolic Pre-tracker and Bayes Linear Reatracker (COASTALT)

Retracking – mixing different models

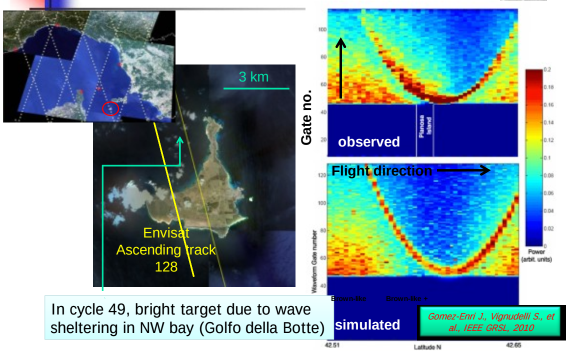
- In many cases there are one (or more) non-Brown component(s) – e.g. A "specular" one superimposed on a Brown-like echo
- This can be tackled with models fitting different waveforms, e.g. one fitting sums of different Brown and non-Brown waveforms (a "mixed" retracked)



Innovative Retracking – Cleaning waveforms in advance

- We observed effects of land and effects of calm waters in the coastal strip
  - Land normally gives 'dark' features (less signal)
  - Calm water cause quasi-specular reflections giving peaky waveforms
- These features migrate in the waveform/gatenumber space following hyperbolae (a parabolic shape is usually a good approximation)
- Because we know the form of the hyperbolae (the speed of the satellite) we can accurately predict its position across a set of waveforms
- Features are reproduced by a simple model of the land/ocean/calm waters response
- The idea is that this should allow removal of the land/calm waters contamination prior to retracking

Example of Pianosa Island

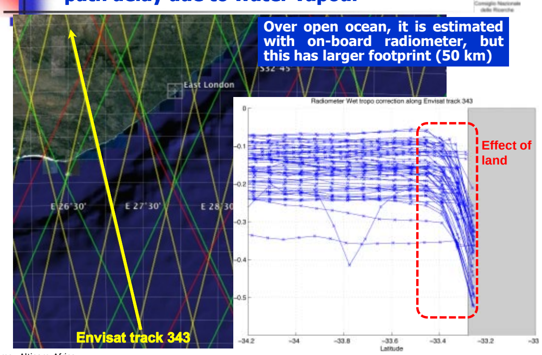


In cycle 49, bright target due to wave sheltering in NW bay (Golfo della Botte)

Innovative Retracking concept – using information in adjacent waveforms

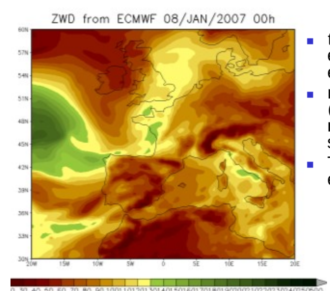
- The hyperbolic "Pre-tracker" to fit and remove bright/dark targets is an example
- Another example is the Bayes Linear retracker
  - Based on the application of Bayesian methods
  - The idea is to treat the posterior from one waveform as the prior for the next
- Both these have been designed within COASTALT and prototyped but not still optimized
- This is a most promising field, already identified in Phase 1 and the difficulties in the development and implementation of some of the ideas tested (Bayes Linear Retracker, 2-D retracker) should not deter from pursuing further development, with the hope of achieving a full validation of these innovative techniques.

Wet Tropospheric Correction corrects for path delay due to water vapour



Source: Alticore-Africa

We can use the model but ....



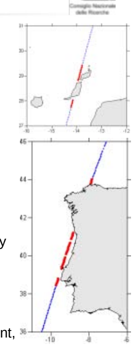
- the wet tropo varies rapidly especially in the coastal environment
- models like this from ECMWF (ZWD=Zenith Wet Delay) may not capture its dynamics and short-scale variability.
- This figure illustrates an example from the model.

Lesson learned III – Re-visiting Wet Troposphere correction

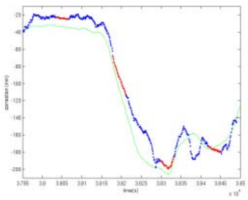
- Three approaches to improve this correction
  - Extending (linking) models with radiometer observations (this is the so-called Dynamically Linked Model approach) - implemented in COASTALT processor
  - Modelling/removing land effect (being developed by PISTACH and NASA)
  - GNSS (GPS) based, develop by Univ. Porto – implemented in COASTALT processor

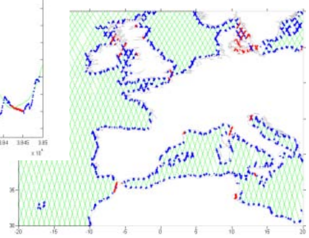
Linking radiometer and model : DLM Approach

- Simple method requiring only GDR fields:
  - Radiometer and ECMWFderived wet corrections
  - MWR flags (LAND flag + MWR QUAL flag for Envisat)
  - Optional information: distance to land
- Data are split into segments
- In each segment identifies "land contaminated zones"
  - Flags only
  - Flags + distance to land
- Two types of algorithms:
  - Island type or 'double-ended' algorithm
    - valid radiometer points on each side of the segment
    - Model field is adjusted to the radiometer field, at the beginning and end of the land contaminated segment, by using a linear adjustment (using time as interpolation coordinate)
  - Continental coastline type algorithm ('single-ended')
    - only valid radiometer points on one side of the segment
    - Model field is adjusted to the radiometer field, at the beginning or at the end of the land contaminated segment, by using a bias correction



DLM Approach - Results

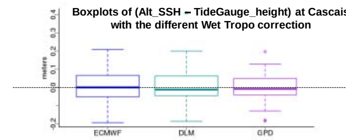




- Bue – corrected points
- Red - uncorrected points

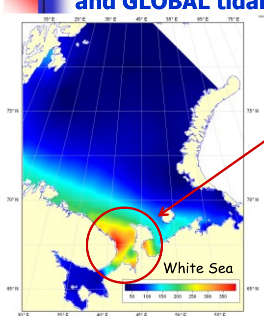
Wet tropo - GPD technique

- First, estimate STD - Slant Total Delay from GPS observations
- Then, map into ZTD - Zenith Total Delay using MIT GAMIT software and Vienna mapping functions
- Estimate 'dry' component (ZHD) from meteo data • derive 'wet' component (ZWD)
- Needs a good network of coastal stations, and possibly coincident meteo observations
- ZTD accuracy – currently ~3 mm. Wet accuracy depends on how good the 'dry' is – but we can get to less that 1 cm.



M.J. Fernandes et al., IEEE GRSL, 2010

Big discrepancies between LOCAL and GLOBAL tidal models

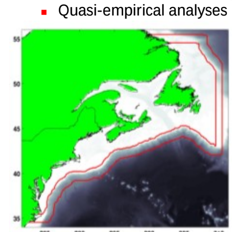


Example: Difference between a local tidal model and a global one (GOT00) over the White Sea (courtesy of S. Lebedev / A. Sirota for ALTICORE)

- Example of regional tidal model from HRC (Russia)
- Difference of order of meters when compared with GOT00 (global)
- Accurate tidal predictions are usually difficult in shallow waters
  - Amplitudes are large
  - Wavelengths are short
  - Nonlinear processes generate many new constituents
- Note that some users may not want this correction to be applied to the SSH fields for their applications.

Lesson learned IV – Improving or replacing global tidal models

- One approach for the tidal correction is to use local models
  - Hydrodynamical modelling + data assimilation of tide gauge and high resolution altimeter data and use of regional bathymetry, e.g. T-UGOm code (ex- Mog2D) in NW Mediterranean
- Another approach is to improve global tidal models
  - Quasi-empirical analyses of altimeter data, e.g. EOT10a, GOT4.7

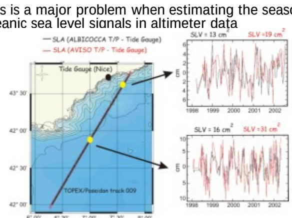


- A novel approach Egbert & Erofeeva's review talk at 5th Coastal Altimetry
  - Huge improvements with a Nested High-Resolution Data Assimilation Modeling + a simple scheme to merge the HR solution with regional and global models

Courtesy by Egbert, OSU

Aliasing due to short-period ocean response to meteorological forcing

- The sea surface rises and falls due to changes in air pressure and winds
- IB approximation used in open ocean
  - formulates merely the hydrostatic equilibrium between the sea level and the applied atmospheric pressure gradients.
  - It totally ignores wind-forced sea level variations
- Significant departures can be observed over continental shelves and marginal seas.
- This is a major problem when estimating the seasonal or longer time scales of oceanic sea level signals in altimeter data



The variance of the residual time series indicates that the model performs systematically better than the IB to explain the tide gauge observations, and that the reduction is significant even in the shelf area

Lesson learned V – De-aliasing using models

- IB correction to be modelled dynamically, correcting high-frequency component
- Option 1: Use archived regional surge fields based on the most recent forecast met information typically a few hours old
  - Problem is that large regions would not be represented
- Option 2.: Use hindcast information several weeks later (or however later is considered acceptable for the altimeter data processing)
  - Assuming that the hindcast data are by then of higher quality than the stored forecast information (probably unlikely as meteorological re-analyses are usually performed over a considerable time later).
- Option 3: Use a global barotropic model forced with global met information.
  - Models presently available include T-UGO (MOG2D)
  - finite element model with a high spatial resolution at the coastline
  - e.g. 15 km elements for the global model, 4 km for regional models)

Sorting out coastal altimetry – in three steps!

- On the Shelf (100-0 km): main problem is the correction of **tides** (and HF atmospheric effects)
  - NEED **GOOD TIDAL & HF MODELS**
- Coastal strip (30-0 km): radiometer-derived **wet tropospheric correction** affected by land vicinity
  - NEED GOOD TIDES/HF + SOME **OPTIMIZED COASTAL WET TROPO**
- Up to the shore (10-0 Km): the altimetric echoes **waveforms** affected by land & specular reflections
  - NEED TIDES+WET TROPO+ **DEDICATED WAVEFORM RETRACKING**

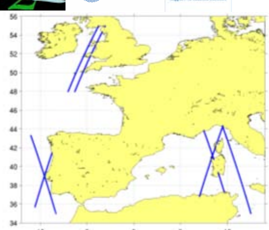
Coastal Altimetry is progressing in processing /products

- More/better (and new) datasets are being produced
  - New/improved retrackers
  - New/improved corrections
  - Reprocessed products now available (PISTACH, XTRACK, COASTALT)
  - Validation and quality control started

Coastal Altimetry Product (1)

COASTALT/ESA

- Developed a baseline processor for Envisat
  - User-configurable and modular software in view of a global reprocessing, expandable to future missions
  - Useful tool for further research and development work on retracking techniques and corrections
  - Reads ENVISAT L2 SGDR files
  - Retracks all waveforms with different models
  - Generates corrections at 18Hz
  - Allows addition of any user-generated corrections
  - Fully Documented
  - Now at Revision 73 ! (just to give an idea of the complexity of this software)
- Coastal geophysical Data Records (CGDRs)
  - Output files in NetCDF
  - Contain output of all retrackers (h, swh, sigma0) and full range of corrections at 1 Hz and 18 Hz
  - Product Specification and User handbook document available
  - v2.0r3 (latest) freely available from web site - www.coastalt.eu
- Retracking & Corrections
  - Optimizing and validating specialized Brown, Specular and Mixed, plus innovative retrackers to get closer to coast
  - Making operational the new approach to Wet tropospheric correction using GNSS/GPS data



http://www.coastalt.eu

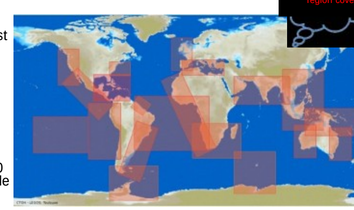
We will test selected tracks around Indonesia within RESELECASEA Project

Coastal Altimetry Product (2)

XTRACK/CTOH

- SLA time series along a nominal ground-track
- MSSH consistent with SLA
- Geophysical (tidal and DAC separetly) corrections included
- Distance to nearest coast
- Non-retracked products
- Access to simple diagnostics
- 1 Hz (7 km) regional operational products
- T/P & Jason 1/2 everywhere, Envisat and GFO on request
- 20 different regions available

Indonesia is one of the region covered!!



NEW!

- Experimental Product 20 Hz (350 m) now available on request for expert users

http://ctoh.legos.obs-mip.fr/products/coastal-products/

Coastal Altimetry Product (3) NEW!

PISTACH/CNES

- Global product distributed since 2008
- at both 1 HZ (7 km) and 20 Hz (350 m) in Netcdf format
- Only Jason-2
- No SLA time series (left to the user choice of corrections, re-trackers, etc.)
- Several MSSH
- New/improved Geophysical corrections included
- Retracked products
- Handbook

- A call in June 2011 for reprocessing over selected areas – 3 selected
  - Agulhas current with the support of Beal (in situ) and Collard (SAR)
  - Florida Strait with the suuport of Kourafalou
  - East US coast with the support of Vandemark
- SLA time series for 3 zones computed by CLS + Noveltis and Legos
  - Calculated from 20 Hz measurements and provided with a final sampling of 5 Hz
  - Editing + low pass filtering
- 3 more areas to be selected in 2012

Why not promoting Indonesia ?

http://www.aviso.oceanobs.com/en/data/products/sea-surface-heigh products/global/coastal-and-hydrological-products/index.html

Coastal Altimetry is progressing towards applications

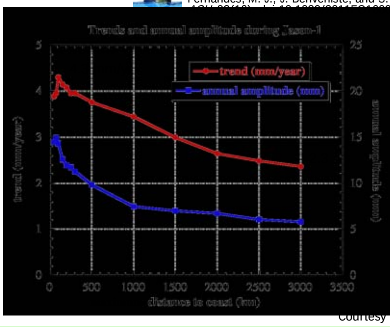
- These recent data products (either retracked or reprocessed) are closer to the coast with high resolution than previous AVISO data.
- They are exploited by scientists and other users
- Mostly used IN COMBINATION with other techniques, or in assimilation schemes, where they can successfully integrate in situ and/or model data.
- Results are coming out, applications are pioneered
- I will show some examples

Coastal altimetry is a legitimate component of a coastal ocean observing system!

Cipollini P., Benveniste J., Gommenginger C., Griffin D., Madsen K., Mercier F., Miller L., Pascual A., Ravichandran M., Shillington F., Snaith H., Strub T., Vignudelli S., Wilkin J., Vandemark D., Woodworth P., **The Role of Altimetry in Coastal Observing Systems**, In Proceedings of Conference OceanObs'09 on Sustained Ocean Observations and Information for Society (J. Hall, D.E. Harrison and D. Stammer Editors), Venice, Italy, 21-25 September 2009, ESA Publication WPP-306, Vol. II, doi:10.5270/OceanObs09.cwp.16 2010.

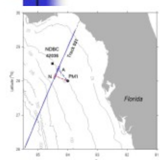
Improved Coastal Altimetry for better Monitoring of Regional Sea Level Trends

Fernandes, M. J., J. Benveniste, and S. Vignudelli (2011), *Eos Trans.* AGU, 92(12), doi:10.1029/2011EO120004

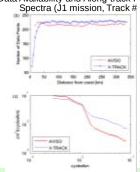


Courtesy by R. Scharroo, Altimetrics

Improved Coastal Altimetry for better understanding of coastal/shelf dynamics

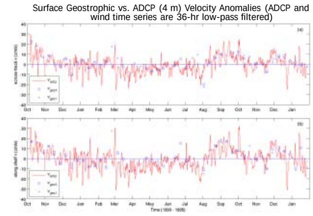


Data Availability and Along-track Power Spectra (J1 mission, Track # 091)



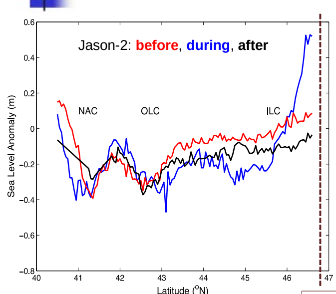
- Case-study of the West Florida Shelf (Gulf of Mexico)
- More data points than the AVISO product, especially near the coastlines.
- More energy in mesoscale activities as seen from the along-track power spectra.
- The rmsd of the estimated and observed velocities range from 7 to 10 cm/s, which is encouraging.

Surface Geostrophic vs. ADCP (4 m) Velocity Anomalies (ADCP and wind time series are 36-hr low-pass filtered)



Liu Y., Weisberg R. H., **Vignudelli S.**, Roblou L., Merz C. R.: **Evaluation of the X-TRACK Coastal Altimetry Estimated Currents with Moored ADCP and HF radar Observations on the West Florida Shelf,** in Special Issue "COSPAR Symposium", Journal of Advances in Space Research, doi:10.1016/j.asr.2011.09.012, 2011.

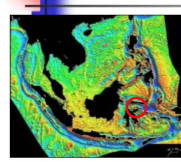
Improved Coastal Altimetry for storm surge forecasting

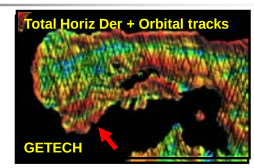


Courtesy by G. Han, DFO

- Coastal altimetry is important as it measures the Total Water Level Envelope (TWLE)
- That's the level you get – inclusive of tides, HF atmospheric effects, wave setup, etc…
- key quantity required by storm surge applications and services
- Of course there is a sampling issue – but altimetry is still useful, in combination with Tide Gauges, to ascertain the modes of variability of the coastal ocean
- ESA has recognized the above needs with two projects:
  - eSurge (Coordinator: P. Cipollini, NOCS, UK)
  - eSurge Venice (Coordinator S. Zecchetto, CNR, Italy)

Improved Coastal Altimetry for better evaluation of hydrocarbon basins





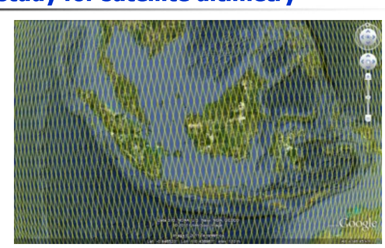
Courtesy by D. Fairhead,

- Free Air Gravity (FAA) is derived from the first vertical derivative of the Sea Surface Height (SSH).
- GETECH Ltd developed a specific processing to resolve gravity anomalies down to 10 km wavelength and to within 5 km of the coast.
- An improved coastal gravity map helps to:
  - better define the extent and structure of offshore basins, especially where little or no other data are available
  - identify subtle but important lineations running from the deep water onto the shelf plan and assist the interpretation of 2D seismic surveys
- The above example in Indonesia shows the existence of possible structures close to the shore.

Revised Error Budget for Coastal Altimetry

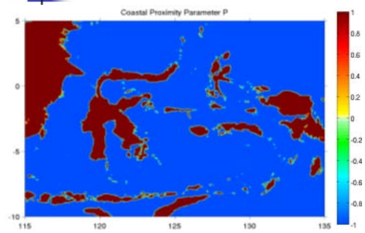
Parameter	0-10 km From coast	10-20 km From coast	20-50 km From coast	>50 km From coast
Wet Tropo PD SSH	2 cm	1-2 cm	1 cm	1 cm
SSH Slope	?	?	?	?
SSH spatial scale	10 km	20 km	20 km	20 km
Tidal Correction SSH	15 cm	Over shelf 15 cm		Open Ocean 2 cm
SSH Slope	?	?		?
SSH spatial scale	10-20 km	40 km		50-500 km
Tracking SSH				
SSH Slope				
SSH spatial scale				
SSH temporal scale				

Indonesia is an important case-study for satellite altimetry



- Several low-lying and densed-populated coastal areas
- Prone to sea level rise and surges
- Satellite altimetry is one piece of the puzzle
- Conceptually simple, but challenged by specific processing
- Multi-Mission Altimetry Ground Track Coverage
- In situ sea level measurements critical for the generation of accurate altimeter-derived estimates

Great target for developing/testing coastal altimetry



- Research is ongoing to assess quality of altimeter data for climate research (ESA Sea Level Climate Change Initiative)
- This includes the coastal areas, where a coastal proximity parameter (shown) indicates predicted effects of land on waveforms and can be used to screen the data
- Indonesia is a natural testbed for this development

Summary

Coastal Altimetry: One topic, many challenges

- Coastal altimetry is an important new field of research
  - A lively international community has quickly gathered around it
  - It needs constant interaction with engineers on technical side and hydrographers, ocean modellers on the application side
- Much progress reported…
  - Springer book is a good account of all that
  - Reprocessed coastal altimeter data sets now available (e.g. PISTACH, CTOH, COASTALT)
  - But we don't have an official AVISO coastal product yet
  - Applications using improved (new) coastal altimetry data are emerging
- COASTALT has contributed a lot
  - Incubator of ideas now developed in follow-on projects
  - Processor – up and running with work in progress to ensure multi-mission and multi-domain capability and move to NRT (e.g. eSurge)
  - Specialized retracking to get closer to coast
  - Much improved global corrections now possible (e.g. DLM and GPD innovative approaches for wet troposphere)
- A main point is that there is still much to do
  - Many challenges but room for improvement remains
  - New CryoSat-2 data look like very promising in the Coastal Zone
  - Forthcoming future missions both nadir viewing (Sentinel-3 sporting the novel delay-Doppler altimeter; SARAL/AltiKa (India), HY-2 (China)) and wide-swath (SWOT), which should improve both quantity and quality of coastal altimetry data

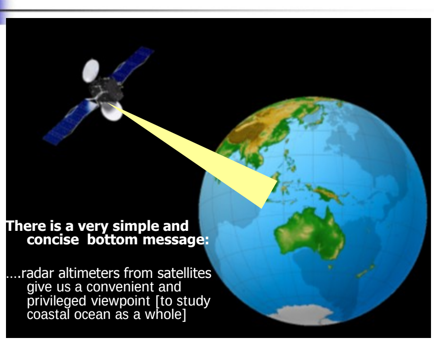
Recommendations from the 5th Coastal Altimetry Workshop

- Do more with the data we've got already
  - But a single point of access to coastal altimeter datasets would be welcome
- Further work is needed on the existing and innovative retrackers (which use information in adjacent waveforms)
  - Both theoretical and in terms of optimization and inter-calibration
  - Important to ensure consistency from the offshore to the inshore
  - Further R&D for innovative algorithms to move from concepts to simulations and eventually confrontation with real data
- The issue of filtering of the various corrections needs to be revisited
  - Correlation scales must be clearly identified and data screening and filtering schemes clearly recommended [these may depend on the application to some extent]
  - We need to quantify the improvement of the new/improved algorithms
  - The SSB correction should be reassessed in the coastal zone, with investigation of specific models

Recommendations from the 5th Coastal Altimetry Workshop (con't)

- Validation is crucial and should be supported further
  - Developing consistent validation protocols and assessments that can be applied to a number of locations with varying geographical and oceanographic conditions
  - We need to quantify the improvement on a regional basis
- The techniques developed in COASTALT, PISTACH and similar projects, and the relevant processors, should be extended to ensure multi-mission and multi-domain capability
  - Making processors open, flexible, expandable, easily upgradable and fully documented
- Coastal Altimetry applications should be supported and encouraged, with easy data access, outreach and training activities, and demonstration studies
  - The eSurge project is a clear example of the transition to applications
  - The RESELECASEA project is a clear example of transferring know-how and best practices

Thank you for your attention!



Retracking

Retracking

Presented by

Stefano Vignudelli
Consiglio Nazionale delle Ricerche, Italy
vignudelli@pi.ibf.cnr.it

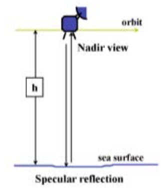
With invaluable help (and material) from
COASTALT Project

S. Vignudelli, A. Scozzari (CNR, Italy)
P. Cipollini, C. Gommenginger, H. Snaith, S. Gleason, G. Quartly, L. West (NOCS, UK)
Henrique Coelho (Hidromod, Portugal)
J. Fernandes, L. Bastos, C. Lázaro, A. Nunes. N. Pires, I. Araujo (U Porto, Portugal)
M. Bos (CIIMAR, Portugal)
S. Barbosa (U Lisbona, Portugal)
Jesus Gómez-Enri (U Cádiz, Spain)
C. Martin-Puig, M. Caparrini, L. Moreno (Starlab, Spain)
P. Woodworth, J. Wolf (POL, UK)
S. Dinardo, B. M. Lucas (SERCo/ESRIN, Italy)
J. Benveniste (ESA/ESRIN, Italy)

particular thanks also go to the Coastal Altimetry Community

Measuring Ocean Topography with Radar

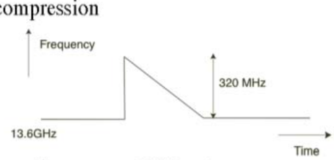
- Measure travel time, 2T, from emit to return
- h = T/c (c = 3 x 10^8 m/s)
- **Resolution to ~cm** would need a precision of 3 x 10^{-10}s, that is 0.3 nanoseconds)



0.3ns…. That is a pulse bandwidth of >3 GHz…. ahem, wait a minute….

Chirp, chirp, …

- So we have to use tricks: chirp pulse compression

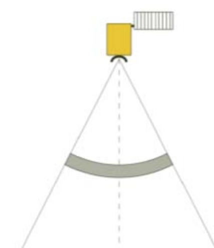


- …and average ~1000 pulses
- It is also necessary to apply a number of corrections for atmospheric and surface effects

Pulse Limited Altimeter

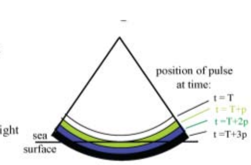
Pulse Limited Altimeter

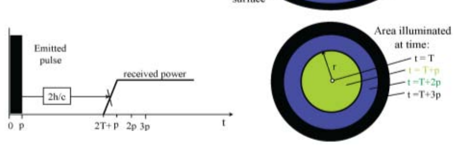
- In a pulse limited altimeter the shape of the return is dictated by the length (width) of the pulse



The "pulse-limited" footprint

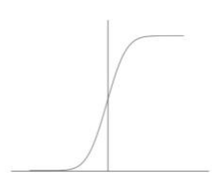
- Full illumination when rear of pulse reaches the sea – then area illuminated stays constant
- Area illuminated has radius $r = \sqrt{(2hcp)}$
- Measure interval between mid-pulse emission and time to reach half full height





This is what we get at end

- A plot of return power versus time for a pulse limited altimeter looks like the integral of the heights of the specular points, i.e. the cumulative distribution function (cdf) of the specular scatterers



The tracking point is the half power point of the curve

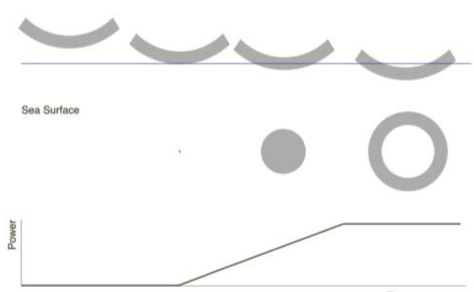
Pulse- vs Beam-

- All the microwave altimeters (including very successful TOPEX/Poseidon, ERS-1 RA and ERS-2 RA, Envisat RA-2) flown in space to date are pulse limited but….
- … laser altimeters (like GLAS on ICESAT) are beam-limited
- As said, delay-Doppler Altimeter can be seen as pulse-limited in the along-track direction
- But to understand the basis of altimetry we first consider the pulse limited design

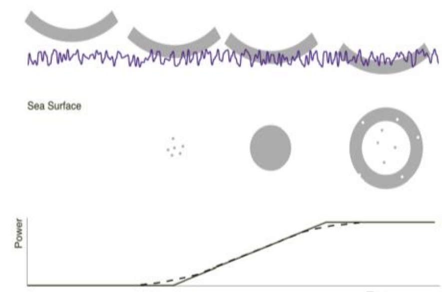
Basics of pulse-limited Altimeter Theory

- We send out a thin shell of radar energy which is reflected back from the sea surface
- The power in the returned signal is detected by a number of **gates** (bins) each at a slightly different time

This is what happens



and if we add waves



The area illuminated

- The total area illuminated is related to the significant wave height
- The formula is
- $$\frac{\pi R_0 (c\tau + 2H_s)}{1 + R_0/R_E}$$

where c is the speed of light, τ is the pulse length, H_s significant wave height, R_0 the altitude of the satellite and R_E the radius of the Earth

From Chelton et al. (1989)

Hs (m)	Effective footprint (km) (800 km altitude)	Effective footprint (km) (1335 km altitude)
0	1.6	2.0
1	2.9	3.6
3	4.4	5.5
5	5.6	6.9
10	7.7	9.6
15	9.4	11.7
20	10.8	13.4

Brown Model - I

The Brown Model

- Assume that the sea surface is a perfectly conducting rough mirror which reflects only at specular points, i.e. those points where the radar beam is reflected directly back to the satellite

Brown Model - II

- Under these assumptions the return power is given by a three fold convolution

$$P_r(t) = P_{FS}(t) * P_{PT}(t) * P_H(-z)$$

where

$P_r(t)$ is the returned power

$P_{FS}(t)$ is the flat surface response

$P_{PT}(t)$ is the point target response

$P_H(-z)$ is the pdf of specular points on the sea surfac

The flat surface response function

- The Flat surface response function is the response you would get from reflecting the radar pulse from a flat surface.
- It looks like

$$P_{FS}(t) = U(t - t_0).G(t)$$

- where U(t) is the Heaviside function
- U(t) = 0 t <0 =1 otherwise
- G(t) is the two way antenna gain pattern

The point target response function

- The point target response function is the shape of the transmitted pulse
- It's true shape is given by

$$P_{PT}(t) = \left[\frac{sin(\pi t/\tau)}{\pi t/\tau}\right]^2$$

- For the Brown model we approximate this with a Gaussian.

The Brown Model - III

$$P_r(t) = P_{FS}(0)\eta P_T \sqrt{2\pi}\frac{\sigma_p}{2}\left[1 + erf\left\{\frac{(t-t_0)}{\sqrt{2}\sigma_c}\right\}\right] \qquad t < t_0$$

$$P_r(t) = P_{FS}(t-t_0)\eta P_T \sqrt{2\pi}\frac{\sigma_p}{2}\left[1 + erf\left\{\frac{(t-t_0)}{\sqrt{2}\sigma_c}\right\}\right] \qquad t > t_0$$

$$\sigma_c^2 = \sigma_p^2 + \frac{H_s^2}{4c^2}$$

$$P_{FS}(t) = \frac{G_0^2 \lambda_R^2 c \sigma^0}{4(4\pi)^2 L_p h^3} \exp\left\{-\frac{4}{\gamma}\sin^2\xi - \frac{4ct}{\gamma h}\cos 2\xi\right\} I_0\left(\frac{4}{\gamma}\sqrt{\frac{ct}{h}}\sin 2\xi\right)$$

The Brown Model - IV

where

$$erf(t) = \frac{2}{\sqrt{\pi}}\int_0^t e^{-x^2}dx$$

Compare with the Normal cumulative distribution function

$$\Phi(t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^t e^{\frac{-x^2}{2}}dx$$

$$\Phi(x) = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right]$$

$I_0()$ is a modified Bessel function of the first kind

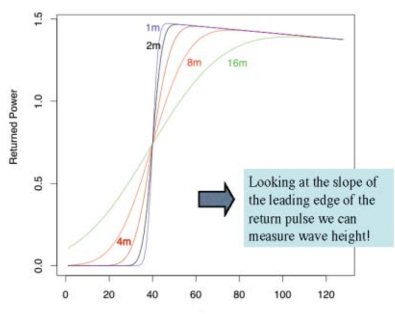
What are we measuring?

- Hs - **significant wave height**
- t_0 - the time for the radar signal to reach the Earth and return to the satellite (we then convert into **height** – see in the next slides)
- σ_0 - the radar **backscatter coefficient**, (somehow related to wind)

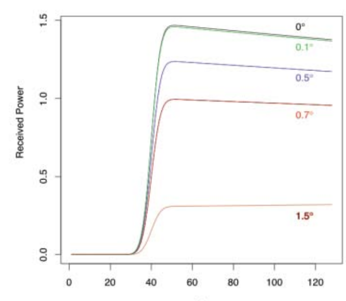
What are the other parameters?

- λ_R is the radar wavelength
- L_p is the two way propagation loss
- h is the satellite altitude (nominal)
- G_0 is the antenna gain
- γ is the antenna beam width
- σ_p is the pulse width
- η is the pulse compression ratio
- PT is the peak power
- ξ is the mispointing angle

Some examples of waveforms



The effect of mispointing



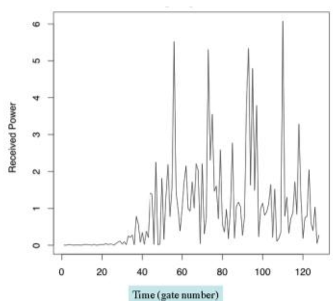
Noise on the altimeter

- If we simply use the altimeter as a detector we will still have a signal - known as the thermal noise.
- The noise on the signal is known as fading noise
- It is sometimes assumed to be constant, sometimes its mean is measured
- For most altimeters the noise on the signal is independent in each gate and has a negative exponential distribution.

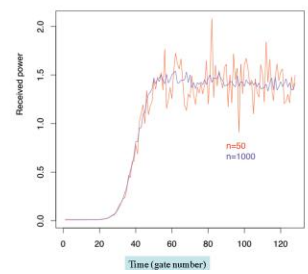
Averaging the noise

- For a negative exponential distribution the variance is equal to the mean. Thus the individual pulses are very noisy
- The pulse repetition frequency is usually about 1000 per second
- It is usual to transmit data to the ground at 20Hz and then average to 1 Hz

A single pulse



This is what happens when we average 50/100 single pulses



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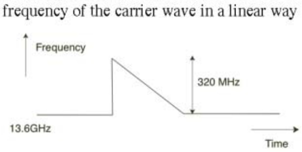
How altimeters really work

- It is very difficult (if not impossible) to generate a single-frequency pulse of length 3 ns
- However it is possible to do something very similar in the frequency domain using a chirp, that is modulating the frequency of the carrier wave in a linear way



The equivalent pulse width = 1/chirp bandwidth

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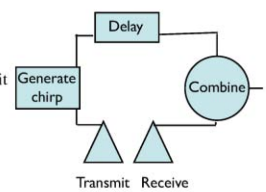
Full Chirp Deramp - I

- A chirp is generated
- Two copies are taken
- The first is transmitted
- The second is delayed so it can be matched with the reflected pulse



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Full Chirp Deramp - II

- The two chirps are mixed.
- A point above the sea surface gives returns a frequency lower than would be expected and viceversa
- So a 'Brown' return is received but with frequency rather than time along the x axis

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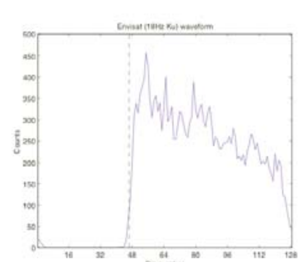
A real waveform from the RA-2 altimeter on ESA's Envisat



Ku band, 13.5 Ghz, 2.1 cm

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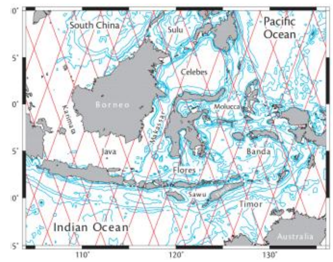
Altimeters – Some instruments flown

- GEOS-3 (04/75 - 12/78)
  height 845 km, inclination 115 deg, accuracy 0.5 m, repeat period ??
- Seasat (06/78 - 09/78)
  800 km, 108 deg, 0.1 m, 3 days
- Geosat (03/85 - 09/89)
  785.5 km, 108.1 deg, 0.1 m 17.5 days
- ERS-1(07/91-2003); **ERS-2 (04/95 – present!)**
  785 km, 98.5 deg, 0.05 m 35 days
- **TOPEX/Poseidon (09/92 – 2006); Jason-1 (12/01-present); Jason-2 (06/08-present)**
  1336 km, 66 deg, 0.03 m 9.92 days
- **Geosat follow-on (GFO) (02/98 - 2007)**
  800 km, 108 deg, 0.1 m 17.5 days
- **Envisat (03/02 - present)**
  785 km, 98.5 deg, 0.05 m 35 days

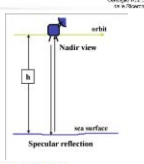
Example - Ground Track coverage of T/P and J1/2 over Indonesia



- Remember that conventional altimeters collecs data along track (i.e. 1D)

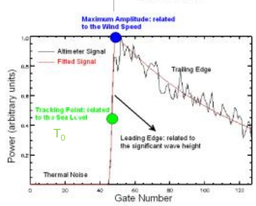
What is retracking ?

- We call "waveform" the ocean return signal
- In open ocean the typical waveform is Brown-like
- We call "retracking" fitting the real waveform with a model before estimating parameters
  - SWH - significant wave height = 4 x std (surface elevation)
  - T_0 - the time for the radar signal to reach the Earth and
  - return to the satellite
  - σ_0 - the radar backscatter coefficient, (somehow related to wind)



- In open ocean the typical waveform is Brown-like
- the Brown model (red line) is usually fitted to the real waveform (black line)
- Then we can estimate the time required for two-way travel of signal (2T0)
- The time is then converted to a measurement of distance, known as range:

h= T_0/c (c = 3 x 10^8 m/s)

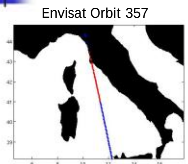


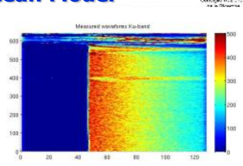
Which retrackers ?

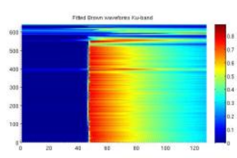
- Non-parametric (empirical methods)
  - Based on geometry
  - Do not estimate any geophysical parameters (apart from tracking point)
  - e.g. Off-center of gravity (OCOG)
    - Based on the definition of a rectangle about the effective center of gravity of waveform, the amplitude and width, the OCOG retracking method uses full waveform samples to locate the half-power point
  - DMU expert system
  - Geometrical shape fitted to the waveforms defined in terms of position of tracking point (e.g. offset center of gravity tracking on board, leading edge detection scheme)
- Model-based or Parametric (physics-based)
  - Use a geophysical model of the surface to build tracker
  - Tracker estimates geophysical parameters
  - Parametric of surface and we estimate them from the waveforms
    - e.g. MLE with Brown (1977) waveform shape offline for J1/n1
    - e.g. MLE tracker on Envisat
- Altimeter waveforms are conventionally tracked/retracked using maximum likelihood (MLE) or least squares to fit a 'Brown' model to the received waveform.

Waveforms & Retracking Brown Theoretical Ocean Model

Envisat Orbit 357



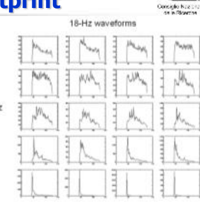


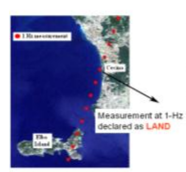


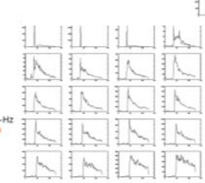
- Brown model is properly working except at land/sea interface, where a rapidly decaying trailing edge reflects the land contamination.

Waveforms may start being non Brown when land enters the footprint

Envisat Ascending Track



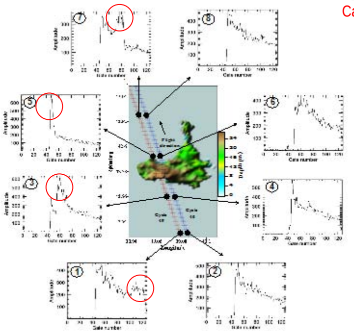


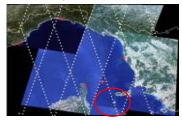


Envisat Descending Track

Waveform Contamination of calm waters

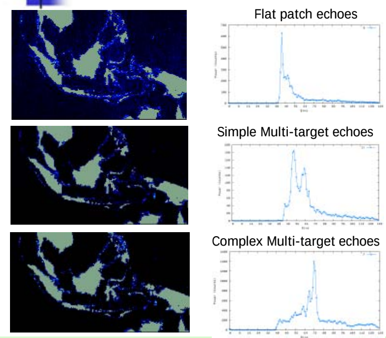
Case-study of Pianosa Island





- Not only land, but also calm waters can contaminate the shape of the waveform
- Calm water cause quasi-specular reflections (so called bright features or "bright targets")
- These features migrate in the waveform/gatenumber space following hyperbolae (a parabolic shape is usually a good approximation)
- We could predict these effects and subtract them in the retracking process

Indonesia is a challenging area



Calm water in coastal regions or with the presence of small islands.

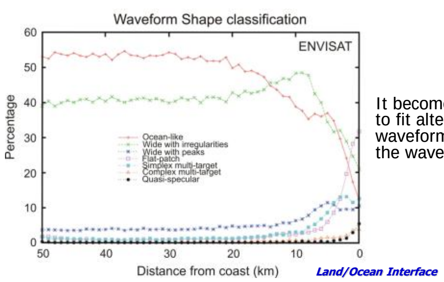
Multiple brightly surfaces reflecting within the altimeter footprint.

Combination of ocean component and rough terrain.

Courtesy by P. Berry, DMU

Coastal retracking

Essential to recover information when waveforms start being non-Brown!



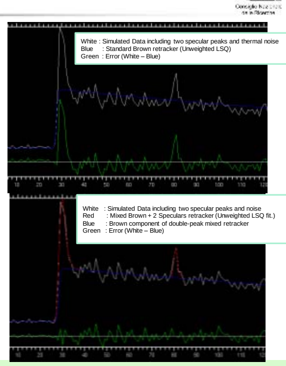
It becomes necessary to fit alternate waveform models to the waveforms

Lesson learned II – Re-thinking retracking

- We learnt that retracking waveforms in the coastal zone is challenging work
  - How close to the coast? – depends on how much high ground can affect tracking window too much
  - 90% of waveforms are Brown-like seaward of 10 km from the coast.
  - Standard (Brown model) retracking should be adequate seaward of 20 km from the coast.
- Identification of some retrackers better performing at the coast
  - e.g. RED3 in PISTACH Project
  - but BAG/ BAGP are even more promising
- Use better waveform models, accounting for change of shape in coastal environment
  - e.g. scattering from non-linear surfaces.
  - e.g. by including the effect of white caps
  - e.g. by mixing different models – Brown, Specular and Mixed (COASTALT)
- Use innovative techniques
  - Denoised estimations with Singular Value Decomposition(PISTACH)
  - Cleaning waveforms (COASTALT)
  - Avoid treating each waveform in isolation but using info from adjacent ones – 2D Hyperbolic Pre-tracker and Bayes Linear (COASTALT)

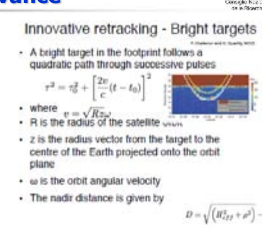
Retracking – mixing different models

- In many cases there are one (or more) non-Brown component(s) – e.g. A "specular" one superimposed on a Brown-like echo
- This can be tackled with models fitting different waveforms, e.g. one fitting sums of different Brown and non-Brown waveforms (a "mixed" retracked)

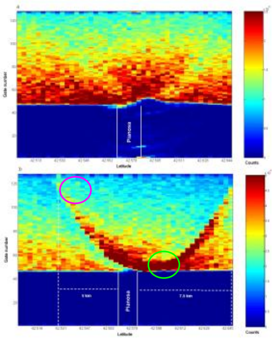


Innovative Retracking – Cleaning waveforms in advance

- We observed effects of land and effects of calm waters in the coastal strip
  - Land normally gives 'dark' features (less signal)
  - Calm water cause quasi-specular reflections giving peaky waveforms
- These features migrate in the waveform/gatenumber space following hyperbolae (a parabolic shape is usually a good approximation)
- Because we know the form of the hyperbolae (the speed of the satellite) we can accurately predic its position across a set of waveforms
- Features are reproduced by a simple model of the land/ocean/calm waters response
- The idea is that this should allow removal of the land/calm waters contamination prior to retracking

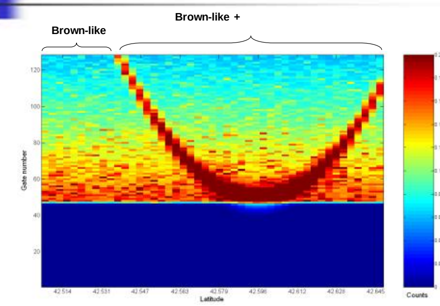


Waveform & Retracking Contamination of calm waters



- Small' influence of the island observed in cycle 46 (most of the waveforms are 'Brown-like')
- Hyperbola found in cycle 49: the appex of the feature corresponds to the north of the island (known as Golfo delle Botte)
- The radar 'senses' the change in ocean reflectance 7-8 km before the satellite overpasses the batch.

Modeling Peak Migration



At the end we could improve the accuracy in the retrieval of the geophysical parameters in the coastal zone

Innovative Retracking – 2D Hyperbolic Pre-tracker

- It is a pre-processor that cleans waveforms before application of other retrackers
- It has been reasonably tested on generic simulated altimetric waveforms.
- To tune the algorithm for best performance, the weights have to be developed with an accurate waveform simulation that matches Envisat RA-2 better. Improving this simulation
- Needs adjustment of simulated instrument characteristics.

Exercise

- A radar altimeter emits a short pulse that is bounced back from the ocean surface and the echo returns to the antenna.
- The recorded power is the convolution of the outgoing pulse with the ocean surface height distribution (i.e. waves), which is well approximated by a Gaussian function.
- The form of the return power is an error function, which is the integral of a Gaussian function.
- A simple model for the expected power versus time is

$$M(t, t_0, \sigma, A) = A\left[1 + \text{erf}\left(\frac{t - t_0}{\sqrt{2}\sigma}\right)\right]$$

- where t is the time since the pulse was transmitted, t_0 is the arrival time of the half power point, σ is the rise time parameter and A is the amplitude of the returned waveform.
- Since the pulse travels from the satellite to the ocean surface and back again, the altitude of the satellite is

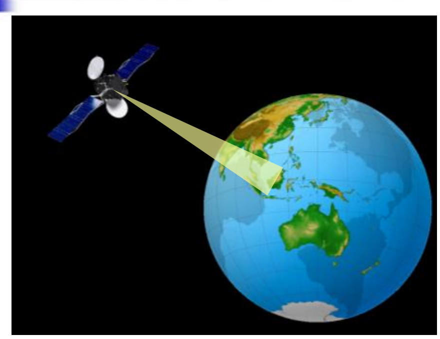
$$r = \frac{ct_0}{2}$$

- where c is the speed of light

Exercise (cont'd)

- 20 altimeter waveforms collected by an altimeter are available in the file "fitwf.dat"
  - The first column of the file is time in nanoseconds since the altimeter started recording (5.3 x 10^{-3} seconds)
  - The second column is the recorded power.
- The student has to:
  - Load the waveform data
  - Plot waveform data as points (power vs time).
  - Generate a simple model waveform from the function (see previous slide)
  - Plot it over the waveform data
  - Estimate the range in meters
  - Estimate the Significant Wave Height (SWH) in meters

Thank you for your attention!



Coastal Altimetry Matlab Toolbox

Coastal Altimetry Matlab Toolbox

Stefano Vignudelli, Jesus Gómez-Enri, Andrea Scozzari, Paolo Cipollini

Recap – WHAT

The overall aim is to demonstrate that "coastal altimetry" is about or (at least) as accurate as "open ocean altimetry"

- Relevant objectives:
  - to make a full internal quality control on the retracked parameters and corrections also checking against the original fields in the SGDR
  - to show that thanks to re-tracking (and new or improved corrections where applicable) COASTALT data are better than SGDR after comparison with *in situ* sea level data

to ensure a proper quality assessment of the product before its exploitation.

Some considerations

- **Three key facts:**
  - We have a global coastal zone
  - We need time series for exploitation
  - We like quality control & validation in a click
- **The actual status from the processor:**
  - Output in netcdf format for a selected pass
  - One file per orbit and cycle
  - Collection of parameters as function of rate, latitude, longitude and time

Along track positions of parameters not coinciding for different cycles

What is the best way to proceed ?

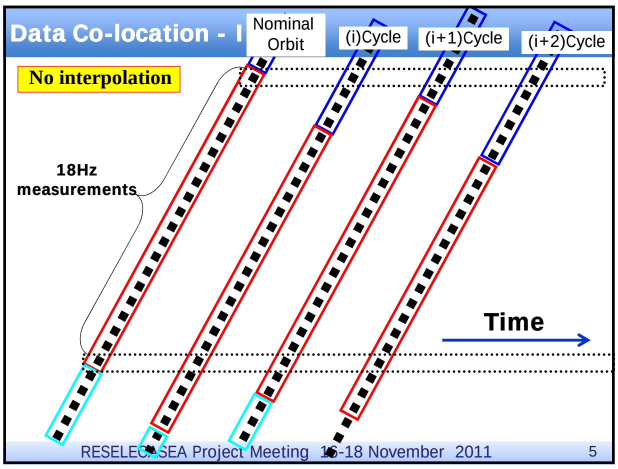
Our strategy

- **To generate altimeter data**
  - Selecting a coastal zone of interest
  - Indentifying relevant passes
  - Running the processor to get all cycles for all selected passes
  - Extracting land/sea interface (coastline or DEM)

- **To reorganize altimeter data**
  - Parameters to be viewed along track (space) and along cycle (time)
  - Building one ASCII file per one point at 1 Hz
    - Using IDL script running in batch mode
  - Each file contains a 2-D data table
    - Parameter vs cycle
    - Maintained correspondence between 1 Hz and 18 Hz fields (see next slide)

- **To process altimeter data**
  - Using Matlab scripts to automate tasks
  - Detecting spikes and flagging them
  - Computing new variables
    - SSH or other quantities
  - Comparing in situ observations
  - Enabling ad-hoc visualizations

Data Co-location - I



Data Co-location - II

Example of ASCII file

Fields

18Hz Measur.

Cycle	Month	Day	Year	Hour	Minute
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
10.0000	10.0000	5.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000
11.0000	11.0000	9.0000	2002.0000	9.0000	56.0000

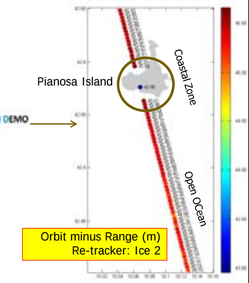
Quality control (what and how)

- Focus on ranges and corrections
- Open ocean is our reference
- Need of identifying anomalies (offsets, trends, jumps, malfunctioning, etc.)
- Priority on ranges - roughly corrections << range and no good correction will help us to get good SSH if range is bad of several meters
  - Orbit minus range – our indicator of anomalies
- Parameter visualization
  - along track for a specific cycle
  - along cycle for a specific ground point
  - along track and along cycle 2-D stacked plots - all cycles or all ground points
  - coming from different sources (e.g. Range, Wet Tropo, Iono) - comparison
- Parameter statistics
  - some key figures (e.g. std, Avg)

Matlab script: Pltalongtrack

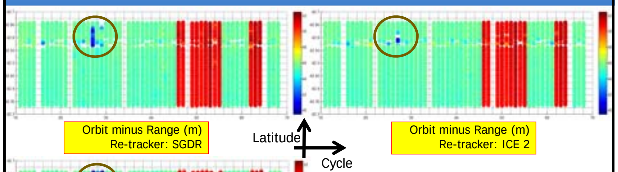
To visualize data along track

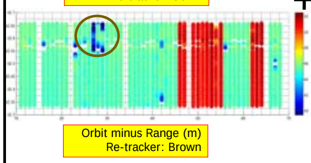
- Ranges now – to be extended to corrections
- Loading data – now C-GDR V 1.0 BUT to be rerun with coming C-GDR V 1.1
- Selecting cycle(s)
- Selecting retracker(s)
- Focusing on two variables (range and orbit minus range)
- Computing statistics (std, Avg)
- Creating 2-D plots (geo-referenced)
- Exploiting Matlab GUI (e.g. zooming)
- A command-line user interface (e.g. change cycle, re-tracker, etc.) and re-do tasks



Along track detection of outliers: based on linear de-trending with flagging of all data that deviate more than 2σ from that.

Example II – SGDR vs ICE 2 vs Brown (all cycles)



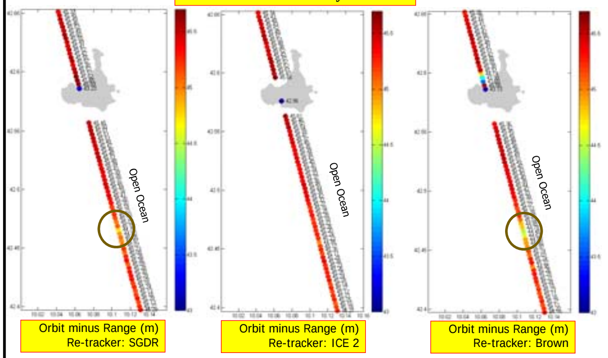


- SGDR, ICE 2 and Brown show similar variability patterns
- Red color lines show USO mal-functioning for those cycles
- The effect of Pianosa Island is visible with all re-trackers around 42.55 and 42.6 °N
- It is not the same for all re-trackers
- Bleu patches indicate anomalous drops in range
- Generally, ICE 2 seems working better than the others

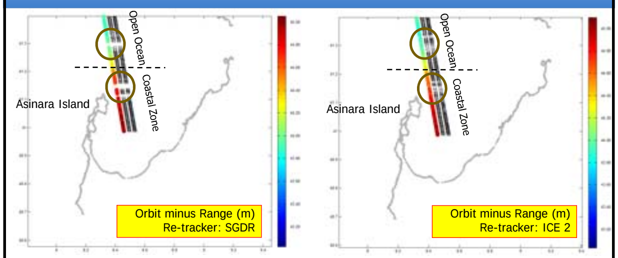
Pianosa: Track 128 – All cycles

Example III – SGDR vs ICE 2 vs Brown (single cycle)

Pianosa: Track 128 – Cycle 25



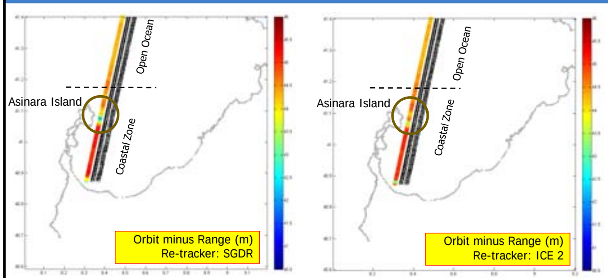
Example IV – SGDR vs ICE 2



Porto Torres: Track 443 – Cycle 10

- SGDR and ICE 2 show similar along track variability
- SGDR shows some data gaps near NW corner of Asinara Island
- SGDR shows some data gaps even in open ocean (causes to be explored)
- To be noted that ICE 2 is capable of filling these gaps

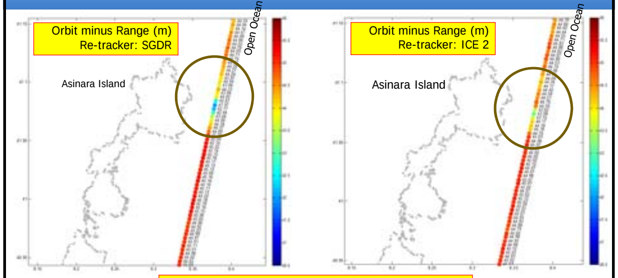
Example V – SGDR vs ICE 2



Porto Torres: Track 65 – Cycle 10

- SGDR and ICE 2 show similar along track patterns – no offset
- Ranges dropping near NW corner of Asinara Island – a bit better result from ICE 2
- The drop is seen in all cycles (probably due to land effect)

Example VI – Zooming and looking at numbers



Porto Torres: track 65 – Cycle 10

- Open Ocean reference
  - SGDR and ICE 2 - ~ 44 m
- NW corner of Asinara Island
  - SGDR more variable along track than ICE 2
  - SGDR (ICE 2) decreasing to ~ 41.9 (43.08) m

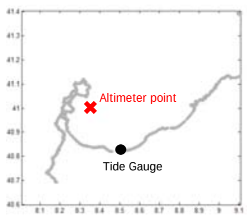
Validation (what and how)

- Focus on SSH/SLA
- In situ data is our reference
- SSH/SLA along cycle for a specific ground point
- SSH/SLA along cycle stacked as 2-D plot - all ground points
- Measure of how closely the altimeter-derived sea level estimates correspond to the in situ values – we will explore the use of co-variance.

Matlab Script: Pltvstime

To visualize data along cycle

- Assumes quality-checking and flagging done
- Loading tide gauge data (format: time, level) – latitude and longitude of station if available
- Selecting ground point(s)
- Generating SSH corrected
- Comparing altimeter-derived sea level estimates with corresponding in situ values
- Exploiting Matlab GUI (e.g. zooming) → DEMO →
- A command-line user interface (e.g. change ground point, change re-tracker, etc.) and re-do tasks
- Keeping track of selected ground points on map



Summary

- Again stressing that C-GDRs data are not directly usable for comparisons with in situ data
- The processor is not actually co-locating altimeter for different cycles
- Workaround
  - Data co-location and export in ASCII tables off-line
  - but to be considered within the processor in the future
- Automation of processing tasks
  - Quality checking of ranges (done)
  - Quality checking of corrections (in progress)
  - Validation (in progress)
- To be able to quality check and validate everywhere
- Some preliminary results
  - Pianosa and Porto Torres - ICE 2 looks like working well
- Plans to explore all pilot sites (NW Med, Gulf of Cadiz) and focus on island sites (selection in progress) when C-GDR 1.1. will be available

Specialized re-trackers would promise more and better data in the coastal zone

Coastal Altimetry Matlab Toolbox (2)

Coastal Altimetry Matlab Toolbox

Stefano Vignudelli, Jesus Gómez-Enri, Andrea Scozzari, Paolo Cipollini

COASTALT

Recap – WHAT

The overall aim is to demonstrate that "coastal altimetry" is about or (at least) as accurate as "open ocean altimetry"

- Relevant objectives:
  - EWP 1.1
    - to make a full internal quality control on the retracked parameters and corrections also checking against the original fields in the SGDR
  - EWP 5.2
    - to show that thanks to re-tracking (and new or improved corrections where applicable) COASTALT data are better than SGDR after comparison with *in situ* sea level data

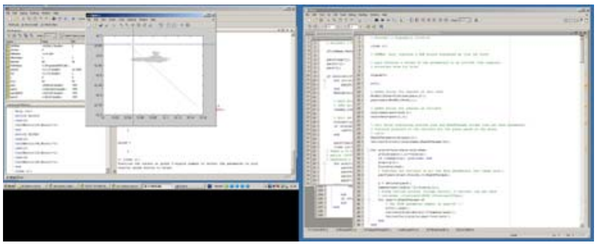
to ensure a proper quality assessment of the product before its exploitation.

Coastal Altimetry Toolbox

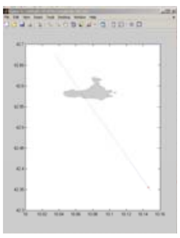
- Developed in Matlab to exploit built-in tools.
- A command-line user interface to select parameters (cycle, re-tracker, correction), create plots (geo-referenced or stacked) and zoom in/out locally.
- Parameters can be visualized along track for a specific cycle (or all cycles in 2-D), along cycle for a specific ground track point (or a subset of ground track points in 2-D), along track and cycle (all cycles for selected ground points in 3-D).
- Added interactive functionality to remove residual outliers using mouse gestures.
- A Matlab GUI permits to select ground track points and decide which range and corrections to use in SSH computation.
- This enables comparison using parameters coming from different sources (e.g. Range, Wet Tropo, Iono).
- Work in progress: comparison with in situ data (visualization and quantification

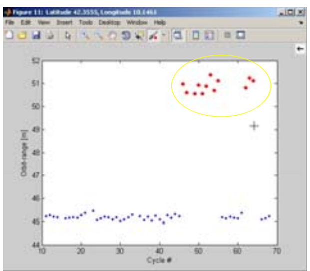
Next slides: showing examples using C-GDRs at Pianosa Island (track 128 - rev 69 and 70)

Example I – Selecting ground track point(s) using mouse



Example II– Visualizing a parameter (e.g. orbit minus range) in the temporal domain at a selected ground track point

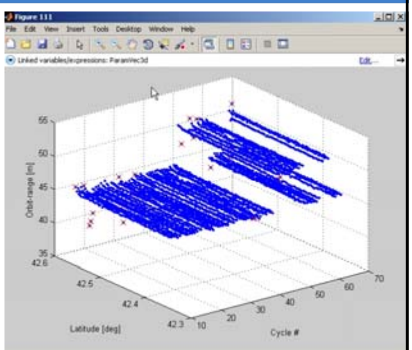




- Ground track point is in open ocean
- Retracker: ICE 2
- USO malfunctioning identified

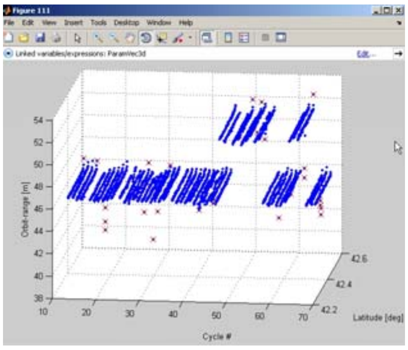
Example III – 3-D visualization of a parameter (all cycles for a subset of ground track points)

- Selected a segment near Pianosa Island
- Decided to visualize orbit minus range
- Red points correspond to outliers that are flagged in the spatial domain.
- We can rotate and view data along track and along cycle
- We can identify missing cycles, anomalous cycles, spatial and temporal patterns (real or artifacts)



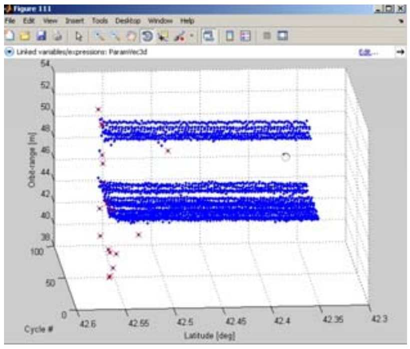
Example IV – Rotating to view data along cycle

- We can see outliers in the temporal domain due to USO malfunctioning

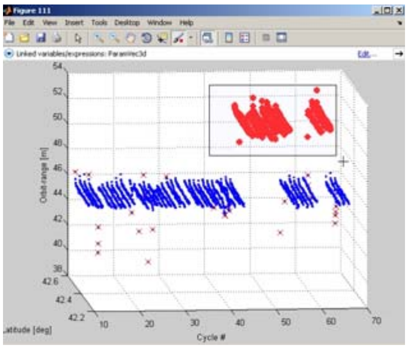


Example IV – Rotating to view data along track

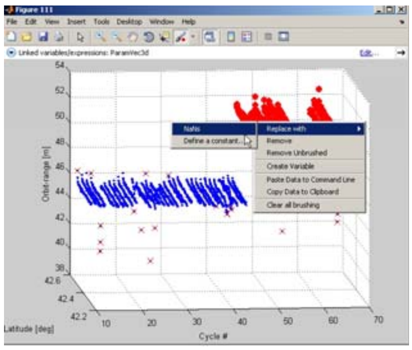
- We can see that outliers in the spatial domain (red points) are mainly located nearer the Island



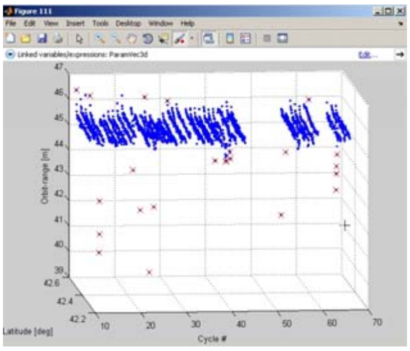
Example V – Selecting outliers to be removed (e.g. USO)



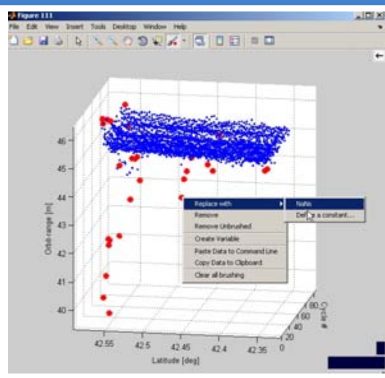
Example VI – Filling USO outliers with “NaN”



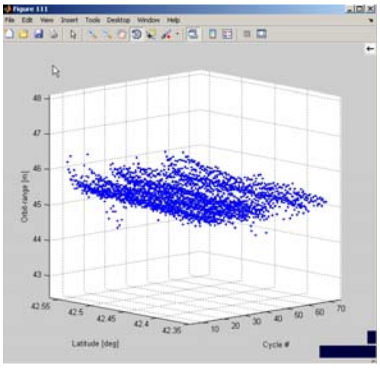
Example VII – Other outliers need to be removed



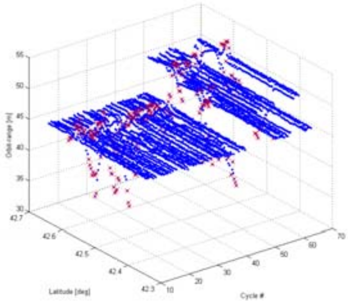
Example VIII – Changing the view makes easier the job



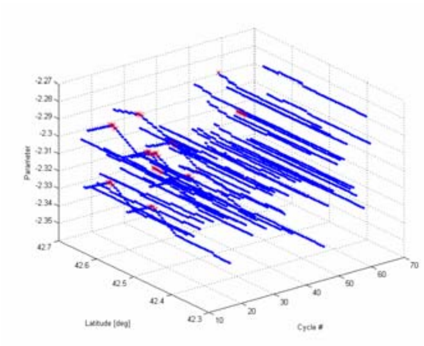
Example IX – We have now a cleaner data set



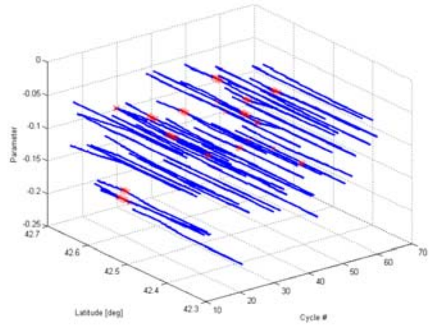
Example X – 3-D view after selecting a sub-track crossing Pianosa Island (Product: rev 70 – Brown Retracker)



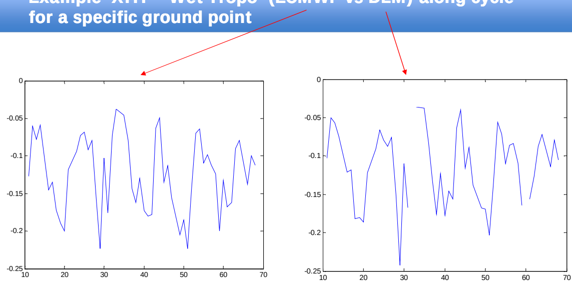
Example XI – Dry Troposphere correction (ECMWF) at 18 Hz around Pianosa Island.



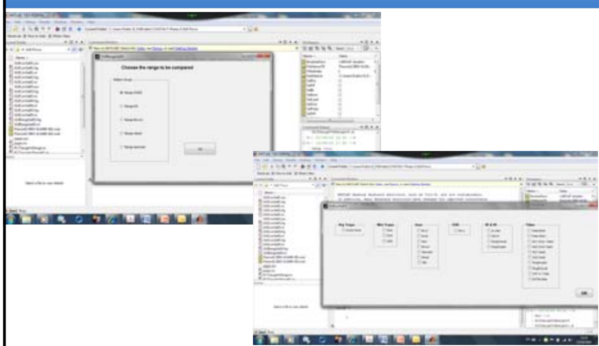
Example XII – DLM (Dynamic Link Method) wet troposphere correction at 18 Hz around Pianosa Island



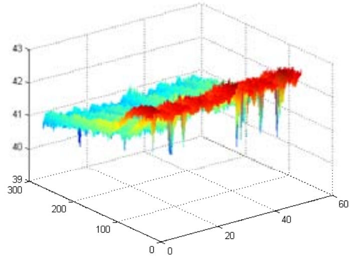
Example XIII – Wet Tropo (ECMWF vs DLM) along cycle for a specific ground point



Example XIV– Selecting ranges and corrections on the fly



SSH in a 3-D View (all cycles) – track 443



SSH corrected = orbit - (range + iono + dry tropo + wet tropo + loading tide + SSB + solid tide + pole tide + wind and pressure effects

Several combinations !!!! But we like measuring of how closely the altimeter-derived sea level estimates correspond to the in situ values

Summary

- A Matlab toolbox for coastal altimetry is under development to facilitate processing tasks.
- This toolbox is intended for experts who like to quality check and validate coastal altimeter data in a selected study area.
- Some examples are presented to show the main functionalities.
- The toolbox will support experts in assessing (qualitatively and quantitatively) the improvement gained from the adoption of specialized re-trackers and corrections in the coastal zone.

Appendix 12

Presentations of Training and Workshop 2012

RESELECASEA

COASTAL ALTIMETRY IN SOUTH EAST ASIA

RESELECASEA REPORT PROGRESS

To Workshop

APN RESELECASEA

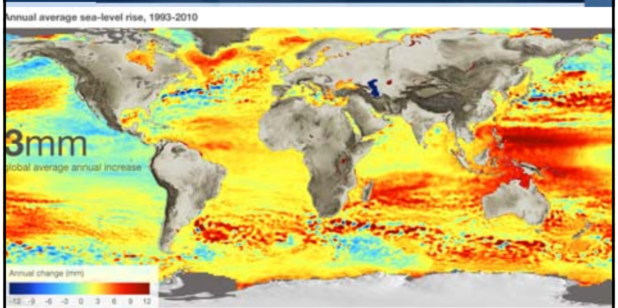
Reconstruction of Sea Level Change in Southeast Asia Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data

Dr. Parluhutan Manurung (BIG)
Dr. Stefano Vignudelli (Research Council (CNR) Pisa, Italy)
Prof. Robert R Leben (University of Colorado USA)
Dr. Jonson Lumbangaol (IPB)
Dr. Benjamin Hamlington (University of Colorado USA)
Dr. Ibnu Sofian (BIG)

Objective

1. Reconstruction of sea level change in SE Asia Seas
2. Coastal Altimetry retracking
3. Capacity Building on satellite altimetry

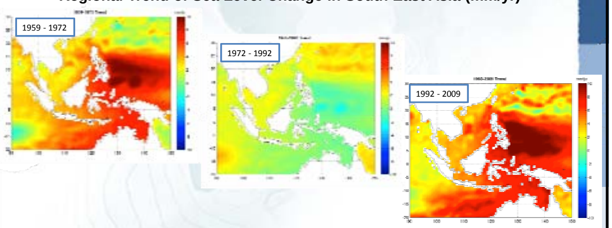
Map of Annual Average Sea Level Rise 1993-2010



Sea Level Rise varies temporall and spatially

Reconstruction Map of SE Asia Seas

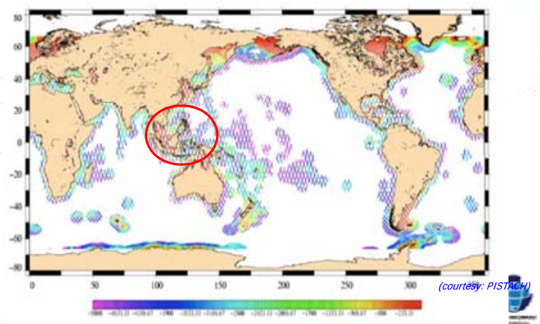
Regional Trend of Sea Level Change in South East Asia (mm/yr)



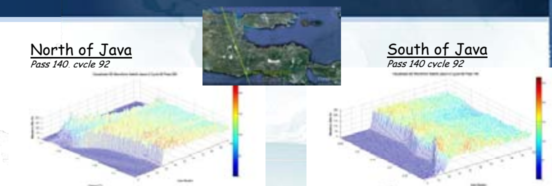
The RESELECASE Project is pioneering this research for SE Asia Seas

Retracking Waveform of Coastal Altimetry

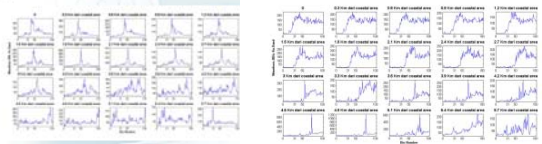
Altimetry data are flagged from 0 to 10 of coastline



Retracking Waveform of Coastal Altimetry



3D Waveforms: 30 km from coastline to offshore



2D Waveforms: 20 Hz sampling from coastline to offshore


Capacity Building: Training and Workshop
Workshop & Training on Coastal Satellite Altimetry 16 -18 November 2011 in Bogor
Training & Workshop on Coastal Satellite Altimetry 12-14 November 2012 in Bogor

Introduction to

Deep Sea Water Altimetry

Introduction to Deep Water Satellite Altimetry

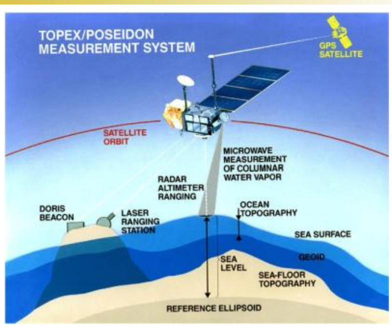
Bob Leben
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

What is an altimeter and radar altimetry?

Altimeter - An instrument that determines height above a reference level, commonly by measuring the change of atmospheric pressure, or by measuring vertical distance directly with a radar or laser system.

Radar Altimetry - The measuring of range from an aircraft or satellite to the sea surface using a short pulse of microwave radiation with known power toward the sea surface. The pulse interacts with the rough sea surface and part of the incident radiation reflects back to the altimeter. The techniques for determining the range to the ocean surface based on the travel time of such a microwave pulse is commonly referred to as altimetry.

Schematic of Satellite Altimeter System



Basic Concept of Satellite Altimetry

The measurement of sea surface height from space by a satellite borne altimeter is deceptively simple:

1. Send a microwave pulse to the ocean surface and detect the reflecte pulse, measuring the two-way travel time between sending and rece the pulse.
2. Calculate the distance of the ocean surface from the satellite, the alt range, by multiplying the one-way travel by the speed of light. The o way travel time is equal to 1/2 the two-way travel time.
3. Adjust range measurement to account for atmospheric, pulse reflect instrument and external geophysical corrections to the path length.
4. Determine the ocean height by subtracting the range from the orbit of the satellite.

While measuring sea surface elevation from space is conceptually simple satellite altimetry is in fact quite complex, requiring nearly 60 algorithı and a variety of external measurements to accurately determine the surface height elevation associated with dynamic ocean currents.

TOPEX Altimeter (ALT)

The ALT is a dual-frequency, nadir-looking, pulse-compression radar.

- Range measurements are made at both Ku-band (13.6 Ghz) and C-band (Ghz) to eliminate the ionospheric electron range error.

The ALT generates a linear-FM (chirp) pulse waveform with a 320 MHz bandwidth and a 102.4 microsecond duration, for both the Ku- and the band.

- The pulse repetition frequency is approximately 4500 for the Ku-band an Hz for the C-band.
- The antenna, shared with the CNES solid-state altimeter (SSALT), is a 1.5 meter diameter parabolic reflector. The antenna beamwidth is approxima 1.1 degrees for Ku-band and 2.6 degrees for C-band.

Measurement geometry

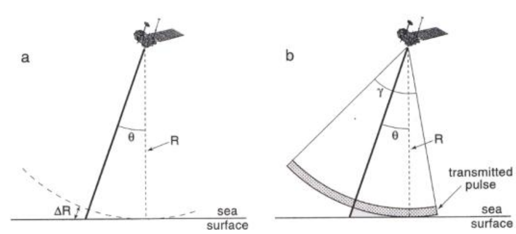
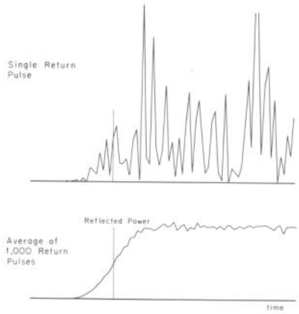
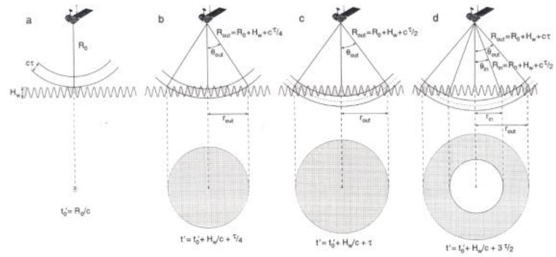


FIGURE 7 The measurement geometry for (a) a very narrow beamwidth-limited altimeter; and (b) a pulse-limited altimeter with a relatively large antenna beamwidth γ. In both cases, the boresight of the antenna views the sea surface at off-nadir angle θ from a height R above the sea surface.

Return pulse averaging



Measurement geometry



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Ocean Satellite Altimeter Missions

Mission	Dates	Agency	Repeat Orbit
Skylab	1973	NASA	non-repeat
GEOS-3	1975-1978	NASA	non-repeat
SEASAT	1978	NASA	partial
GEOSAT	1985-1989	U.S. Navy	non-repeat, 17-day
ERS-1	1991-2000	ESA	3-day 35-day, 176-day
TOPEX/POSIEDON	1992-2006	NASA/CNES	10-day
ERS-2	1995-2011	ESA	35-day
GFO	1999-2008	U.S. Navy	17-day
Jason-1	2001-present	NASA/CNES	10-day
ENVISAT	2001-2012	ESA	35-day
Jason-2/OSTM	2008-present	NASA/CNES	10-day

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Seasat

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Seasat Jul-Aug 1978: Loop Current and Eddy

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GEOSAT

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U.S. Navy's GEOSAT

The U.S. Navy GEOdetic SATellite carried an altimeter that was capable o measuring the distance from the satellite to the ocean surface with a relative precision of about 5 cm.

- Primary mission phase, the Geodetic Mission, was dedicated to mappi the marine geoid at high spatial resolution. Data were originally class The data around Antarctica were declassified in 1990 and the entire d set in June, 1995.
- Launched on March 12, 1985.
- Near circular orbit, inclination 108°, period 101 min, and altitude 800
- The Exact repeat mission phase began on November 8, 1986 after the satellite was maneuvered into a 17-day repeat orbit (actually 17.05 da until the satellite ultimately failed in January 1990.
- Public release of the high resolution Geodetic data allowed the estima of sea floor topography using satellite altimetry.

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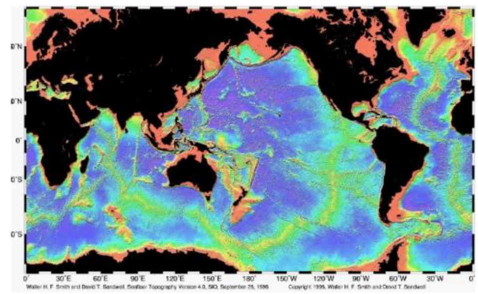
Sea Floor Topography



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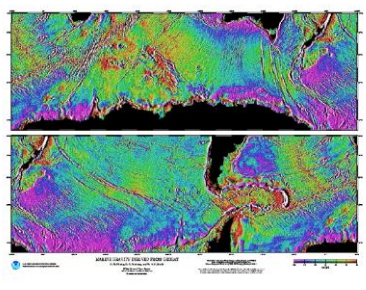
Marine Gravity



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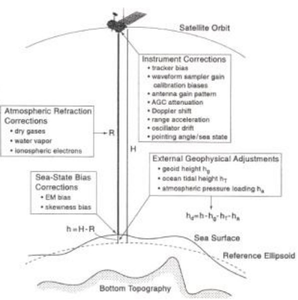
Schematic Summary of Corrections



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Altimeters Range Corrections

Altimeter range corrections can be grouped as follows:

- Atmospheric Refraction Corrections
- Sea-State Bias Corrections
- External Geophysical Corrections
- Instrument Corrections

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Atmospheric Range Corrections

The presence of dry gases, water vapor and free electrons in atmosphere reduces the propagation speed of the radar p These are the so-called atmospheric range corrections.

- Dry Gases
- Water Vapor
- Ionospheric Free Electrons

All of these corrections cause a delay in the returned signal a are often referred to as a *path delay*, acting to make the ra measurement too long.

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Atmospheric Range Corrections: Dry Gases

At microwave frequencies the troposphere is a non-dispersiv medium, and the index of refraction is independent of frequency. For convenience the path delay is broken into a dry and wet component. The dry component reflects prim the refractive effects of oxygen on the path delay.

A simplified expression for the dry troposphere range correcti which takes into account the variation in gravity with latit is given by the formula:

ΔR_dry ≈ 0.2277*P(1 + 0.0026cos(2 latitude))

Where P is the sea level pressure in millibars and ΔR_dry is i cm.

This range correction averages 226 cm with variations of 2 c The uncertainty associated with errors in the pressure fiel from numerical weather models is about 1 cm.

Atmospheric Range Corrections: Water Vapor

The atmospheric range correction associated with columnar water vapor is called the *wet troposphere* correction and reflects water vapor and cloud liquid water droplet contributions to atmospheric refraction.

This effect is parameterized by empirical formula:

ΔR_wet ≈ 1.6 L

where L is the integrated columnar liquid water in gm/cm^2 ΔR_wet has units of cm.

This range correction averages 10 cm at high latitudes to 24 in tropical regions. Time variations are about 5 cm. The uncertainties is about 1 cm when corrected using a three-frequency microwave radiometer.

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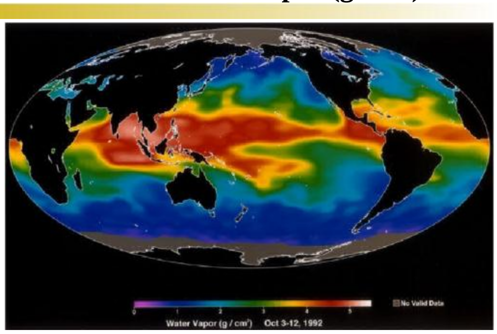
TMR Water Vapor (g/cm2)



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Microwave Radiometry

Modern altimeter rely on bore-sight radiometers to estimat ΔR_wet.

- Algorithms using three frequency (18, 21 and 37 GHz) brightness temperature trained on a large global database radiosonde profiles to estimate ΔR_wet have accuracies of about 1 cm in rain free conditions
- Algorithms based on the two frequencies (23.8 and 36.5 G used in the ERS radiometers have accuracies of about 2 cm rms.

Note: The ability to correct satellite altimeter data for water vapor attenuation requires coincident measurements from passive microwave radiometer onboard the satellite becau the columnar water vapor at any particular location varies with time.

This was an important lesson learned from GEOSAT.

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Jason Microwave Radiometer (JMR)

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Atmospheric Range Corrections: Ionospheric Free Electrons

Electrons liberated from atoms in the ionosphere by energet solar radiation interact with microwaves to slow their propagation. Since the ionosphere is a dispersive medium, refraction is a function of the frequency so that the free electron density can be calculated using the ranges measuremetns at different frequencies.

The ionosphere range correction is calculated from the total electron content unit (TECU) using the formula:

ΔR_iono = 0.22 TECU

where TECU is given in 10^16 electrons per meter^2 with ΔR_iono in cm.

Like the wet troposphere correction, accurate measurements TECU are required for accurate altimetry given the time ar space scales of ionospheric variability

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Scales of the Ionospheric Delay

The ionosphere exhibits spatial and temporal variations that difficult to reproduce with numerical models. Observation show:

- Mean values of the ionospheric delay range from 12 cm n the equator to 6 cm at higher latitudes.
- Variations about the mean are as large as 5 cm near the equator and 2 cm at higher latitudes.
- Meridional gradients as large as 2 cm per 100 km can occ during mid to late afternoon at latitudes of 20° to 30°.
- Uncertainty in the measurements are about 1 cm after smoothing the ionospheric correction at length scales less 100 km.

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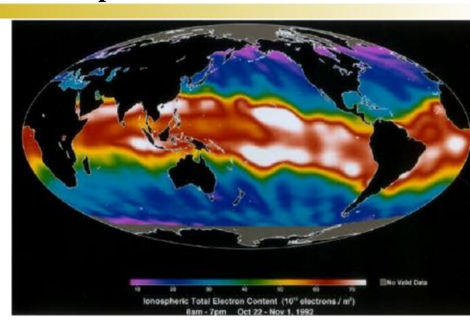
Ionospheric Total Electron Content



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Sea State Bias Corrections

The sea state bias is made up of two components

- Electromagnetic (EM) Bias - the difference between mean level and the mean scattering surface.
- Skewness Bias - the difference between the mean scatteri surface and the median scattering surface.

Recall that the returned signal measured by an altimeter is t pulse reflected from the small wave facets within the ante footprint that are oriented perpendicular to the incident w fronts.

The shape of the returned waveform is thus determined fro distribution of these scatterers rather than the distributio the actual sea surface height.

The half power point on the leading edge of the returned w form corresponds to the median scattering surface.

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External Geophysical Corrections

- Geoid height - An accurate geoid is needed to calculate th total dynamic topography signal that includes both the m ocean circulation and its variations. Early geoids have not been accurate enough for this application, however, by including gravity measurements form GRACE mission have reduced geoid errors at scales greater than 300 km so that scientifically useful information can be derived.
- Ocean and solid earth tidal height - Both ocean and solid tides are measured by the altimeter and are considered no on the non-tidal dynamical signal. Existing models derived from T/P data are accurate to better than 2 cm rms in the ocean.

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External Geophysical Corrections (cont.)

- Atmospheric pressure loading - This is simply the depression of the se surface by the atmosphere pressure force on the ocean surface. Spati temporal variations of this force are compensated partially by variatio the surface elevation. To first order, the ocean response as an "inverse barometer", changing height by about one centimeter per milli bar of pressure change.

$$\Delta \text{ IB (cm)} \approx 0.995 \text{ (P-1013)}$$

where P is the sea level pressure and 1013 is the mean sea level pressure

In reality, the ocean responds both statically and dynamically depending the spatial and temporal scales of the forcing.

- Barotropic ocean signals, which are have significant power at periods shorter than 20 days and are aliased by altimetric sampling, is also an important external geophysical correction being studied. Barotropic models forced with wind and pressure can be used to correct for baro variability altimetery measurements.

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Instrument Corrections (some)

- Doppler shift - Doppler shifting of the transmitted chirp affects the ra calculation. This is corrected using the range rate, the rate of change range. Range rate is calculated in ground processing by least squares fitting of the range data over about 3 seconds of TOPEX data.
- Range acceleration - The tracker algorithm is affected by the range acceleration. The range acceleration is calculated using the least squa employed for the range rate. Range rates can be as high as 10 meters second^2 over ocean trenches.
- Oscillator drift - any drift in the frequency of the oscillator direct affe the range calculated by counting cycles of the on board oscillator. Thi calibrated by timing of telemetry signals at a ground receiving station distinction between frequency and counts per second resulted in an e in the ground based software for TOPEX causing a significant drift an bias in the altimeter measurement.
- Pointing angle/sea state - the largest source of instrumental error is c by of nadir pointing of the altimeter instrument. To varying degrees t affects the adaptive tracker unit (ATU) estimates of two-way travel tir the significant wave height and the sigma naught.

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TOPEX/POSEIDON

TOPEX/POSEIDON

A joint NASA/CNES satellite altimeter mission launched on August 10, 1992.

- Carried two altimeters: the dual frequency TOPEX altimet and the solid-state Poseidon altimeter, which shared a sing antennae on the satellite.
- Highly successful primary and extended missions collecte 10-day repeat cycles of data through 8/11/2002.
- TOPEX and Jason-1 flew in the same orbit (with Jason lea by 60 seconds) for the first 21 repeat cycles of the Jason mission to intercalibrate the satellites.
- Starting on August 15, 2002 T/P was maneuvered into an interleaved orbit for tandem sampling mission with Jason The interleaved mission phase started on September 20, 2
- Decommissioned in January 2006.

What's wrong with this picture?

ENVISAT

Envisat

Envisat: This is the European Space Agency (ESA) Environmental Satellite (Envsat) a follow-on to the ERS-1&2 altimeter missions.

- Launched March 1, 2002.
- Envisat replaced the ERS-2 satellite. Tandem mission pla are not clear, but CU/CCAR has existing processing capabilities to use data as soon as available, as was done during the ERS-1&2 tandem missions in 1995-1996.
- Calibration and validation was completed and the satelli became operational in January 2003.
- Placed in a 35-day repeat orbit, but recently moved in to 30-day near repeat.
- Satellite abruptly stopped working in April 2012.

Current Satellite Altimetry Missions:

Operational Missions: Near real-time and archival data a available from the following ongoing missions:

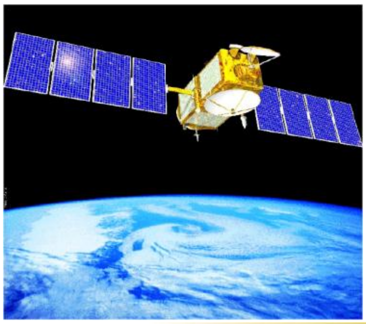
- Jason-1
- OSTM/Jason-2
- Cryosat

All of these data are currently being processed and arch at CU/CCAR.

http://eddy.colorado.edu/ccar/data_viewer/index

Data can also be acquired from NASA and CNES/AVISO.

Jason-1



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Jason-1

Jason-1: A joint U.S./French NASA/CNES satellite altimeter mission.

- Jason-1 is a T/P "follow-on" and was placed in the T/P 10-day repeat orbit.
- Launched on December 7, 2001.
- Initial 6-month calibration phase, in which Jason-1 was on orbit 60 seconds behind T/P, was followed by a maneuver of T/P into a "tandem" interleaved 10-day repeat orbit to increase mesoscale sampling. T/P was placed into "interleaved" orbit on September 20, 2002.
- After calibration of Jason-2/OSTM, Jason-1 was placed into in the "interleaved" orbit.
- Recently placed in a 513-day repeat Geodetic Orbit.

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OSTM/Jason-2

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OSTM/Jason-2

Ocean Surface Topography Mission (OSTM)/Jason-2: A joint U.S./French NASA/CNES satellite altimeter mission.

- OSTM/Jason-2 is a T/P "follow-on" mission and was placed in the T/P 10-day repeat orbit.
- Launched on June 20, 2008.
- Initial 6-month calibration phase, in which Jason-2 was in orbit 58 seconds behind Jason-1, was followed by a maneuver of Jason-1 into the "tandem" interleaved 10-day repeat orbit to increase mesoscale sampling on 14 Feb 2009.

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Ocean Altimeter Mission Summary

Satellite	Agency	Mission period	Measurement precision (cm)	Orbit accuracy (cm)	Repeat period (days)
Skylab	NASA	May 1973– February 1974	100	>1000	
GEOS-3 (Geodetic Earth Orbiting Satellite 3)	NASA	9 April 1975– December 1978	25	~500	
SEASAT	NASA	28 June 1978– October 1978	5	~100 (20)	17.05 3
Geosat (Geodetic Satellite)	U.S. Navy	12 March 1985– December 1989	4	30–50 (10–20)	~23.07 17.05
ERS-1 (Earth Remote Sensing Satellite 1)	ESA	17 July 1991– May 1996	3	8–15 (<5)	3,35,168
TOPEX/Poseidon (TOPography Experiment)	NASA/ CNES	10 August 1992– January 2006	1.7	2–3	9.9156
ERS-2 (Earth Remote Sensing Satellite 2)	ESA	21 Apr 1995– July 2011	3	7–8 (< 5)	35
GFO-1 (Geosat Follow-On 1)	U.S. Navy	10 February 1998– December 2008		10 (5)	17.05
JASON-1 (T/P Follow-On)	NASA/ CNES	7 December 2001– present	1.5	1 (goal)	9.9156
ENVISAT (ENVIronmental SATellite)	ESA	2 March 2002– 8 April 2012		1 (goal)	35
OSTM/Jason-2	NASA/ CNES	20 June 2008– present	1	1 (goal)	9.9156

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Exact Repeat Sampling

The ground track spacing at any latitude between individual ascending and descending passes is:

Spacing(degrees) = 360/N

where N is the number of orbital revolutions in the exact re

- **For T/P, Jason-1, OSTM/Jason-2 this spacing is 360/127 or about 2.83**
- **For Geosat/GFO this spacing is 360/244 or about 1.48°.**
- **For ERS/Envisat this spacing is 360/501 or about 0.72°.**

The spatial sampling is directly a function of the repeat period because t ground speed of sampling along track varies only slightly with altitud

The distance between ground tracks also varies with increasing latitude because of the circumference of lines of latitude decreases as a functi the cosine of the latitude.

Exact repeat orbits are used to reduce errors in referencing sea surface he measurement to a mean sea surface.

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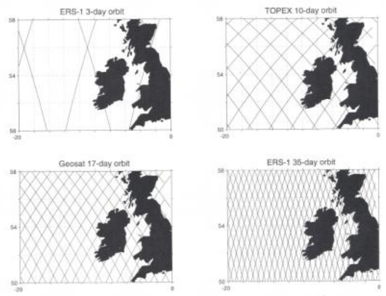
Example Repeat Ground Tracks



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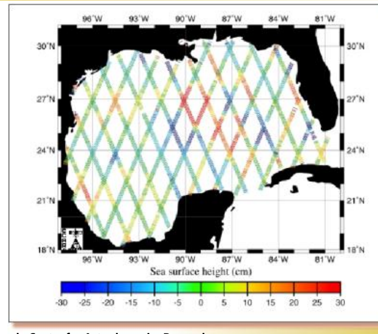
GFO Along-Track Mar 3 - 21, 2001



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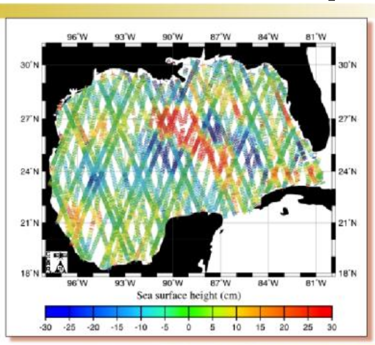
TOPEX/ERS-2/GFO Mar 1 2001 - Apr 1 2001:



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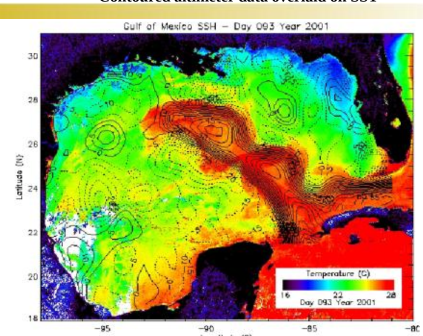
Sample Altimeter Data Product

Contoured altimeter data overlaid on SST



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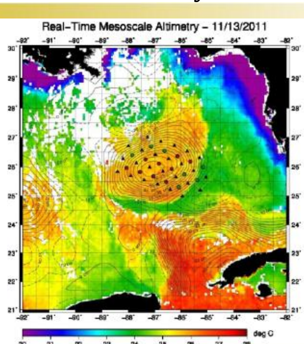
SSH Contour Overlay on SST Image



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Online References

CNES Radar Altimetry Toolbox
- http://www.altimetry.info/

WOCE/NASA Altimeter Algorithm Workshop
- http://oceanesip.jpl.nasa.gov/sealevel/wocealt87.pdf

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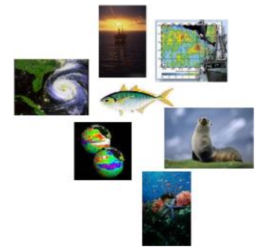
Satellite Altimetry Applications

GMSL



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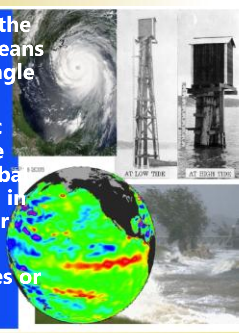
What is Global Mean Sea Level?

- "Global Mean Sea Level" is the the average height of the oceans over the entire globe at a single point in time.
- Mean Sea Level at a specific location in the ocean may be higher or lower than the global mean because of differences in ocean temperature and other effects.
- Does not include ocean tides or storm surge.



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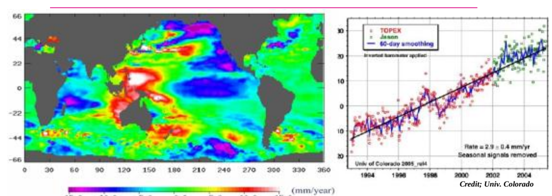
Global mean sea level rise

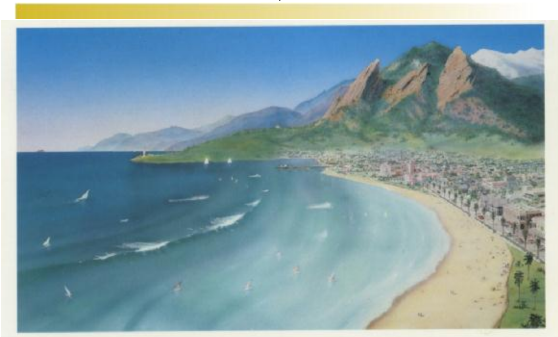


This global map of the trend of sea surface height (SSH) is estimated from the combined data from TOPEX/POSEIDON and Jason-1 from 1993 through 2004. Complex patterns of spatial variability are clearly shown. In the North Pacific the pattern of variability is similar to that of the Pacific Decadal Oscillation, in part caused by wind-driven long-period Rossby waves. The SSH trends in the North Atlantic are caused by a slowdown of the circulation of the subpolar gyre of the North Atlantic Ocean, leading to a decrease of the northward heat transport of the ocean.

In the South Atlantic and South Pacific, the marked striations are roughly consistent with the characteristics of Rossby wave fronts, reflecting a possible role of Rossby waves in the decadal change of ocean circulation. In the Southern Ocean the spatial pattern shows the characteristics of a wavenumber-2 Antarctic Circumpolar Wave, with two minima centered at longitudes of 30°-60° and 210°-240°. These waves travel eastward around Antarctica in 8 to 9 years.

The decadal trend of SSH in the Indian Ocean suggests that there is a decrease in the northward geostrophic flow of the upper ocean and hence a reduction of the ventilation of the tropical Indian Ocean by the cold water from the South Indian Ocean, responsible for a long-term warming of the upper Indian Ocean.

Boulder, Colorado



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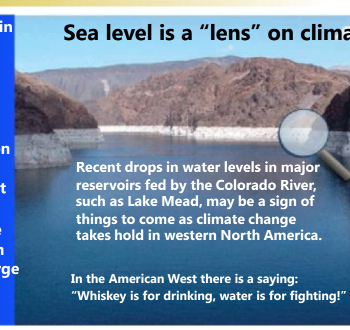
Why worry about sea level when you live over a mile high?

Signs of shifting climate in the western U.S. :
- rising temperatures
- earlier snowmelt
- northward-shifting winter storms
- increasing precipitation intensity and flooding
- record-setting drought
- plummeting Colorado River reservoir storage
- widespread vegetation mortality and more large wildfires

(Overpeck et al., 2010).



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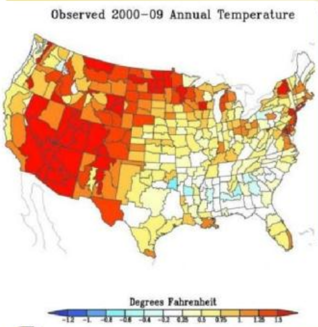
Western U.S. Warming



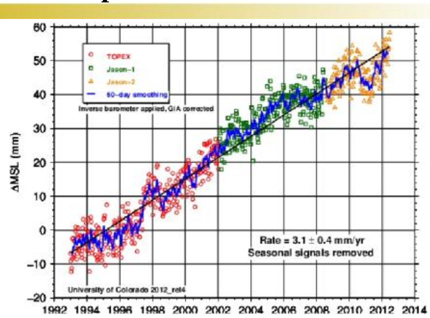
- Map of the observed difference between th average annual U.S. temperatures for this century (2000 to 2009 and those of the last century (1900 to 1999

(Credit: NOAA)

1-meter Sea Level Rise - Indonesia

Sea Level Rise of 1 Meter

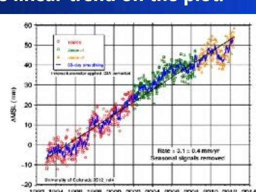
http://sealevel.colorado.edu



Matlab Exercises - Intro

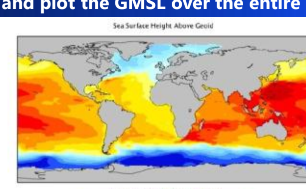
Exercise #1

1. Load "gmsl.mat" data from sealevel.colorado.edu websit
2. Plot GMSL versus time.
3. Calculate the linear trend in GMSL over the length of the record using MATLAB function "polyfit".
4. Overlay the linear trend on the plot.



Exercise #2

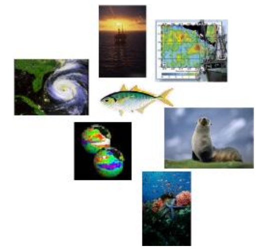
1. Load aviso_1deg_month.mat the AVISO Level 4 CMC "absolute dynamic height data" – the sea surface height above geoid.
2. Plot one of the maps and put the date in the title.
3. Calculate and plot the GMSL over the entire record.



Exercise #3

1. Load the aviso_1deg_month.mat
2. Calculate and plot the "mean dynamic topography" field
3. Calculate the sea surface height anomaly (SSHA) relative the MDT you calculated.
4. Calculate and plot the linear trend map.
5. Save the results in a matfile so you don't have to recalcul them.

Climate



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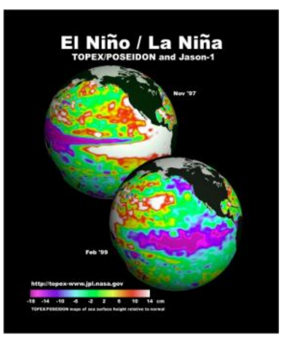
El Niño and La Niña forecasting & monitoring



Images produced by Dr. Victor Zlotnicki, Dr. Lee -Lueng Fu and Akiko Hayashi, of the Oceans Research Element at NASA's Jet Propulsion Laboratory.

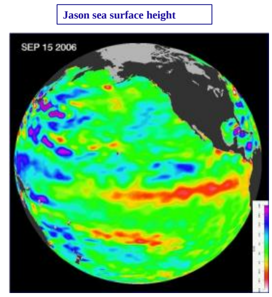
- TOPEX/Poseidon and Jason provide important extended time series monitoring of El Niño and La Niña events "
- NOAA's long term climate forecasts, based in part on ocean altimeter data, include flood control, agricultural strategy, water and energy use planning"
- Worldwide damage from the 1997-1998 El Niño probably exceeded $20 billion*. Reliable predictions could help minimize economic impacts."
- Media outlets use the data to explain weather and climate to the public "
- TOPEX/Poseidon and Jason data are recognizable to more than a billion people worldwide"

*D. Anderson, European Center for Medium-Range Weather Forecast

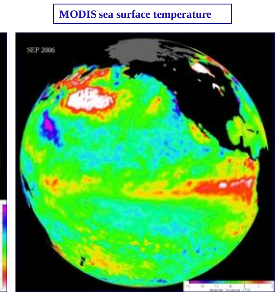
2006 El Niño

A mild El Niño formed in the eastern tropical Pacific in September 2006. Sea level anomalies of 15 cm from Jason-1 and temperature anomalies of 2 deg C from MODIS were observed.

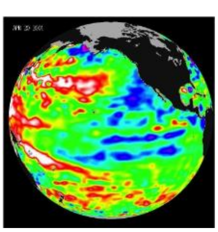
Jason sea surface height

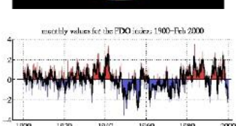


MODIS sea surface temperature



Pacific decadal oscillation (PDO)

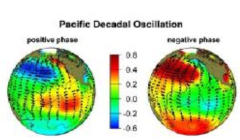




• In this April 2001 image, the Pacific Decadal Oscillation pattern had persisted for three years

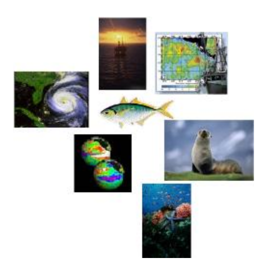
• Warm water (high sea levels in red and white)

• Cooler water (lower sea level in blue)



PDO images are courtesy of Nathan Mantua & Steven Hare, "
University of Washington, "
Units are degrees Celsius"

Hurricanes



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Hurricane Katrina Heats up in the Gulf

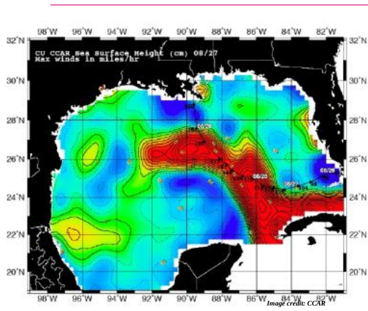


Image credit: CCAR

SSH highs at the center of the Loop Current reached 50-70cm in this image from August 27, 2005. Wind speeds of Hurricane Katrina, indicated in black along the path of the storm, reached highs of 173 mph.

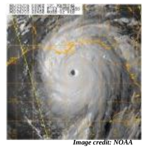
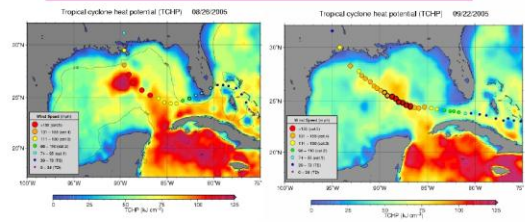


Image credit: NOAA

Maximum wind speeds of Hurricane Katrina increased dramatically as that storm passed over the warm waters of the Loop Current in the Gulf of Mexico in late August 2005. The storm evolved quickly from a category 3 to category 5 event in a matter of 9 hours as it drew heat from the Loop Current and a large warm core eddy evident in the sea surface height derived from merged TOPEX/Poseidon, Jason-1, GFO, and Envisat altimeter data processed by the Univ. of Colorado's CCAR group.

(R. Leben, G. Born)

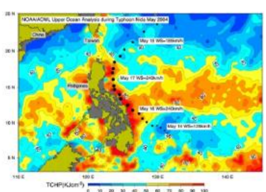
Packing Heat in the Gulf



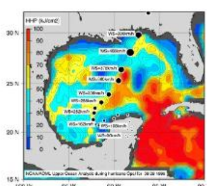
(G. Goni and J. Trinanes, NOAA/AOML)

Tropical Cyclone Heat Potential (TCHP) fields are derived from altimetry data for hurricanes Katrina (left) and Rita (right) in 2005. The path of each hurricane is indicated with circles, their size and color representing intensity (see legend), as the storms made their way across the Gulf of Mexico. Both hurricanes rapidly intensified to category 5 as they passed over the Loop Current and a warm ring, then diminished to category 4 and category 3, respectively, by the time they traveled over cooler waters outside the warm ring. NOAA's Atlantic Oceanographic and Meteorological Laboratory uses blended satellite altimetry data, including those from NASA's TOPEX/ Poseidon and Jason-1 missions, to estimate TCHP (a measure of the oceanic heat content from the sea surface to the depth of the 26°C isotherm) in the Gulf of Mexico in near-real time. High values of TCHP may be linked to hurricane intensification. These fields are critical to scientists and forecasters in better understanding the link between the ocean and the intensification of hurricanes. See http://www.aoml.noaa.gov/phod/cyclone/data/ for more information.

Hurricane monitoring and forecasting



Typhoon Nida intensified from category 2 to category 4 in 10 hours when it crossed a region of high TC Heat Potential.

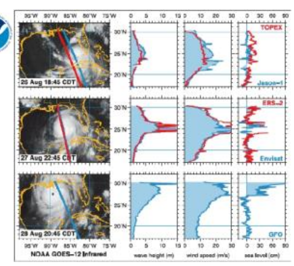


Hurricane Opal intensified from category 1 to category 4 while traveling over warm features in the Gulf of Mexico.

(Goni, others)

Ocean altimeter data is used for long term seasonal forecasts of the numbers and strengths of hurricanes expected in a given hurricane season, as well as short term forecasts of the strength of individual hurricanes. These images from the U.S. Naval Research Laboratory illustrate altimetry combined with sea surface temperature data and a two-layer model to show ocean heat potential. Ocean altimetry data is routinely used by the National Hurricane Center for improved hurricane intensity forecasts. This research demonstrates that storms and hurricanes may intensify when they travel over warm ocean features. Tropical Cyclone Heat Potential maps are derived from sea height anomaly and sea surface temperature fields. These fields are produced in near-real time in all seven basins where TCs occur and are distributed daily on the web (http://www.aoml.noaa.gov/phod/cyclone/data/).

Hurricane storm surge seen with altimetry



Credit: NOAA

The left column shows a comparison of GOES 12 infrared images and altimeter data collected by (top) Jason 1 and TOPEX, (middle) Envisat and ERS-2, and (bottom) GFO during near-coincident overflights of Hurricane Katrina on 26, 27, and 28 August 2005. The three columns on the right show the altimeter measurements of wave height, wind speed, and sea level anomaly, respectively, as a function of latitude along the altimeter tracks shown on the infrared images.

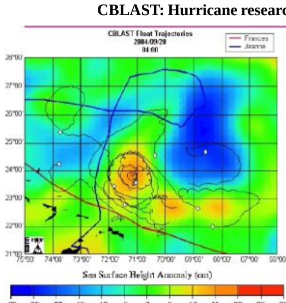
(R. Scharroo, W. Smith, J. Lillibridge)

For the first time, a hurricane storm surge has been observed by an ocean altimeter. The panels here depict significant wave height, wind speed and the residual sea level anomaly during Hurricane Katrina in late August 2005. The bottom rightmost panel from the Geosat Follow-On (GFO) altimeter shows sea level windward of the hurricane eye rising toward the shoreline and reaching 90 cm at the coast. This, apparently, is the wind driven storm surge.

Satellite altimeters play an important role in forecasting ocean conditions that can intensify a tropical storm and can observe the storm conditions at the sea surface. Altimeter data also indicate that Katrina intensified over areas of anomalously high dynamic topography rather than areas of unusually warm surface waters.

(Eos, Vol. 86, No. 40, 4 October 2005)

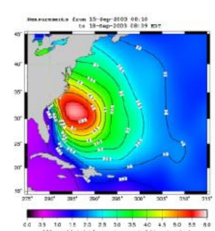
CBLAST: Hurricane research with altimetry"



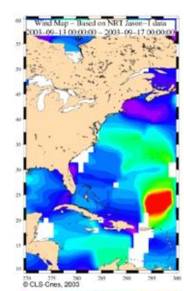
CBLAST float trajectories are shown overlaid on CCAR SSH anomaly. The white crosses show the final float positions on the date and time noted. Nine floats were deployed ahead of hurricane Frances in an effort to sample properties in the surface layer in near-real time. Sea surface height anomaly images were downloaded during the sampling period. Investigators were able to see the correspondence of their trajectories with sea surface elevation. *(Credits Scripps)*

Scripps Institution of Oceanography investigators have been using the CCAR near real-time altimetry to monitor ocean circulation features during deployment of CBLAST floats during the recent hurricane season. CBLAST floats are used to study the upper ocean mixed layer. The primary goal is to improve our understanding of air-sea surface flux processes in high winds, specifically in the complex conditions of tropical hurricanes where swell, sea spray and secondary boundary layer circulations play a role. The ultimate goal and prime motivation for this work is to parameterize these new observations and improve the accuracy of hurricane intensity prediction. http://www.sdcoos.ucsd.edu/data/floats2004/

Jason-1 Sees Isabel

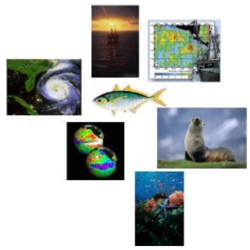


Jason significant wave height data during Hurricane Isabel, September 2003."



Wind data from Jason NRT data during Hurricane Isabel, September 2003."

Currents



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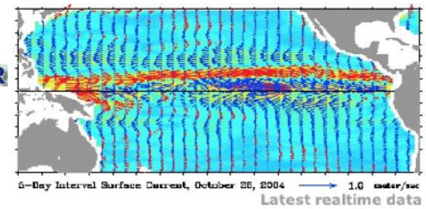
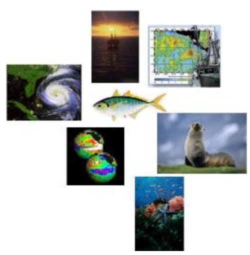
Ocean Surface Current Analysis - Real time (OSCAR)



(Cheney, Mitchum, Lagerloef, Bonjean, others)

Ocean Surface Current Analysis - Real time (OSCAR) is a pilot processing system and data center providing operational ocean surface velocity fields from satellite altimeter and vector wind data. Surface currents are computed from satellite altimeter and vector wind data using methods developed during the Topex/Poseidon mission. OSCAR is a transition to operational oceanographic applications using Jason altimeter data. The regional focus is the tropical Pacific, where the value for a variety of users is demonstrated, specifically for fisheries management and recruitment, monitoring debris drift, larvae drift, oil spills, fronts and eddies, as well as on-going large scale ENSO monitoring, NOAA's CoastWatch, and climate diagnostics and prediction programs. Other potential uses include search and rescue, naval and maritime operations.

Marine Industry



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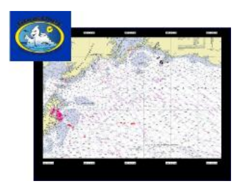
GhostNet Project: Derelict fish net detection

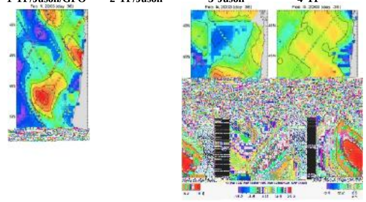


Flight track and debris sightings

Lost or abandoned fishing nets threaten fish, birds, sea turtles, and marine mammals in the open ocean. When entangled in coral reefs, these nets can also damage the reef environment. The GhostNet project (an industry, Government, and academia partnership) utilizes circulation models, drifting buoys, satellite imagery, and airborne surveys with remote sensing instruments in the detection of derelict nets at sea. These components were employed for the detection of marine debris during a 14-day aircraft survey of the Gulf of Alaska. Altimeter data from CCAR at the University of Colorado was among the suite of data used to locate convergent areas where nets were likely to collect. An aircraft survey with visible and IR cameras and a LIDAR instrument located debris in the targeted locations."

Tandem Mission Data; Mesoscale Circulation in the California Current

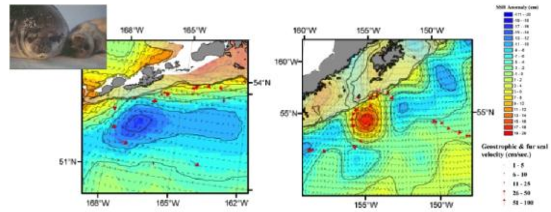
1-TP/Jason/GFO 2-TP/Jason 3-Jason 4-TP 5- CODAR



(Strub)

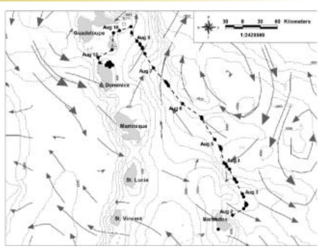
Altimeter data and coastal radar surface velocity fields collected at Oregon State University′s College of Oceanic and Atmospheric Sciences (COAS) quantify and explain changes in mesoscale circulation in the California Current off Oregon. Increased resolution from the Tandem Mission (panels 1 & 2) provides the ability to monitor the development of eddies off Oregon. Coverage by the individual altimeters (panels 3 and 4) distorts the SSH fields. These panels resolve anticyclonic eddies - one off Oregon between 43N and 44N and another between 41N and 42N. Overlaying the CODAR velocity field on a surface temperature field from the AVHRR sensor (panel 5) confirms the location of these eddies. The anticyclonic eddy between 41N and 42N draws warmer water from the south into its clockwise circulation, forming a sharp boundary between the warm water in the eddy and the cooler water surrounding the eddy.

Stellar sea lion research



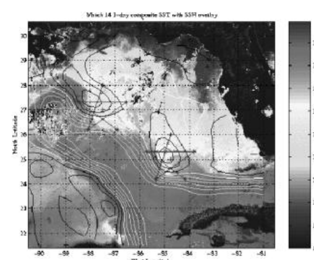
NOAAs National Marine Mammals Laboratory tracks Stellar sea lions in the North Pacific Ocean using blended altimeter data, including TOPEX/Poseidon and Jason OSDRs (SSH and current velocity vectors) from the University of Colorado′s CCAR group. The data indicates that the sea lions travel 100′s of miles across the North Pacific from shore to feed around the edges of ocean eddies. The figure on the left shows a mesoscale cold-core eddy near the Aleutian Islands, and the figure on the right indicates a cold-core eddy spun off the Alaska Stream. Each image is one tagged animal, with red vectors show heading and mean speed on a given day."

Satellite-tracked Sea Turtle migratory patterns



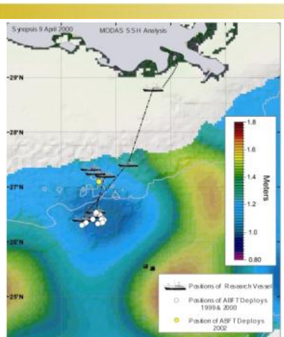
- Seaturtle.org uses CCAR near-real time mesoscale geostrophic velocity anomaly fields"
- Study aid on migratory routes of hawksbill turtles in relation to surface eddy fields in near real-time"
- Plan is to incorporate the data into graphical interfaces hosted on their web site"
- Shown is a migration route from Barbados to Dominica overlaid on coincident geostrophic velocity streamline vectors.

Cetacean surveys in the Gulf of Mexico



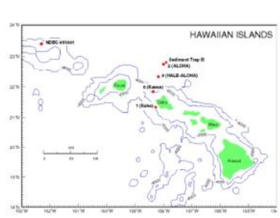
The MMS and the NOAA National Marine Fisheries Service (NMFS) conducted studies on sperm whales and deepwater acoustics in the Gulf of Mexico. The CCAR/TAMU cooperation provided NRT analyses of SST overlaid with SSH provided by CCAR using data from TP and ERS-2 altimeters. The example shown above gives suggested locations for XBT surveys of two cyclonic features in which a NOAA Ship searched for sperm whales, between March and April 2001. This application of remote sensing provided a "route map" for marine mammal biologists working aboard the vessel to locate cyclones (biological "oases") and anticyclones (biological "deserts")."

Tuna tagging

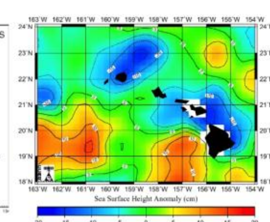


Researchers from the Monterrey Bay Aquarium tag tuna using Navy MODAS data assimilation and TP sea surface height analyses"

Sediment transport research"



The study region is centered on station 2 (Aloha).

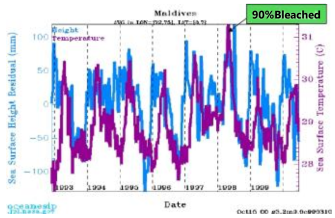


Sample SSH anomaly data product in HOTS study region.

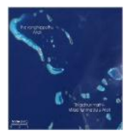
Erik Fields, a computing and network technologist working for Professor David Siegel at the University of California Santa Barbara, is using along track Jason data from the CCAR Along-track Data Host (http://www-ccar.colorado.edu/~realtime/global_realtime/alongtrack.html) to make Objective Analysis (OA) maps of sea surface height anomaly at sea. The OA maps will be used with hydrographic surveys and acoustic Doppler current profilers to predict the path of neutrally buoyant sediment traps deployed as part of the VERTIGO sediment transport experiment. This experiment is described at the web page: http://www.whoi.edu/science/MCG/vertigo. The cruise worked in the vicinity of the Hawaii Ocean Time-Series (HOTS) Aloha station for several weeks for this study.

Coral bleaching and climate change

- TOPEX/Poseidon and Jason altimeter sea level and"
  NOAA AVHRR sea surface temperature data"
  monitor and assess global coral reef environments."
  "
- High and low tropical sea levels and ocean"
  temperatures caused by the '97 to '98 El Niño/"
  La Niña "bleached" 25% of all coral reefs."
  "



Biodiversity - Coral ecosystems are our oceans "rainforests"



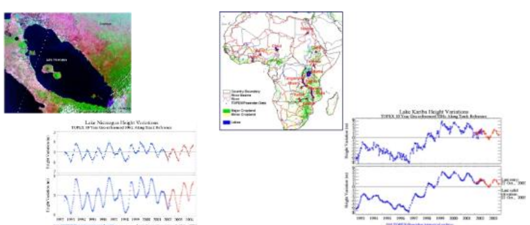
Maldive Islands, Central Indian Ocean, NASA Landsat 7 image

Land Operations

Colorado Center for Astrodynamics Research
University of Colorado at Boulder

International Workshop On Coastal Altimetry
November 16&17, 2011 Bogor, Indonesia

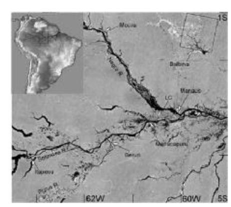
Near real-time measurement of inland waters"



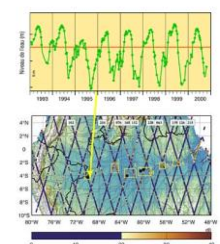
(Birkett, others)

Satellite radar altimeters are used to monitor the variation of surface water height of large inland water bodies. Using near-real time Jason data, a time series of surface water height variations is constructed. A semi-automated data ingestion/analysis system delivers time series products to a website for public access and to serve the USDA/FAS for its flood/drought investigations. This project is the first of its kind to utilize near-real time altimeter data over inland water in such an operational manner. Users: Primarily the US Dept. of Agriculture, Foreign Agriculture Service, PECAD division (Production Estimation and Crop Assessment Division), http://www.fas.usda.gov/pecad.

Amazon River level variation"



Radar mapping of the Amazon basin (credit D. Alsdorf, UCLA)

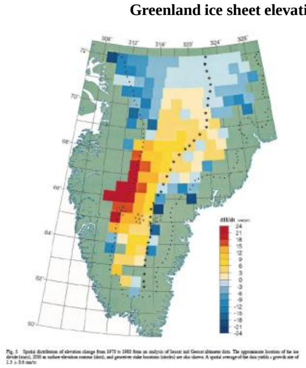


Water level variations since 1993 on the upper part of the Amazon, over the Topex/Poseidon ground track #102 (upper). Yellow and red indicate flooded regions, where the altimeter radar beam is well reflected (lower).
(Credits Legos)

(Cazanave, et al)

Satellite altimetry is used to measure river level variations in areas historically difficult to reach due to large distances, limited access, and low population density (and therefore limited infrastructure) as the Amazon river basin in Brazil.

Greenland ice sheet elevation changes"



Another example of land applications of ocean altimeter data is its use to measure surface elevation change on the southern Greenland ice sheet. In a study funded by NASA's Polar Program, the ESE, and JPL*, researchers found that the average elevation change above 2000 m elevation from 1978 to 1988 was not significant, contrary to reports that positive ice sheet growth rates suggest increased precipitation due to warmer polar climate.!

*Davis, C., Kluever, C., Haines, B., Perez, C., and Yoon, Y., Improved elevation-change measurement of the Southern Greenland Ice Sheet from satellite radar altimetry, IEEE transactions on Geoscience and Remote Sensing, Vol. 38, No. 3, May 2000!

Education

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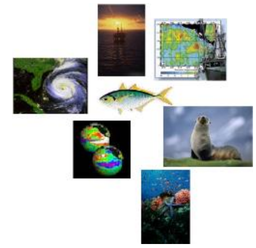
Altimetry in the classroom

In addition to the scientific and operational uses of the data, altimeter missions have provided product content and programs for both formal and informal educational settings. The educational community has embraced the unique concepts highlighted by altimeter missions like TOPEX/Poseidon and Jason-1 as a resource for teaching basic ocean awareness and ocean science to students from grade school through college and to all ages and backgrounds of the general public. The partnership between NASA/JPL and CNES/AVISO in collaboration with classrooms, schools, and informal education facilities has made it possible to widen the reach of activities and become a resource for science team member participation. Available products and activities include classroom visits, posters, CDs, web sites, online activities, literature, school programs, exhibit materials and more.

http://sealevel.jpl.nasa.gov

NRT Data Resources



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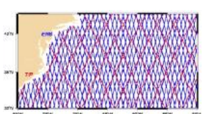
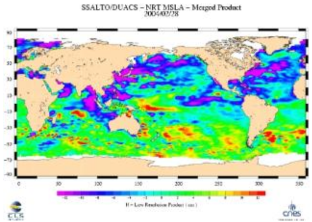
Ssalto/Duacs NRT operational oceanography



Ground tracks from TP & ERS



(Le Traon, Dibarboure et al.)

The CNES/CLS Ssalto/Duacs (Developing Use of Altimetry for Climate Studies) multi-altimeter processing system provides operational oceanography and climate forecasting centers with high quality near-real time altimeter data to improve climate simulations and, more specifically, seasonal climate forecasts. The NRT and historical products developed and refined with Duacs are widely used in the scientific community covering a large spectrum of operational oceanography needs, from mesoscale to climate applications. The data is used in particular for the Mercator project (http://www.mercator-ocean.fr), the French contribution to GODAE, using IGDR data from all available altimeters.

Other Applications

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Other users/applications

- Insurance Claims Adjustors
- Marine Architects
- Fisheries Managers
- Commercial Fishermen
- Search and Rescue
- Ocean Circulation Nowcasts/Forecasts/Hindcasts
- Forensic Oceanographers

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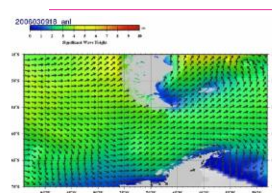
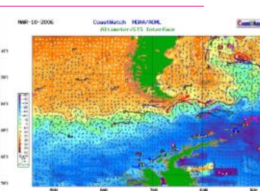
Volvo Ocean Race Support



Significant wave height and wind direction from NOAA WaveWatch III Model.



Geostrophic currents and drift trajectories

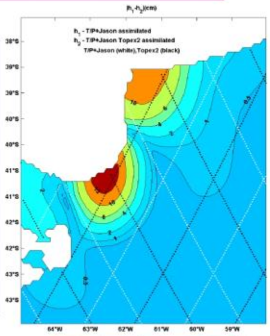
NOAA-AOML provided near-real time surface currents from altimetry, SSTs, and surface winds to 2006 Volvo Ocean Race teams. VOR, held every 4 years, covered 31,000 nautical miles in 9 legs, starting in Vigo, Spain in Nov. 2005 and finishing in Goteborg, Sweden in Jun. 2006. A dedicated AOML web page displayed data distributed to the sailboats (*http://www.aoml.noaa.gov/phod/VOR/*). Racing teams used this information to negotiate (un)favorable currents or winds during the race. This collaboration in turn provided feedback on data products, as well as atmospheric and sailboat drift data to NOAA from the teams, helping with validation efforts.

G.Goni, NOAA

Patagonian Coastal Shelf Tides

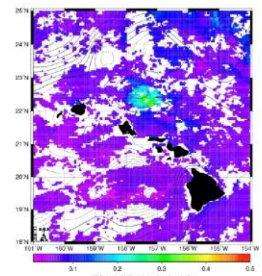
Tandem Mission data provides critical information required to resolve tides on the continental shelves, where the tidal range is generally larger and wavelengths are shorter than in the open ocean. In this example off the Patagonian shelf, complex shallow water tidal wave systems produce some of the world's largest tidal amplitudes.

The figure illustrates the impact of including the Tandem Mission data in a hydrodynamic assimilation of the M2 tides. The colors indicate the magnitude of the difference between a model based on assimilating T/P or Jason alone (ground tracks denoted by white lines), and a model assimilating the combined Tandem Mission dataset, including data along the interleaved tracks of the Tandem Mission (denoted by black lines).



G. Egbert, OSU

Ocean color & SSH view ocean eddies



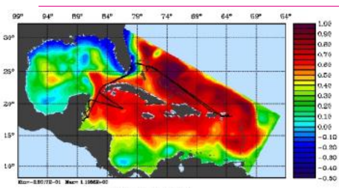
Hindcast SSH anomaly contours overlaid on chlorophyll concentration derived from 7-day composite of MODIS ocean color imagery north of the Hawaiian Islands. Image shows an anticyclonic eddy with high chlorophyll concentration. Graphic generated from CCAR online data visualization tool.

Allison Fong of the Univ. Hawaii at Manoa studies the spatial and temporal abundances of nitrogen-fixing bacteria that may play an important role in open-ocean biogeochemical cycling, using data from the HOT program[1]. In July 2005, the project sampled a region of enhanced chlorophyll north of Oahu. Satellite-derived ocean-color (MODIS), and sea surface height data (Topex/Poseidon) from the Univ. Colorado Center for Astrodynamics Research (CCAR) near-real time (NRT) web site indicated the feature was coincident with the decay of an anti-cyclonic eddy. The CCAR NRT and hind-cast data allowed tracking and sampling of the feature for both biogeochemical and biological parameters. The images were used to track the progression of this and similar eddies, providing compelling evidence suggesting increased productivity due to these mesoscale features.

[1]Hawaii Ocean Time-series (HOT) program

A. Fong, U. Hawaii

Intra-Americas Sea Trials



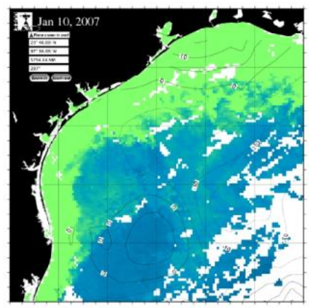
Sea surface height forecast for 21 Jan 2007 from the ROMS modeling system which is run in real-time on board the Royal Caribbean International vessel Explorer of the Seas. The black line shows the vessel's cruise path. See http://marine.rutgers.edu/po/ias/

University of California, Santa Cruz researchers are assimilating CCAR NRT sea surface height data into a Regional Ocean Modeling System (ROMS). ROMS is used for data assimilation and ocean prediction in the Intra-Americas Sea (IAS) with particular emphasis on the Caribbean Sea. In partnership with the University of Miami, NOAA, NSF and the Royal Caribbean Cruise Line, the cruise ship, *Explorer of the Seas*, has been equipped with oceanic and atmospheric sensors providing continuous observation along two cruise tracks that circumnavigate the Caribbean Sea once every two weeks. The objectives and scientific goals of the program are:

- To develop a real-time data assimilation and prediction system for the IAS based on a continuous upper ocean monitoring system;
- To demonstrate, as a proof of concept, the utility of a real-time data assimilation and prediction system in a real-time, sea-going environment, and to demonstrate the value of collecting routine ocean observations from specially equipped ocean vessels, in this case cruise liners;
- To develop much needed experience in both the assimilation of disparate ocean data and the prediction of ocean circulation using regional ocean models.

B. Powell, A. Moore, UC Santa Cruz

Hilton's Realtime Navigator

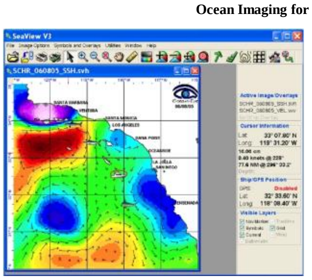


CCAR sea surface height contours and ocean color overlay hosted on the Realtime-Navigator website.

- Private company provides fishing charts and atlas
- Clients: Large game (marlin, tuna) fisherman
- Offshore Gulf of Mexico
- Altimeter and ocean color data maps provided via CCAR web site
- CCAR produces daily sea surface height (from Jason-1, GFO, and Envisat) and chlorophyll concentration maps (MODIS) for 10 regions in the Gulf and along the Atlantic Coast.

http://www.hiltonsoffshore.com/

Ocean Imaging for Fishing



A SeaView screen shot of a Southern California coastal image showing SSH anomaly and ocean current analyses updated 5-7 times per week. Symbols used to manage fishing strategy are also shown on the image.

Ocean Imaging Corporation (OI) has supplied ready-to-use oceanographic analysis products to commercial and recreational fishing fleets worldwide since 1983. OI provides 500-meter ocean color, plankton and altimeter derived sea surface height anomaly imagery (SSH) and ocean current products to clients worldwide. OI research investigated the correlation of albacore tuna catch data to SSH anomaly patterns and geostrophic near-surface flow. Significant correlations were found between albacore location and 'catchability' and the altimeter-derived data. Operational products are distributed to vessels at sea in near real time via the SeaView data retrieval and visualization system.

The data are pre-processed by CCAR and provided on a daily basis in an ASCII format listing the lat/long, SSH anomaly (cm) and the U/V components of geostrophic surface flow. The data are then processed at OI to generate SeaView-compatible SSH anomaly analyses and ocean current vector overlays. The data are posted to FTP and web servers within 30 minutes of retrieving the 'raw' data from CCAR allowing 24/7 access to the final products by OI customers via internet connection. The majority of end-users download the products directly to their onboard PC while out at sea either using cellular or satellite telephone.

http://www.oceani.com

Coastal-Altimetry-Comparison

Coastal Altimetry - Comparison

Presented by

Stefano Vignudelli

Consiglio Nazionale delle Ricerche, Italy

vignudelli@pi.ibf.cnr.it

With invaluable help (and material) from

COASTALT Project

S. Vignudelli, A. Scozzari (CNR, Italy)
P. Cipollini, C. Gommenginger, H. Snaith, S. Gleason, G. Quartly, L. West (NOCS, UK)
Henrique Coelho (Hidromod, Portugal)
J. Fernandes, L. Bastos, C. Lázaro, A. Nunes. N. Pires, I. Araujo (U Porto, Portugal)
M. Bos (CIIMAR, Portugal)
S. Barbosa (U Lisbona, Portugal)
Jesus Gómez-Enri (U Cádiz, Spain)
C. Martin-Puig, M. Caparrini, L. Moreno (Starlab, Spain)
P. Woodworth, J. Wolf (POL, UK)
S. Dinardo, B. M. Lucas (SERCo/ESRIN, Italy)
J. Benveniste (ESA/ESRIN, Italy)

particular thanks also go to the Coastal Altimetry Community

1

Calibration vs Validation

- Calibration is "quantitatively defining the system response to known controlled signal inputs" (http://calvalportal.ceos.org/)
  - Instrument Calibration is the responsibility of agency
  - Instrument gains/offsets, etc
  - It requires dedicated activities and teams with clear reporting lines and often mission/financial implications.
- Validation is the process of assessing by independent means the quality of the data products derived from the system outputs.
- CEOS WCGV is currently working to establish common approaches to validation through a specific GEO task titled "Developing data quality assurance strategy for GEOSS".
- Validation is acknowledged one key element of the processing chain to create a satellite-derived product suitable for a specific decision-making context .

2

The context

- GGEO and CEOS are working on Establishing an Operational Framework for Quality Assurance of Calibration and Validation Processes
- GEO and ESA, Workshop on Calibration & Validation Processes, 2-4 October 2007, Geneva, Switzerland, Minutes Version 1.1 04, 35 pp, November 2007.
- The general idea is to outline a set of commonly used methodologies / protocols / best practices necessary to allow data to have a quality-assured stamp
- Ground-based data used to validate satellite-derived products should be traceable to standards (i.e. stations designed according to specific recommendations and operating in specific conditions
- A better use of the existing in situ data measurement programmes is recommended in particular considering that in situ monitoring is an expensive activity.

3

Satellite altimetry VS Tide Gauges (I)

- Altimeter data are basically along-track;
- The SSH measurement along the altimeter ground track is spaced about every 7 km for standard products and be in theory even much less (at maximum 0.35 km) using experimental coastal products;
- It act as a tide gauge and the data set can be viewed as a set of tide gauges spaced every 7 km along the ground track;
- However, the SSH measurements are an average (across the effective footprint and along the track);
- In this way differ from a pointwise height of the sea surface at a given location provided by a traditional shore-based tide gauge;

4

The satellite altimetry system and tide gauge systems differ in several respects

- The temporal sampling of satellite altimeters is of order of 10 days or more while for tide gauges is of the order of minutes or less;
- The altimeter range (R) need to be corrected for various instrumental (both systematic and irregular) and geophysical effects (as seen previously) while the tide gauge measurement is immediately available;
- The corrected altimeter-derived SSH needs that the satellite's altitude is known with proper accuracy;
- The corrected altimeter-derived SSH is relative to a different reference (ellipsoid) while the tide gauge provide spot height of the sea surface referred to a fixed and permanent bench mark on the land where they are located;
- The SLA that can be derived knowing MSS is relative to a fixed time period;
- The ADT that can be derived knowing MDT is relative to a fixed time period;
- The use of different missions needs specific processing to intercalibrate the different altimeters due to the use of different orbits and correction sources.

5

Comparison of satellite altimetry and tide gauge observations (I)

- Tide gauges are usually housed in facilities nearby coast;
- On the other hand, the satellite altimeter can measure the height of the sea surface in open ocean where no tide gauges could be placed;
- The satellite altimeter and tide gauge can only overlap by chance;
- Therefore, tide gauges and satellite altimeters do not necessarily observe the same area;
- There are many things that perturb the height of the sea surface. Changes measured at a particular place are the result of a number of metocean processes (e.g., tides, currents, rainfall, atmospheric forcing, etc);
- But tide gauges could be also affected by other localized conditions (e.g., subsidence, bathymetry, sheltering). Subsidence can affect the fixed and permanent bench mark on the land, however, this is critical factors rather for climate than storm surge studies;
- On the opposite, sheltering and bathymetry may have effects on the space scales of agreement of tide gauge and altimeter data This fact has to be taken into account when comparing the two different datasets in order to understand the main signals.

6

Comparison of satellite altimetry and tide gauge observations (II)

- The SLA provided by the satellite altimetry system essentially contains information about changes in sea surface related to ocean currents and tides, dynamic response to atmospheric pressure and winds;
- It also retains errors from the satellite altimetry processing, e.g., mismodeled corrections for instrumental and geophysical effects (skewness, sea state bias, tropospheric corrections, ionospheric correction, etc.), differences between the true and the computed MSS at the altimeter location;
- Moreover, in the case of removal of tides and dynamic atmospheric signals (that is the case of oceanographic applications) it also includes differences between real tides and the tidal models as well as a possible residual difference due to the mismodeling of dynamic response to atmospheric pressure and winds.

7

Comparison of satellite altimetry and tide gauge observations (III)

- The method to compare satellite altimetry and tide gauge observations is not unique and depends on the region and goals of the analysis;
- In general, the comparison is usually done in a relative sense, i.e., taking into account the variation of the height of the sea surface over a fixed time period that in the case of the satellite altimeter is the period on which SLA (SSH variation around the MSS) is computed;
- SLA altimetric time series near to a tide gauge is usually constructed and then compared to the time series obtained from the tide gauge itself. The comparisons can be done using monthly, daily or near-simultaneous;
- In oceanographic and climate studies, the most important aspect concerns the selection of corrections (tides dynamic response to atmospheric pressure and winds) to be applied to both satellite altimetry and tide gauges;
- There is also an open debate if it is preferably to apply model corrections to both data sets to ensure consistency or to do not apply corrections to avoid errors of the models.

8

Comparison of satellite altimetry and tide gauge observations (IV)

- An important distinction between the satellite and tide gauge systems concerns tides.
- The altimeter sees the "geocentric tide" which consists of the "solid earth tide" and the "ocean tide" itself.
- On the other hand the tide gauge sees only the ocean tide because it is positioned on the land. The solid earth tide include the effects of the direct astronomical forcing (called "body tide") and the effect of the crustal loading due to ocean tide (called "loading tide").
- Both satellite altimetry and tide gauge systems see the "pole tide" which is due to variations in the Earth's rotation

9

Comparison of satellite altimetry and tide gauge observations - Case-study of storm surge applications

- With reference to the area of storm surge studies, there are no results coming from the bibliography that give us guidance on the optimal comparison methodology;
- Body tide and loading tide corrections have to be applied to ensure consistency. No pole tide correction has to be applied because both systems measure it;
- Storm surges are short-term phenomena, therefore, the near-simultaneous comparison method between satellite altimetry and tide gauge observations is the more appropriate.;
- The tide gauge observations have to be sub-sampled to the near time of the altimeter observation. The SLA altimetric time series if uncorrected for ocean tide and meteorological effects (wind and pressure) would be similar to those observed by a tide gauge;
- The comparison helps to identify problems on satellite data. It also provides a measure of how closely the altimeter-derived SLA estimates correspond to the in situ values. In the cases of the satellite altimeter flying over the storm at a given location, the SLA observed by the radar altimeter should detect the rise in the sea surface, which can be considerably larger than other background signals.

10

Accuracy of altimetric observations (I)

- We assume that the altimeter's measurements are sample values from probabilistic distributions;
- Then accuracy is the relationship between the mean of measurement distribution and its "true" value, whereas precision, also called reproducibility or repeatability, refers to the width of the distribution with respect to the mean;
- Different applications may have different requirements in terms of accuracy and/or precision. For instance, the estimation of the rate of global sea level rise from altimetry requires accuracy, but not necessarily precision given the huge numbers of measurements available to compute the mean rate;
- Instead, storm surge studies require both accuracy (to discriminate the anomalous raised SSH value with respect to the mean) and precision;
- Over the open ocean there is a long history of research quantifying uncertainty in altimeter data. The accuracy of a single SSH measurement will vary depending on the knowledge of the range, the orbit and the various corrections;
- The table reported in Chelton et al. [2001] provides an error budget for the T/P measurement system in open ocean. The single-pass overall accuracy of SSH measurements is approximately 4 cm. This figure is computed as root sum of squares of the various errors (from cal/val studies), including range noise (1.7 cm), orbit (2.5 cm), wet and dry troposphere (1.2 and 0.7 cm), ionosphere (0.5 cm), EM bias and skewness (2 cm and 1.2 cm). By averaging the T/P data over large spatial scales, the performance can be further enhanced.

11

Accuracy of altimetric observations (II)

- While the error is rather accurate over the open ocean, the error increases when approaching the coast. Only if the SSH variations are much higher than the total error budget they can be reliably exploited;
- The error budget in the coastal ocean was revisited at last 5th Coastal Altimetry Workshop in San Diego. Wet troposphere represents the major area of improvement (2 cm the error contribution to SSH until 20 km from the coast);
- The error budget for range is still not quantified. It varies according to the surface roughness and the selected satellite mission. More complex retracking algorithms can contribute to increase the quantity and quality of data collected;
- Comparisons to tide gauge observations also provide a measure of how closely the altimeter-derived sea level estimates correspond to this independent data set;
- This may give some measure of the expected accuracy for a local region. The altimetric ground points of closest approach to the tide gauges are usually selected to form comparison time series;
- Required accuracies are variable according to application or science investigation. RMS differences of 2-3 cm can be statistically achieved on seasonal and longer time scales (e.g., Mitchum, 1994; Verstrate and Park, 1995; Picaut et al., 1995; Youn et al., 2003). Larger RMS differences are observed at shorter scales due to a lower signal-to-noise ratio (Vignudelli et al. 2005). Climate investigations require an accuracy that ensures long-term trends and seasonal variations are readily discernible. For the storm surge studies a single SSH rather than a time series of SSH should be considered.

12

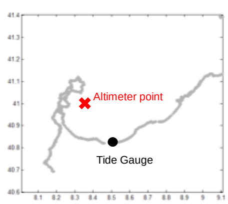
Some thoughts

- The validation exercise need to address **usage** and therefore need to have one or more categories of 'user' in mind
  - Example: NRT use /operational vs. Climatic study
- Many products and services are coming out – how do we position ourselves?
  - Users are confused
- Defining an error budget is tricky – the comparison w.r.t. tide gauges and other independent data will only provide a partial representation of errors. The 'end to end' error (satellite to product) is a different thing

Validation (what and how)

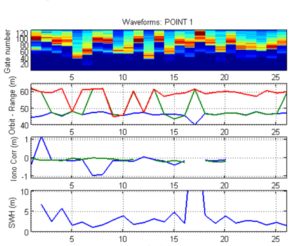
- Focus on SSH/SLA
- In situ data is our reference
- SSH/SLA along cycle for a specific ground point
- SSH/SLA along cycle stacked as 2-D plot - all ground points
- Measure of how closely the altimeter-derived sea level estimates correspond to the in situ values

- Assumes quality-checking and flagging done
- Loading tide gauge data (format: time, level) – latitude and longitude of station if available
- Selecting ground point(s)
- Generating SSH corrected
- Comparing altimeter-derived sea level estimates with corresponding in situ values

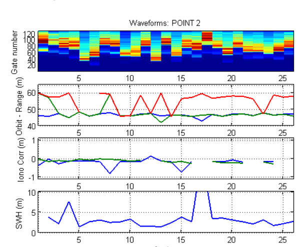


Track segment used for quality control of the COASTALT processor outputs

Descending pass 446
Segment: [35ºN – 37.5ºN]
Coastline at ~37.15ºN
Cycle 10 to 43
Processor version 2.0



Blue: COASTALT Brown retracker
Green: SGDR Ocean retracker
Red: SGDR Ice2 retracker



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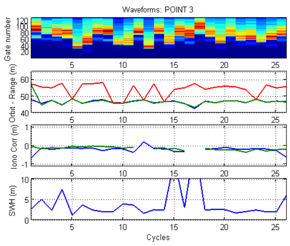

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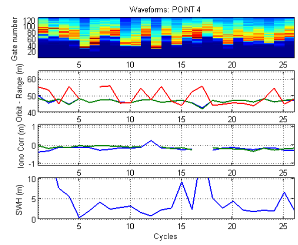

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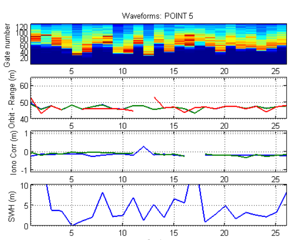

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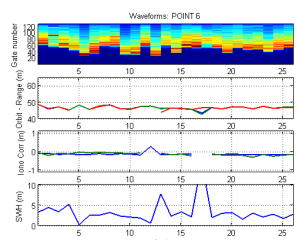

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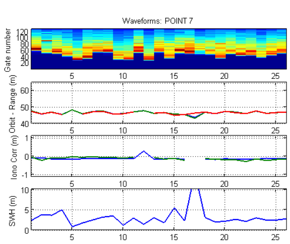
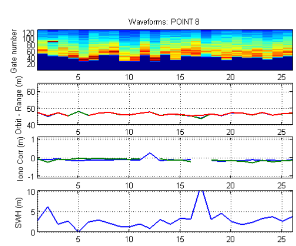
Green: SGDR Ocean retracker
Red: SGDR Ice2 retracker

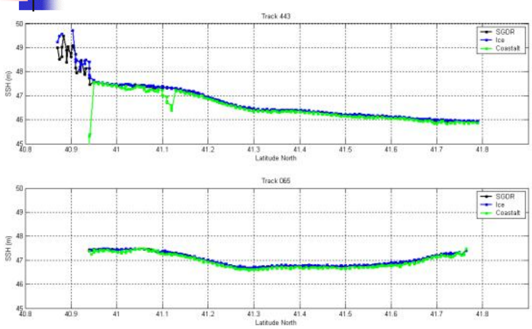


Blue: COASTALT Brown retracker
Green: SGDR Ocean retracker
Red: SGDR Ice2 retracker

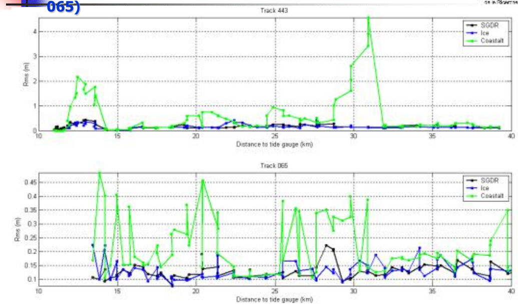


Blue: COASTALT Brown retracker
Green: SGDR Ocean retracker
Red: SGDR Ice2 retracker

Averaged SSH corrected for SGDR (black), Ice (bleu) and Brown (green) – Pass 887 (track 443) and pass 130 (track 065)



Rms of the difference between SSH corrected for SGDR (black), Ice (bleu) and Brown (green) and sea level observed at tide gauge – Pass 887 (track 443) and pass 130 (track 065)



Exercise I – Playing with in situ sea level time series

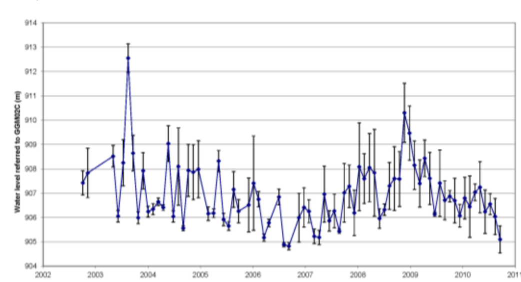
- A Matab file called "tssl.mat" contains hourly sea level data. The units of the sea-level elevation data are in millimeters. Time is expressed in year, month, day, hour
- Load this file onto your computer.
- Create a time series of yearly mean sea level for years with more than 4000 hourly observations and plot the results.
- Break the record into two parts (before and after 1965) and calculate the sea-level rise in each of those segments.

Exercise II – Playing with in situ sea level time series

- A Matab file called "tssl.mat" contains hourly sea level data. The units of the sea-level elevation data are in millimeters. Time is expressed in year, month, day, hour
- Load this file onto your computer.
- Select a record length of one year (e.g 2002 to 2003)
- Apply the lsq1.m code to the selected hourly record to estimate the frequency of the major tidal constituents.
- Do this by fitting a range of frequencies to the data (one at a time) with periods ranging from 11 to 26 hours with increments of 0.01 hours.
- Plot the result as amplitude as a function of period.

Lake Toba

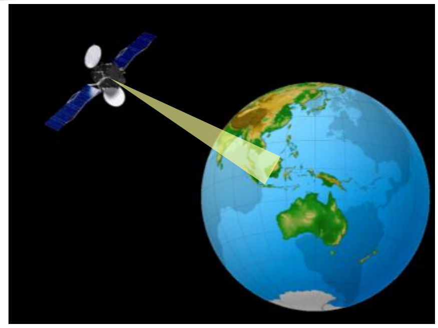
Lake Toba – Water Level variability (from Envisat track 0079)



Exercise III – comparing in situ and altimeter levels

- A Matab file called "altimeter.mat" contains times and level data. The units of the level data are in meters. Time is expressed in matlab format
- Open the Matlab script file called "LevelTruth_students.m"
- This file also contains in situ data (monthly min, monthly max, daily)
- Complete the script as follows:
  - Compare monthly in situ min/max with daily data
  - Compare monthly in situ min/max with altimeter data
  - Compare in situ daily with altimeter data
  - Plot correlation between in situ and altimeter data
  - Plot the difference between in situ daily and altimeter data and compute rms

Thank you for your attention!



Reading Geophysical Data Record Satelite Altimetry in Netcdf and Retracking

APN

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Reading Geophysical Data Record Satelite Altimetry in Netcdf and Retracking

Parluhutan Manurung
Dewangga

APN

Netcdf Format

- **Network Common Data Form** (Netcdf); a standard format for altimetry data
- Altimetri Data:
  - *Geophysical Data Record* (*GDR*): validated in 30 days.
  - Sensor Geophysical data record (SGDR); GDR, plus info and retracked data
  - *Interim Geophysical Data Record* (*IGDR*): not validated but it is *ground retracked IGDR* latency is 2-3 days
  - *Operational Sensor Data Record* (OSDR): unvalidated, using orbit from *DORIS navigator* and it display *ground retracking*. Latency 3-5 days
- Info : Jason GDR www.aviso.oceanobs.com

Jason-2/OSTM Level-2 Products

OSTM/JASON-2	OGDR Family	IGDR Family	GDR Family
Reduced 1Hz	OGDR-SSHA	IGDR-SSHA	GDR-SSHA
1Hz + 20Hz	OGDR OGDR-BUFR*	IGDR	GDR
1Hz + 20Hz + Waveforms		S-IGDR	S-GDR
Latency:	3-5 Hours	1-2 Days	~ 60 Days

Size & Complexity

Latency Accuracy

* All files in NetCDF format except OGDR-BUFR, which contains no 20-Hz data

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[redacted]

- Preparation
  1. Matlab Versi 2012 is equipped with toolbox
  2. Matlab versi < 2012 tool box can be download via: www.unidata.ucar.edu/netcdf/
  3. GDR/SGDR netcdf can be downloaded via:
     - www.aviso.oceanobs.com
     - podaac.jpl.nasa.gov

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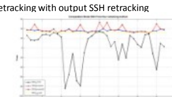
Program Descripton

- Reselecase Project provide 3 Sub-programs developped during the project:

1. nc_view : to view and display 2D dan 3D.

2D and 3D North of Java Island pass 140 cycle 92

2. nc_retracking : for retracking with output SSH retracking



Retracked SSH using OCOG, Threshold and Threshold improvment dan SSH on board

3. nc_retracking_writing : to input data from matlab program to netcdf.

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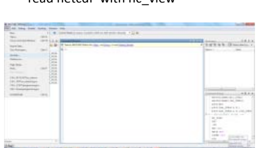
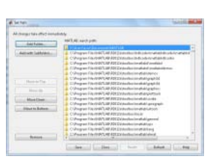
Using the Program

- 3.1 . Open Matlab
- 3.2. Set Path folder in matlab
  - set path to netcdf data
  - read netcdf with nc_view





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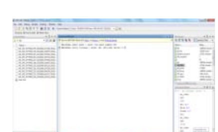
Using nc_view

- Run program nc_view
  nc_view to display waveforms 20hz in 2D and3D.
- Run script and set path to altimetry data
  Example:
  x:\DATA SGDR dan GDR JASON 2 2011\New folder\92
  The following is the dsplay



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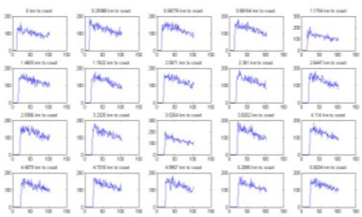
Running script

- The script display 2D



Display of waveforms 20hz from 0 to 6 km from coastline

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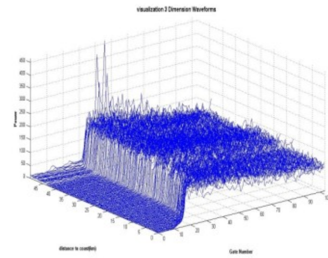
Visualisation of 3D waveforms



Display of 3D waveforms 20hz from 0 to 50 km from coastline

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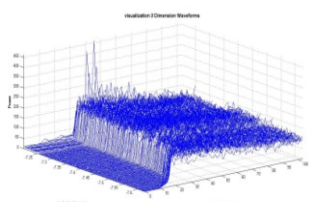
Visualisation of 3D waveforms



Display of 3D waveforms 20hz from 0 to 50 km from coastline

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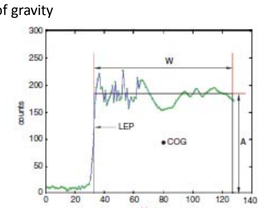
Run script nc_retracking

- Script provides 3 options: OCOG, retracking threshold, retracking threshold and improved threshold
- Retracking the offset centre of gravity (OCOG) retracking algorithm to computed centre of gravity



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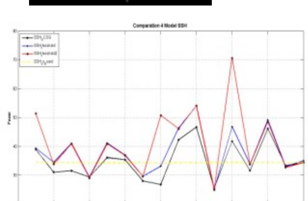
SSH Comparison



Result compariosn of SSH using OCOG,retracking threshold,retracking threshold improvment and GDR SSH (onboard of data)

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Exporting Matlab data to netcdf

- nc_retracking_writing process is similar to nc_retracking
- nc_retracking_writing is aimed at converting the retracked data back to netcdf
- The retracked data in netcdf format can then be used with BRAT for further dsplay and processing

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DATA PROCESSING SATELLITE ALTIMETRY USING BRAT

RESELECASEA

COASTAL ALTIMETRY IN SOUTH EAST ASIA

DATA PROCESSING SATELLITE ALTIMETRY USING BRAT (*Basic Radar Altimetry Toolbox*) SOFTWARE

BRAT
BASIC RADAR ALTIMETRY TOOLBOX

Introduction

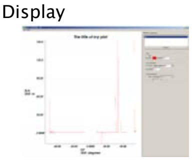
- *Basic Radar Altimetry Toolbox* (BRAT) is a collection of tools and tutorial documents designed to facilitate the processing of radar altimetry data (BRAT *User Manual,* 2009)

- The main BRAT functions are:
  - Data import and Quick look
  - Data export
  - Statistics
  - Combinations
  - Resampling
  - Data Editing
  - Exchange
  - Data Visualisation

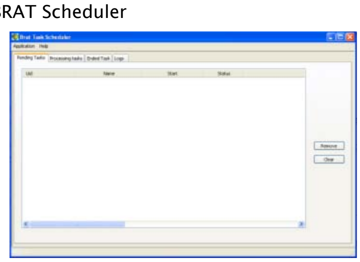
- BRAT Consists of the following parts:
  - BRAT Library : The core part, provide data ingestion functionality for each of supported data products.
  - BRAT Console Applications: contains a number of console applications that are to be run from the command-line
  - BRAT GUI Applications : in order to provide a truly pleasant, user-friendly interface to the BRAT functionality, BRAT also contains three applications that present a Graphical User Interface (GUI).

- BRAT GUI Applications consists of:
  - BRAT GUI

  - BRAT Display

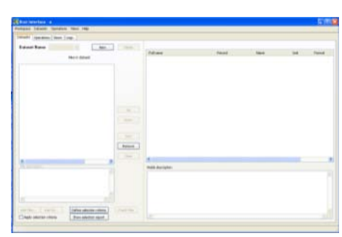


- BRAT Scheduler



BRAT GUI

- BRAT GUI consists of:
  - Workspace menu
  - Data set tab
  - Operation tab
  - Views tab
  - Log tab



BRAT Installation

- BRAT binaries are available as single-file installer packages for the three major operating systems: Windows, Linux, and Mac OS X.
- These standalone installers can be download from the BRAT Website
  http://earth.esa.int/BRAT/html/data/toolbox_en.html

BRAT Applications:

- Geodesy and Geophysics: Shapes and sizes of The Earth, Gravity Anomaly (ERS-1 dan Geosat).
- Ocean : Sea Surface Height, Sea Level Anomalie (Jason-1 dan 2, ERS-2, GFO).
- Ice : Glacier Topography (ERS 1 dan 2, Envisat)
- Climate: El Nino (TOPEX/Poseidon).
- Athmosphere, Wind dan Wave: Measuring Sea Wave Height, Wind Speed(Jason-1, ERS-2).
- Hidrology and Land: Monitoring ground vegetations, Lake, River (TOPEX/Poseidon, Jason-1).
- Coastal : Tidal (TOPEX/Poseidon, Jason-1).

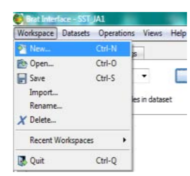
Starting with BRAT GUI

- Using BRAT GUI is basically a 4-step process
  1. Workspace
  2. Dataset(s)
  3. Operation(s)
  4. View(s)

Note : BRAT GUI is organised in four tabs (Datasets, Operations, Views and Logs) and a 'Workspace' menu. Each tab corresponds to a different function, and to a different step in the process, so you'll have to use all of them one after the other.

Workspace

parent of a whole project that is used to process the data satellite altimetry

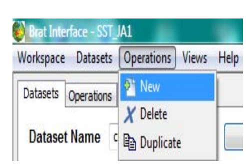


Dataset(s)

a facility in the BRAT software that is used to inserts, adds, and view the properties of satellite altimetry data.

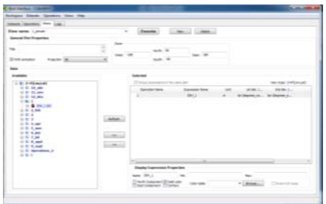
Operation(s)

a facility in the BRAT software that is used to insert, add, process and store the result of processes satellite altimetry data.



View(s)

a facility in the BRAT software that is used to visualize the result of processing satellite altimetry data(s).



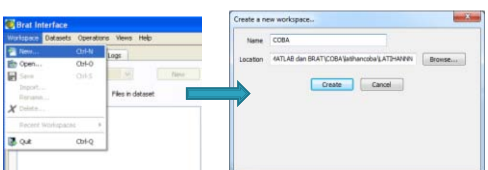
Examples using BRAT for SSH

- In Altimetry, BRAT can process some parameter, examples : Sea Surface Height (SSH) and SLA (Sea Level Anomaly)
- Data : SGDR Jason-2
- Year: 2011
- Month: Januari-Maret
- Pass Number: 51,64,127,140,203,229,242 (Java Island)
- Cycle : 92-128

Processing Stage of SSH-BRAT

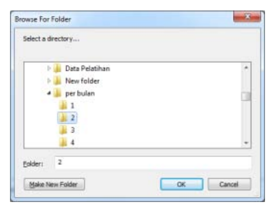
1. Create new Workspace:

Workspace-new-change the name of workspace-choose the workspace folder location-create



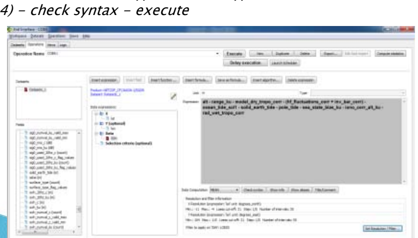
2. Create new Dataset:

Click new - changed the name of dataset - click add directory or file - ok



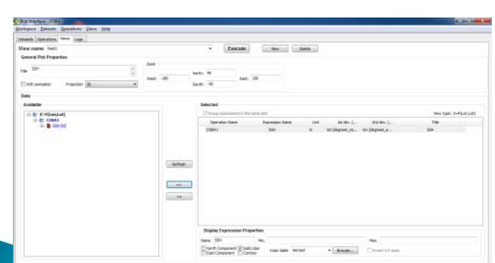
3. Data Operation:

Click new - changed the name of the operation- clickfile dataset - data expressions - for varibel X (latitude) - Y (longitude) - Data - Set Resolution/Filter - Insert Expression - changed the name of the expression - insert formula - Choose SSH_Jason2-unchecklist "As alias" - Selection criteria-type (surface_type == 0) && is_bounded(-11,lat,-4) - check syntax - execute

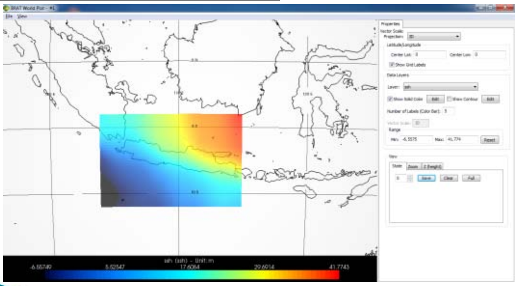


4. View(s):

changed the name of the view - give the title for the result - avialable - Choose the Data that you want to use (ssh (m)) - add selected file to the "data formula" - execute

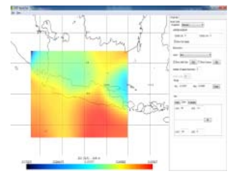


SSH Visualization

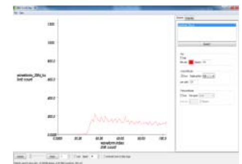


Sea Surface Height (SSH) Around Java Island on Januari-Maret 2011 by Jason-2 Satellite Altimetry Data

Other Parameters Visualization using BRAT software



Sea Level Anomaly (SLA)



Waveform

Thank you...

Understanding CSEOFs

1. Understanding CSEOF

UNDERSTANDING CSEOFs

Dr. Benjamin Hamlington
Dr. Robert Leben

University of Colorado

Colorado Center for Astrodynamics Research
University of Colorado at Boulder

International Workshop On Coastal Altimetry
November 12-13, 2012, Bogor, Indonesia

Signals and Noise

- "The large amounts of data that are usually studied in climate exhibit a complex mixture of **signal and noise**. The purpose of statistical analysis is to disentangle this mixture to find the needle (the signal) in the haystack (the noise).
- The allegory with the needle in the haystack has two sides. First, it is difficult to find the needle in the haystack. Second, after it has been found, it should be easily recognizable as a needle simply by looking at it.
- To identify a climatic signal, advanced techniques may be required, but after its identification, the signal usually may be described by means of simple techniques such as composites, correlations, etc."

- Von Storch & Frankinoul (1998)

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EOFs

- **A fundamental characteristic of ocean data is the high dimension of the variables representing the state of the system at any given time. Often it is advantageous to perform a subspace decomposition to split the full phase space into two subspaces, i.e. the signal subspace and the noise subspace.**
- **One such statistical method is Empirical Orthogonal Functions.**
- **The roots of this method arose in the early 1900's as objective tests of intelligence were being developed. Although, later on several other fields independently developed the statistical techniques.**

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Consider the Data Matrix - F

Time ⟶

$$\mathbf{F} = \begin{bmatrix} F_1(1) & F_1(2) & \dots & F_1(N) \\ F_2(1) & F_2(2) & \dots & F_2(N) \\ \dots & \dots & \dots & \dots \\ F_M(1) & F_M(2) & \dots & F_M(N) \end{bmatrix} \downarrow \text{Location}$$

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Computing EOFs with SVD

Basic Algorithm

1. Put the data into a matrix, **F**, so that each row is a time series of the data at a point and the columns are variables or spatial data at specific times.
2. Remove the mean from each row so that there is no time mean signal in the data set.
3. Use **SVD** to decompose the data into three matrices:

F = U*S*V^T

where:

U = the left eigenvectors
V^T = the right eigenvectors
S = singular values

In this example:

U = the **EOFs** (spatial patterns or **Loading Vectors** (LVs)
S*V^T = the EOF time series or **Principal Components** (PCs).

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Some Nomenclature

There is no consistent terminology for EOF and PC analyses. Here are some terms commonly used.

- **EOF spatial patterns** may be called the loading vectors, principal component loading patterns, principal vectors, or principal loadings.
- The **EOF time series** may be called eigenvector time series, expansion coefficient time series, expansion coefficients, time coefficients, time components, principal component time series, scores, principal component scores, principal component amplitudes, or principal components.

We will call the EOFs spatial patterns the **loading vectors (LVs)** and the EOF time series the **principal components (PCs)**.

Note that switching the association of time and space indices in the data matrix, F, does not make a difference in the SVD decomposition. The EOFs are now associated with V^T and the PCs with U*S.

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Percent of Variance Explained

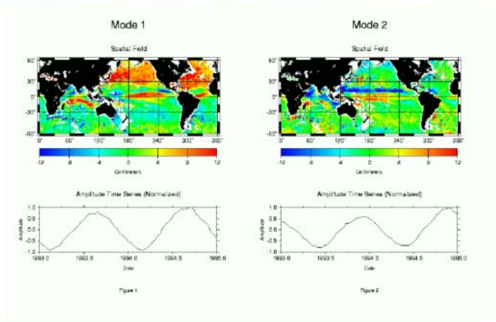
The **eigenvalues** of the expansion are equal to the **square of the singular values**. To compute the percent of variance explained by a given EOF use the following formula:

% variance of component i = S_i^2 / trace(SS^T)

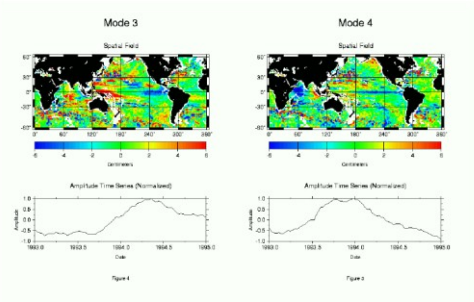
or

% variance of all components = diag($S*S^T$)/ trace(SS^T)

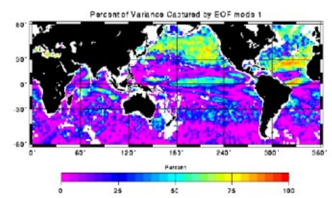
Global SSH EOF LVs and PCs - Modes 1 & 2



Global SSH EOF LVs and PCs - Modes 3 & 4



Spatial Map of Percent Variance EOF 1



Basis Functions: CSEOF vs. EOFs

Most SST and sea level reconstructions have relied on EOFs as basis functions.

- Techniques like EOF analysis do not accommodate time-dependent spatial patterns and, therefore, enforce stationarity.
- EOFs are prone to mode mixing, particularly with regards to the annual signal.

To address this and other problems, Kim et al. (1996; 2001) introduced the concept of cyclostationary empirical orthogonal function (CSEOF) analysis.

- CSEOF analysis has been shown to extract the annual and ENSO signals from the satellite altimetry data (Hamlington et al., 2010; 2011).
- By using CSEOFs in place of EOFs, an alternative and improved reconstruction could be computed.

Basis Functions: CSEOF vs. EOFs

- In traditional EOF analysis, space-time data are represented in terms of **loading vectors** (LVs) and their **principal components** (PC).

$$T(r,t) = \sum_n P_n(t) LV_n(r)$$

  - LVs represent spatial patterns of variability, PC time series represent temporal evolution of these patterns.
  - The underlying assumption in EOF analysis is the stationarity of the analyzed data; the covariance function does not vary in time.
  - This is rarely justifiable for geophysical and climate variables → physical inferences based on EOFs can be misleading and potentially erroneous.
- Many climate signals show the presence of seemingly random fluctuations in addition to a deterministic component like the annual cycle.
  - Such signals change in time with well-defined periods in addition to fluctuating at longer timescales and have a time-dependent covariance function → periodically correlated or cyclostationary.

Cyclostationary Empirical Orthogonal Functions

- In contrast to EOFs, CSEOFs have time-dependent LVs.

$$T(r,t) = \sum_n P_n(t) LV_n(r,t)$$

$$LV_n(r,t) = LV_n(r,t+d)$$

  - The temporal evolution of the spatial pattern of the CSEOF LVs is constrained to be periodic with a "nested period".
  - When studying the annual cycle, for example, the LVs would represent the one-year nested periodicity, while the PC time series would describe the change in amplitude of the annual cycle over time.
  - Each CSEOF mode is composed of 52 LVs and one PC time series when using, for example, weekly data (AVISO) and a one-year nested period.

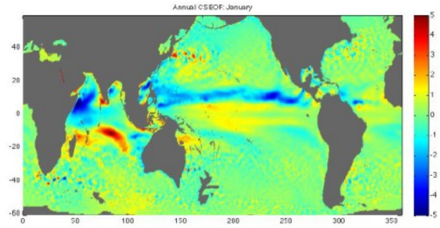
CSEOFs: Nested Period

- Nested period must be determined *a priori*, based on a physical understanding of the physical process to be investigated.
  - In many cases, there is an obvious choice for the nested period.
  - For studying the annual cycle, a one year nested period would be used.
  - Similarly, for datasets dominated by ENSO variability, a one year nested period can again be used.
  - Stationarity, and hence EOFs, is a special case of CSEOFs, in which the nested period is equal to one.
  - As the period of a signal becomes much larger than the selected nested period, the loading vectors for that mode also approach a single time-independent pattern.

CSEOF Analysis: Satellite Altimetry

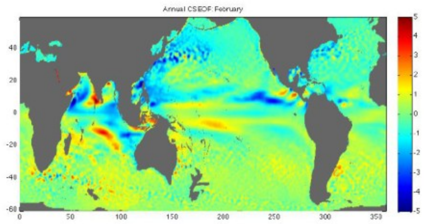
- Details on computing CSEOFs can be found in Kim and North (1997).
  - Essentially involves computing EOFs in Fourier space.
  - Dr. Kwang-Yul Kim originally provided FORTRAN codes for the computation of CSEOFs.
  - New codes for computing CSEOFs have been written in MATLAB.
- CSEOF basis functions were computed from ¼° resolution multiple altimeter AVISO dataset spanning 1993 to 2009.
  - Time series at each gridpoint was individually detrended using a least squares fit.
    - No other filtering performed on the data.
  - Nested period of one-year was used to distinguish variability associated with the annual cycle and ENSO signal.
  - 19 leading modes describe 95% of the variability in the original dataset.
  - Since AVISO data has weekly temporal resolution, each CSEOF mode has 52 LVs and 1 PC time series spanning the period from 1993 to 2009.

CSEOF : Annual Signal

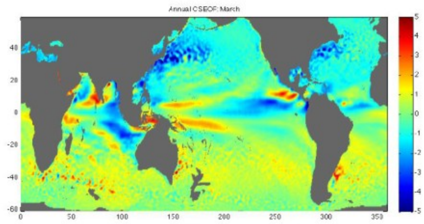


- Performing a CSEOF decomposition of AVISO satellite altimetry data with a nested period of one year gives the annual cycle as the first mode and ENSO as the second mode.

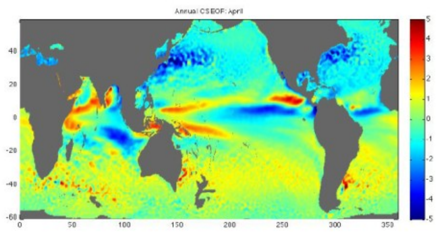
CSEOF: Annual Signal



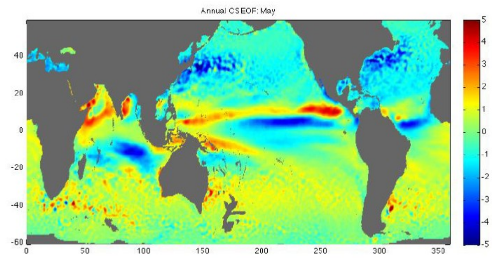
CSEOF: Annual Signal



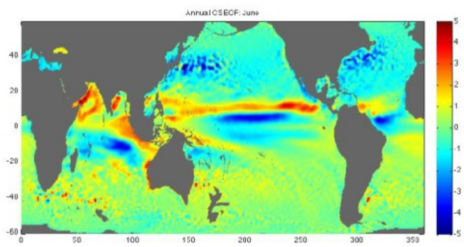
CSEOF: Annual Signal



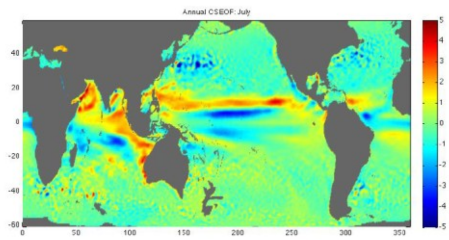
CSEOF: Annual Signal



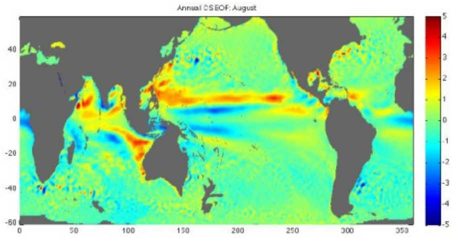
CSEOF: Annual Signal



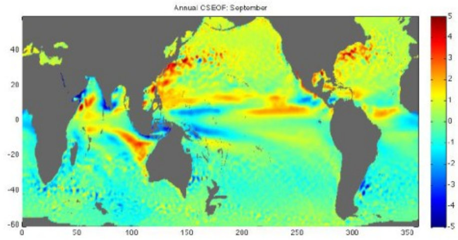
CSEOF: Annual Signal



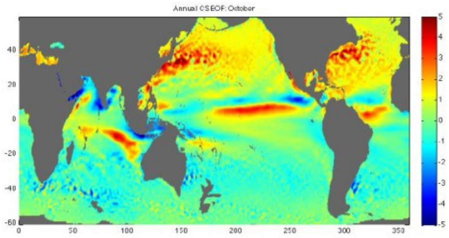
CSEOF: Annual Signal



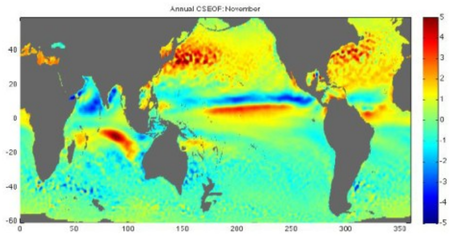
CSEOF: Annual Signal



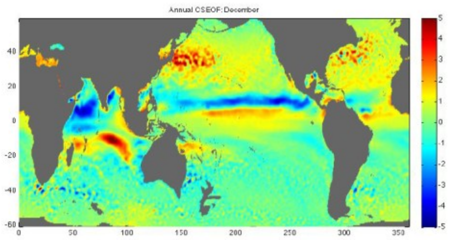
CSEOF: Annual Signal



CSEOF: Annual Signal

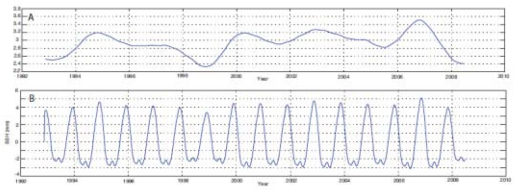


CSEOF: Annual Signal



CSEOF: Annual Signal

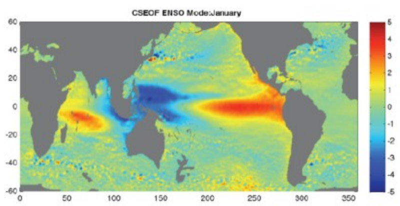
- The amplitude modulation of the annual cycle is represented by the PC time series (Fig. A). By combining the LVs and PC time series, we can compute the contribution of the annual cycle to GMSL (Fig. B).



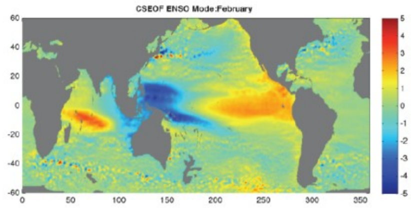
CSEOF Analysis: ENSO

- ENSO is another example of a signal that fluctuates in time at longer timescales than its well-defined period.
  - Includes biennial and lower frequency components.
  - CSEOF analysis has been shown to extract the ENSO using a one-year nested period. (Jin et al., 1996; Kim and Chung, 2001; Trenberth et al., 2005; Hamlington et al., 2010; Hamlington et al., 2011).
  - Second mode from satellite altimetry describes the Eastern Pacific El Niño, while the third mode represents the Central Pacific El Niño.

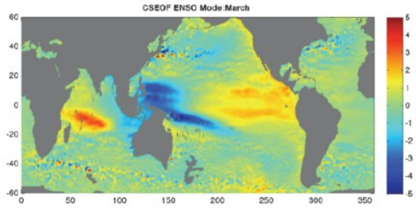
CSEOF Analysis: ENSO



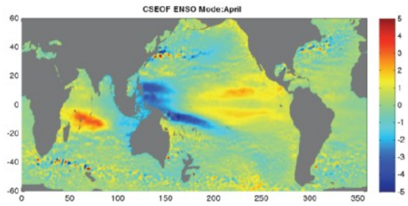
CSEOF Analysis: ENSO



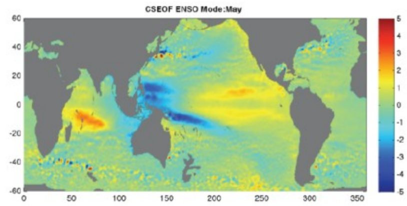
CSEOF Analysis: ENSO



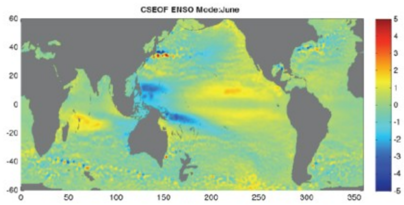
CSEOF Analysis: ENSO



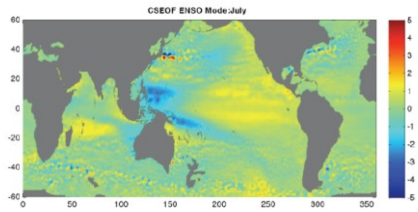
CSEOF Analysis: ENSO



CSEOF Analysis: ENSO



CSEOF Analysis: ENSO



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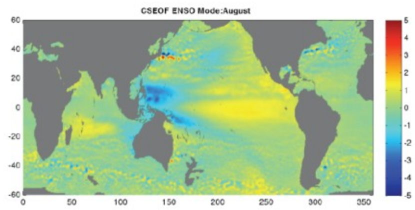

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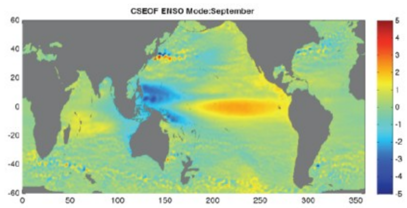

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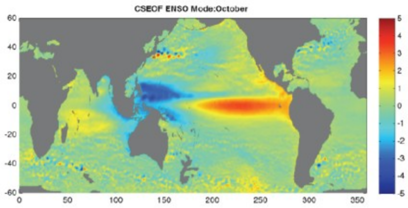

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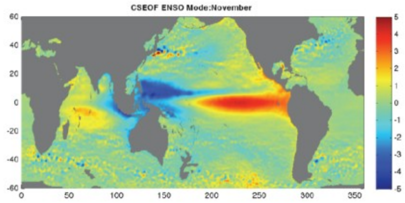

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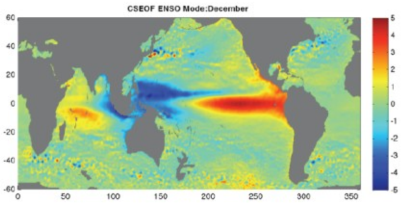
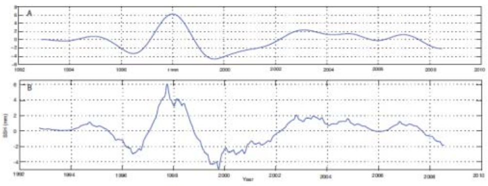
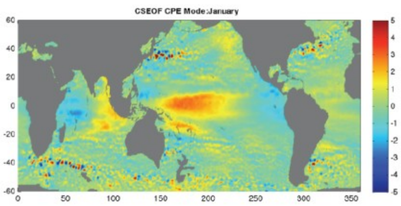


CSEOF Analysis: ENSO

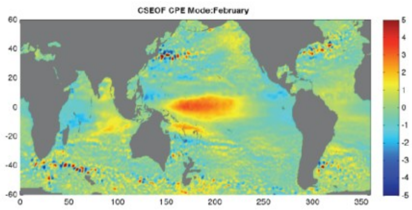
- The amplitude modulation of ENSO is represented by the PC time series (Fig. A). By combining the LVs and PC time series, we can compute the contribution of ENSO to GMSL (Fig. B). Correlation between the Multivariate ENSO Index (MEI) and PC time series is 0.95.



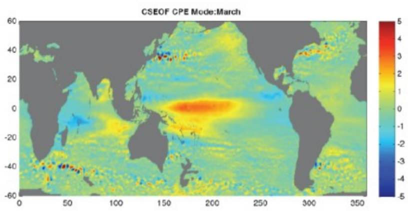
CSEOF Analysis: CP ENSO



CSEOF Analysis: CP ENSO



CSEOF Analysis: CP ENSO



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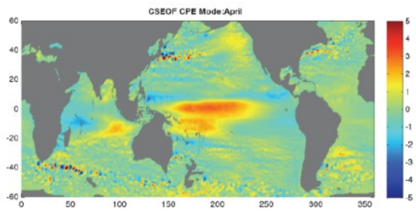
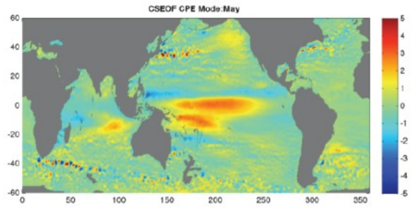


CSEOF Analysis: CP ENSO



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November 12-13, 2012, Bogor, Indonesia

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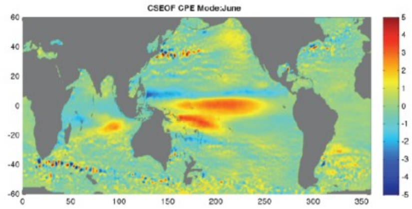

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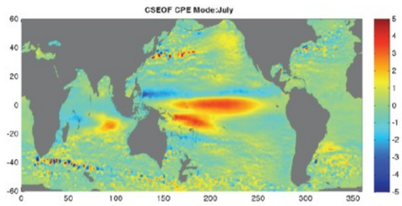

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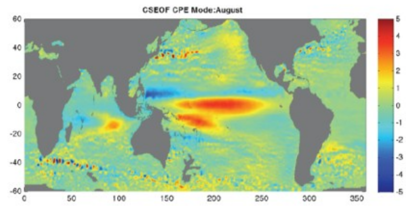

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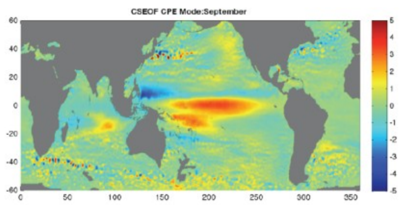

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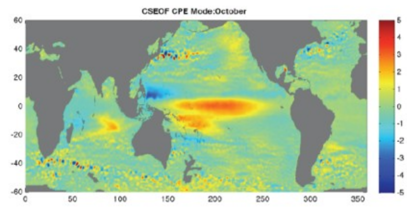

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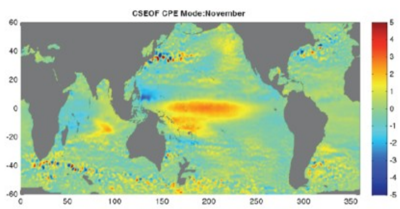

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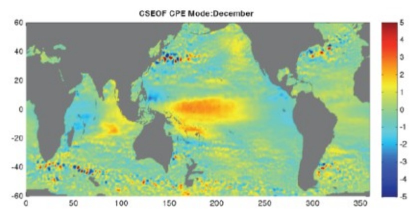

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Waveforms and Retracking

Waveforms and Retracking

Presented by
Stefano Vignudelli
Consiglio Nazionale delle Ricerche, Italy
vignudelli@pi.ibf.cnr.it

With invaluable help (and material) from
COASTALT Project

S. Vignudelli, A. Scozzari (CNR, Italy)
P. Cipollini, C. Gommenginger, H. Snaith, S. Gleason, G. Quartly, L. West (NOCS, UK)
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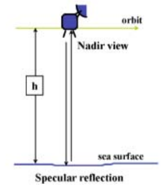
J. Benveniste (ESA/ESRIN, Italy)

particular thanks also go to the Coastal Altimetry Community

Measuring Ocean Topography with Radar

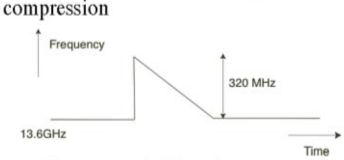
– Measure travel time, 2T, from emit to return
– h = T/c (c = 3 x 10^8 m/s)
– **Resolution to ~cm** would need a precision of 3 x 10^{-10}s, that is 0.3 nanoseconds)



0.3ns…. That is a pulse bandwidth of >3 GHz…. ahem, wait a minute….

Chirp, chirp, …

– So we have to use tricks: chirp pulse compression

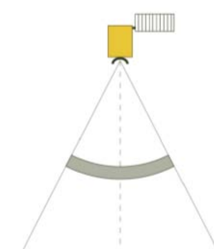


– …and average ~1000 pulses
– It is also necessary to apply a number of corrections for atmospheric and surface effects

Pulse Limited Altimeter

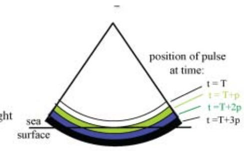
Pulse Limited Altimeter

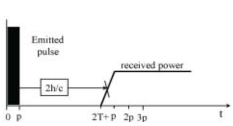
- In a pulse limited altimeter the shape of the return is dictated by the length (width) of the pulse

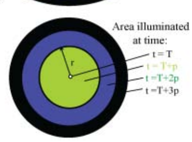


The "pulse-limited" footprint

- Full illumination when rear of pulse reaches the sea – then area illuminated stays constant
- Area illuminated has radius $r = \sqrt{(2hcp)}$
- Measure interval between mid-pulse emission and time to reach half full height

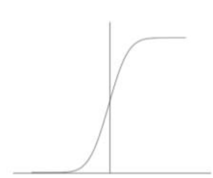






This is what we get at end

- A plot of return power versus time for a pulse limited altimeter looks like the integral of the heights of the specular points, i.e. the cumulative distribution function (cdf) of the specular scatterers



The tracking point is the half power point of the curve

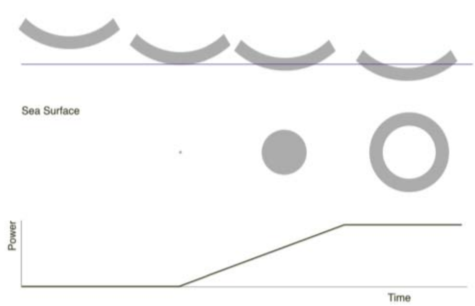
Pulse- vs Beam-

- All the microwave altimeters (including very successful TOPEX/Poseidon, ERS-1 RA and ERS-2 RA, Envisat RA-2) flown in space to date are pulse limited but….
- … laser altimeters (like GLAS on ICESAT) are beam-limited
- As said, delay-Dopper Altimeter can be seen as pulse-limited in the along-track direction
- But to understand the basis of altimetry we first consider the pulse limited design

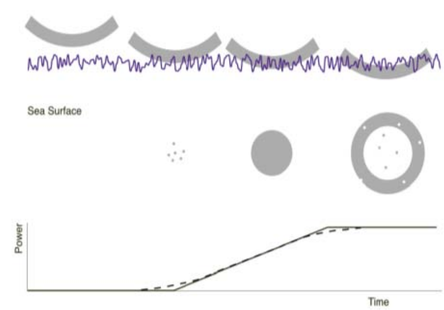
Basics of pulse-limited Altimeter Theory

- We send out a thin shell of radar energy which is reflected back from the sea surface
- The power in the returned signal is detected by a number of **gates** (bins) each at a slightly different time

This is what happens



and if we add waves



The area illuminated

- The total area illuminated is related to the significant wave height
- The formula is
- $$\frac{\pi R_0(c\tau + 2H_s)}{1 + R_0/R_E}$$

where c is the speed of light, τ is the pulse length, H_s significant wave height, R_0 the altitude of the satellite and R_E the radius of the Earth

From Chelton et al. (1989)

Hs (m)	Effective footprint (km) (800 km altitude)	Effective footprint (km) (1335 km altitude)
0	1.6	2.0
1	2.9	3.6
3	4.4	5.5
5	5.6	6.9
10	7.7	9.6
15	9.4	11.7
20	10.8	13.4

Brown Model - I

The Brown Model

- Assume that the sea surface is a perfectly conducting rough mirror which reflects only at specular points, i.e. those points where the radar beam is reflected directly back to the satellite

Brown Model - II

- Under these assumptions the return power is given by a three fold convolution

$$P_r(t) = P_{FS}(t) * P_{PT}(t) * P_H(-z)$$

where

$P_r(t)$ is the returned power

$P_{FS}(t)$ is the flat surface response

$P_{PT}(t)$ is the point target response

$P_H(-z)$ is the pdf of specular points on the sea surfac

The flat surface response function

- The Flat surface response function is the response you would get from reflecting the radar pulse from a flat surface.
- It looks like

$$P_{FS}(t) = U(t - t_0).G(t)$$

- where U(t) is the Heaviside function
- U(t) = 0 t <0 =1 otherwise
- G(t) is the two way antenna gain pattern

The point target response function

- The point target response function is the shape of the transmitted pulse
- It's true shape is given by

$$P_{PT}(t) = \left[\frac{sin(\pi t/\tau)}{\pi t/\tau}\right]^2$$

- For the Brown model we approximate this with a Gaussian.

The Brown Model - III

$$P_r(t) = P_{FS}(0)\eta P_T \sqrt{2\pi}\frac{\sigma_p}{2}\left[1 + erf\left\{\frac{(t - t_0)}{\sqrt{2}\sigma_c}\right\}\right] \qquad t < t_0$$

$$P_r(t) = P_{FS}(t - t_0)\eta P_T \sqrt{2\pi}\frac{\sigma_p}{2}\left[1 + erf\left\{\frac{(t - t_0)}{\sqrt{2}\sigma_c}\right\}\right] \qquad t > t_0$$

$$\sigma_c^2 = \sigma_p^2 + \frac{H_s^2}{4c^2}$$

$$P_{FS}(t) = \frac{G_0^2 \lambda_R^2 c \sigma^0}{4(4\pi)^2 L_p h^3} \exp\left\{-\frac{4}{\gamma}\sin^2\xi - \frac{4ct}{\gamma h}\cos 2\xi\right\} I_0\left(\frac{4}{\gamma}\sqrt{\frac{ct}{h}}\sin 2\xi\right)$$

The Brown Model - IV

where

$$erf(t) = \frac{2}{\sqrt{\pi}}\int_0^t e^{-x^2} dx$$

Compare with the Normal cumulative distribution function

$$\Phi(t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^t e^{\frac{-x^2}{2}} dx$$

$$\Phi(x) = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right]$$

$I_0()$ is a modified Bessel function of the first kind

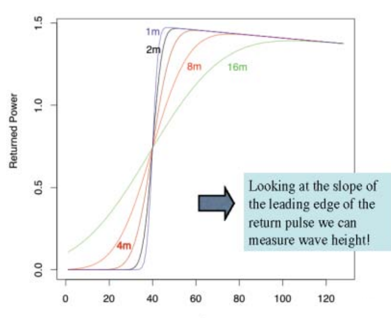
What are we measuring?

- Hs - **significant wave height**
- t_0 - the time for the radar signal to reach the Earth and return to the satellite (we then convert into **height** – see in the next slides)
- σ_0 - the radar **backscatter coefficient**, (somehow related to wind)

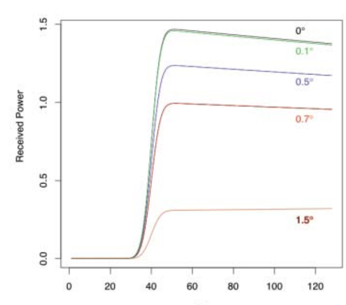
What are the other parameters?

- λ_R is the radar wavelength
- L_p is the two way propagation loss
- h is the satellite altitude (nominal)
- G_0 is the antenna gain
- γ is the antenna beam width
- σ_p is the pulse width
- η is the pulse compression ratio
- PT is the peak power
- ξ is the mispointing angle

Some examples of waveforms



The effect of mispointing



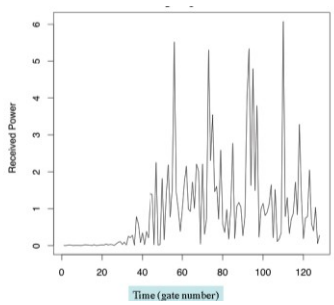
Noise on the altimeter

- If we simply use the altimeter as a detector we will still have a signal - known as the thermal noise.
- The noise on the signal is known as fading noise
- It is sometimes assumed to be constant, sometimes its mean is measured
- For most altimeters the noise on the signal is independent in each gate and has a negative exponential distribution.

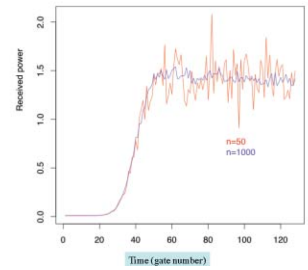
Averaging the noise

- For a negative exponential distribution the variance is equal to the mean. Thus the individual pulses are very noisy
- The pulse repetition frequency is usually about 1000 per second
- It is usual to transmit data to the ground at 20Hz and then average to 1 Hz

A single pulse

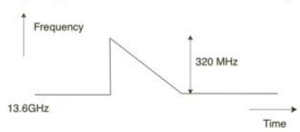


This is what happens when we average 50/100 single pulses



How altimeters really work

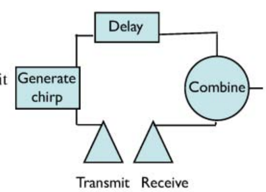
- It is very difficult (if not impossible) to generate a single-frequency pulse of length 3 ns
- However it is possible to do something very similar in the frequency domain using a chirp, that is modulating the frequency of the carrier wave in a linear way



The equivalent pulse width = 1/chirp bandwidth

Full Chirp Deramp - I

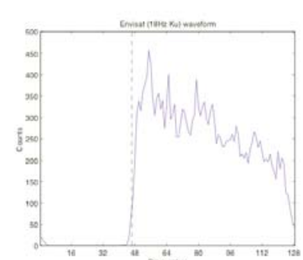
- A chirp is generated
- Two copies are taken
- The first is transmitted
- The second is delayed so it can be matched with the reflected pulse



Full Chirp Deramp - II

- The two chirps are mixed.
- A point above the sea surface gives returns a frequency lower than would be expected and viceversa
- So a 'Brown' return is received but with frequency rather than time along the x axis

A real waveform from the RA-2 altimeter on ESA's Envisat

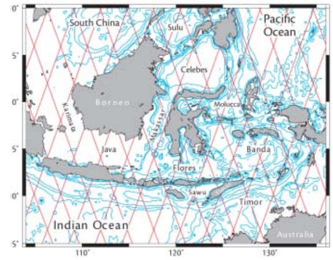


Ku band, 13.5 Ghz, 2.1 cm

Altimeters – Some instruments flown

- GEOS-3 (04/75 - 12/78)
  height 845 km, inclination 115 deg, accuracy 0.5 m, repeat period ??
- Seasat (06/78 - 09/78)
  800 km, 108 deg, 0.1 m, 3 days
- Geosat (03/85 - 09/89)
  785.5 km, 108.1 deg, 0.1 m 17.5 days
- ERS-1(07/91-2003); **ERS-2 (04/95 – present!)**
  785 km, 98.5 deg, 0.05 m 35 days
- **TOPEX/Poseidon (09/92 – 2006); Jason-1 (12/01-present); Jason-2 (06/08-present)**
  1336 km, 66 deg, 0.03 m 9.92 days
- **Geosat follow-on (GFO) (02/98 - 2007)**
  800 km, 108 deg, 0.1 m 17.5 days
- **Envisat (03/02 - present)**
  785 km, 98.5 deg, 0.05 m 35 days

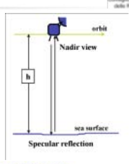
Example - Ground Track coverage of T/P and J1/2 over Indonesia



- Remember that conventional altimeters collect data along track (i.e. 1D)

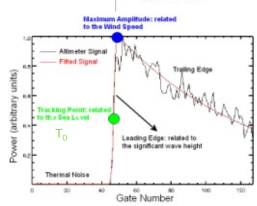
What is retracking ?

- We call "waveform" the ocean return signal
- In open ocean the typical waveform is Brown-like
- We call "retracking" fitting the real waveform with a model before estimating parameters
  - SWH - significant wave height = 4 x std (surface elevation)
  - T_0 - the time for the radar signal to reach the Earth and return to the satellite
  - σ_0 - the radar backscatter coefficient, (somehow related to wind)



- In open ocean the typical waveform is Brown-like
- the Brown model (red line) is usually fitted to the real waveform (black line)
- Then we can estimate the time required for two-way travel of signal (2T0)
- The time is then converted to a measurement of distance, known as range:

$h= T_0/c$ (c = 3 x 10^8 m/s)

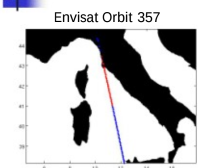


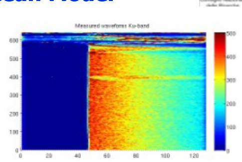
Which retrackers ?

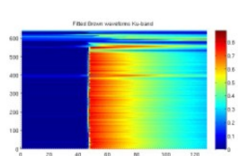
- Non-parametric (empirical methods)
  - Based on geometry
  - Do not estimate any geophysical parameters (apart from tracking point)
  - e.g. Off-center of gravity (OCOG)
    - Based on the definition of a rectangle about the effective center of gravity of waveform, the amplitude and width, the OCOG retracking method uses full waveform samples to locate the half-power point
  - DMU expert system
  - Geometrical shape fitted to the waveforms defined in terms of position of tracking point (e.g. offset center of gravity tracking on board, leading edge detection scheme)
- Model-based or Parametric (physics-based)
  - Use a geophysical model of the surface to build tracker
  - Tracker estimates geophysical parameters
  - Parametric of surface and we estimate them from the waveforms
    - e.g. MLE with Brown (1977) waveform shape offline for J1/n1
    - e.g. MLE tracker on Envisat
- Altimeter waveforms are conventionally tracked/retracked using maximum likelihood (MLE) or least squares to fit a 'Brown' model to the received waveform.

Waveforms & Retracking Brown Theoretical Ocean Model

Envisat Orbit 357



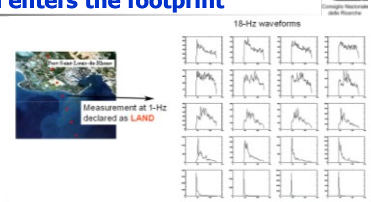


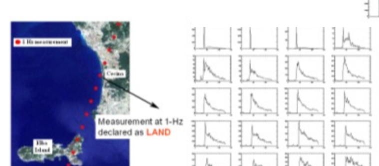


- Brown model is properly working except at land/sea interface, where a rapidly decaying trailing edge reflects the land contamination.

Waveforms may start being non Brown when land enters the footprint

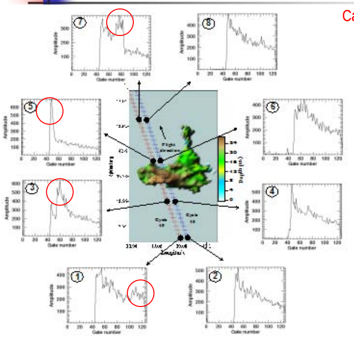
Envisat Ascending Track



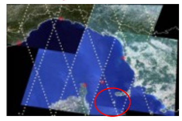


Envisat Descending Track

Waveform Contamination of calm waters

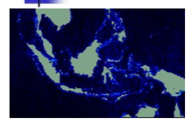


Case-study of Pianosa Island

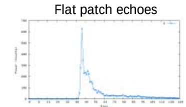


- Not only land, but also calm waters can contaminate the shape of the waveform
- Calm water cause quasi-specular reflections (so called bright features or "bright targets")
- These features migrate in the waveform/gatenumber space following hyperbolae (a parabolic shape is usually a good approximation)
- We could predict these effects and subtract them in the retracking process

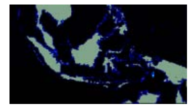
Indonesia is a challenging area



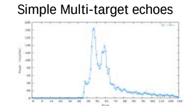
Flat patch echoes



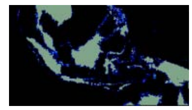
Calm water in coastal regions or with the presence of small islands.



Simple Multi-target echoes



Multiple brightly surfaces reflecting within the altimeter footprint.



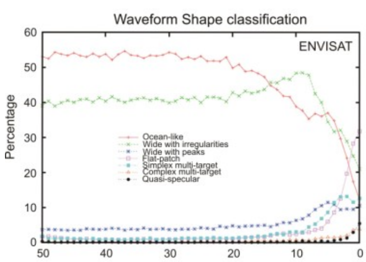
Complex Multi-target echoes

Combination of ocean component and rough terrain.

Courtesy by P. Berry, DMU

Coastal retracking

Essential to recover information when waveforms start being non-Brown!



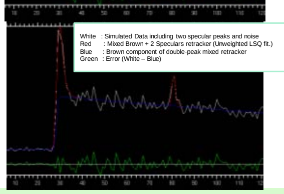
It becomes necessary to fit alternate waveform models to the waveforms

Lesson learned II – Re-thinking retracking

- We learnt that retracking waveforms in the coastal zone is challenging work
  - How close to the coast? – depends on how much high ground can affect tracking window too much
  - 90% of waveforms are Brown-like seaward of 10 km from the coast.
  - Standard (Brown model) retracking should be adequate seaward of 20 km from the coast.
- Identification of some retrackers better performing at the coast
  - e.g. RED3 in PISTACH Project
  - but BAG/ BAGP are even more promising
- Use better waveform models, accounting for change of shape in coastal environment
  - e.g. scattering from non-linear surfaces.
  - e.g. by including the effect of white caps
  - e.g. by mixing different models – Brown, Specular and Mixed (COASTALT)
- Use innovative techniques
  - Denoised estimations with Singular Value Decomposition(PISTACH)
  - Cleaning waveforms (COASTALT)
  - Avoid treating each waveform in isolation but using info from adjacent ones – 2D Hyperbolic Pre-tracker and Bayes Linear (COASTALT)

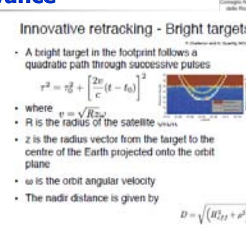
Retracking – mixing different models

- In many cases there are one (or more) non-Brown component(s) – e.g. A "specular" one superimposed on a Brown-like echo
- This can be tackled with models fitting different waveforms, e.g. one fitting sums of different Brown and non-Brown waveforms (a "mixed" retracked)

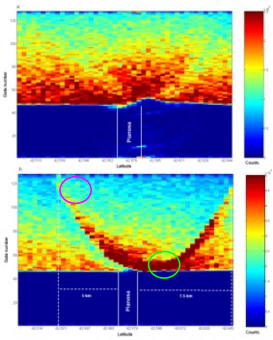


Innovative Retracking – Cleaning waveforms in advance

- We observed effects of land and effects of calm waters in the coastal strip
  - Land normally gives 'dark' features (less signal)
  - Calm water cause quasi-specular reflections giving peaky waveforms
- These features migrate in the waveform/gatenumber space following hyperbolae (a parabolic shape is usually a good approximation)
- Because we know the form of the hyperbolae (the speed of the satellite) we can accurately predic its position across a set of waveforms
- Features are reproduced by a simple model of the land/ocean/calm waters response
- The idea is that this should allow removal of the land/calm waters contamination prior to retracking

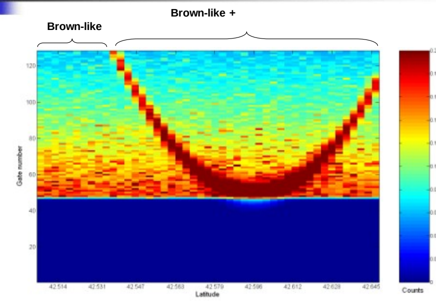


Waveform & Retracking Contamination of calm waters



- Small' influence of the island observed in cycle 46 (most of the waveforms are 'Brown-like')
- Hyperbola found in cycle 49: the appex of the feature corresponds to the north of the island (known as Golfo delle Botte)
- The radar 'senses' the change in ocean reflectance 7-8 km before the satellite overpasses the batch.

Modeling Peak Migration

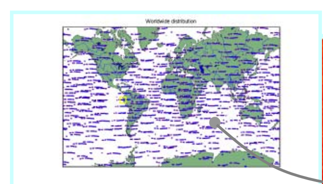


At the end we could improve the accuracy in the retrieval of the geophysical parameters in the coastal zone

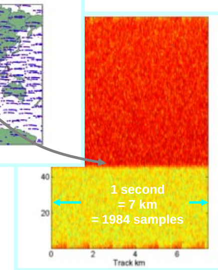
Innovative Retracking – 2D Hyperbolic Pre-tracker

- It is a pre-processor that cleans waveforms before application of other retrackers
- It has been reasonably tested on generic simulated altimetric waveforms.
- To tune the algorithm for best performance, the weights have to be developed with an accurate waveform simulation that matches Envisat RA-2 better. Improving this simulation
- Needs adjustment of simulated instrument characteristics.

Envisat Individual Echoes – Abileah and Vignudelli (results showed at 6th CAWS – Riva del Garda, Italy)



Sample of worldwide distribution of 1-second IE records

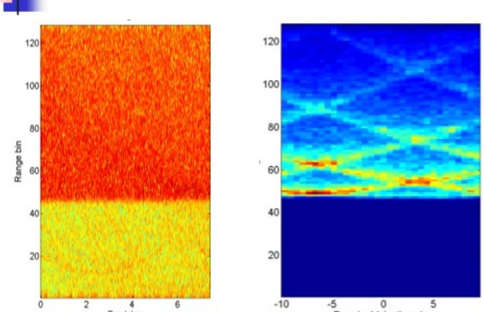


1-second record (amplitude, phase not shown)

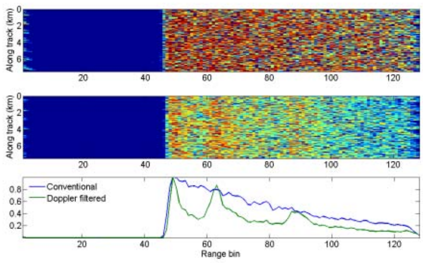
Envisat Individual Echoes - Inventory

- **Data collection started on September 2004**
- **330 GB / year**
- **1 second out of every 1 minute**
- **1800 Hz**
- **Global coverage**
- **Level 1b processed data available via GPOD**

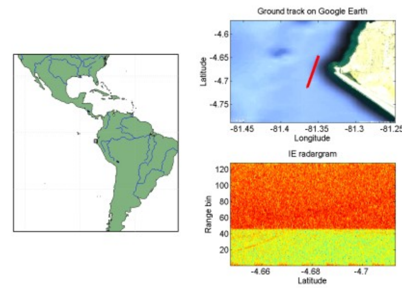
Envisat Individual Echoes – Doppler Processing



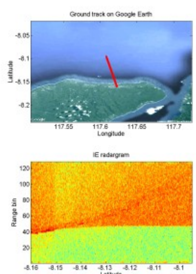
Envisat Individual Echoes – Open Ocean Example



Envisat Individual Echoes – Coastal Ocean Example

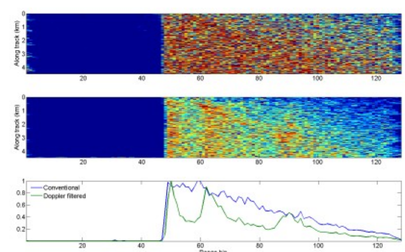


Envisat Individual Echoes – Pulau Mojo Indonesia

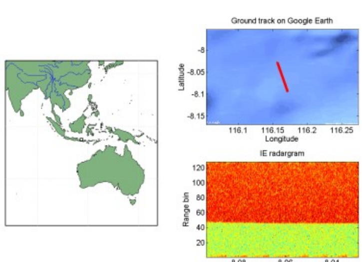


Possible land contamination in the conventional processing

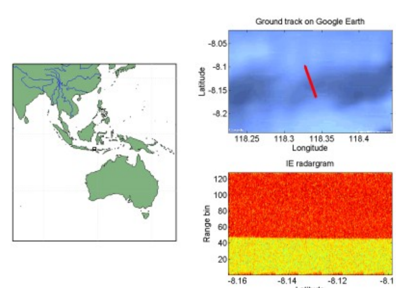
Envisat Individual Echoes – Pulau Mojo Indonesia Furthest 4 Km



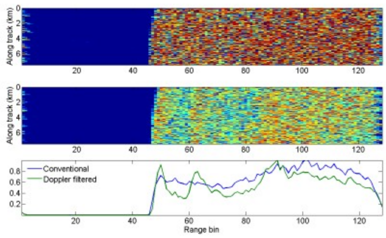
Envisat Individual Echoes – Lombok Indonesia Slopping Seas Topography (?)



Envisat Individual Echoes – Sumbawa Indonesia 118



Envisat Individual Echoes – Sumbawa Indonesia 118



Envisat Individual Echoes – Sumbawa Indonesia 118 40 km to Mt Tambora elev 2722 m

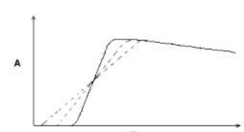
- Sumbawa case shows a great deal of waveform contamination . It turns out to be 40 km from volcano Tambora (elevation 2722 m). This would be a possible explanation for the peculiar waveform. The volcano is cross track, which can explain why Doppler filtering does relatively little to mitigate the interference.

Envisat Individual Echoes – Sumbawa Indonesia 118 40 km to Mt Tambora elev 2722 m

- Traditional processing of Envisat radar altimeter data assumes independent individual echoes (IE) and uses incoherent pulse averaging
- Envisat's 1800 Hz rate provides sufficient pulse-to-pulse coherence for Doppler processing
- A new method called zero-Doppler to process Envisat IEs is proposed and demonstrated.
-
- The new method has the potential to mitigate errors from ocean surface backscatter inhomogeneity and nearby land backscatter.
- The archive of Envisat IE data may be therefore reprocessed for improved water levels in open ocean, coastal and inland waters.

Exercise I – Implementing a Brown model

- The student has to plot an altimeter waveform generated according to Brown Model
- A function called BROWNMODEL(SAT,TP,SIGMA0,HS,THNOISE, SIGH) computes a Brown model waveform for a given altimeter,
  - SIGMAO in dB, significant wave height HS n meters
  - THNOISE is the input thermal noise
  - SAT is a two-character string specifying% the satellite of choice (currently only Envisat is implemented, for % which must be SAT='n1')
  - TP is the tracking point which (for Envisat can normally be set at TP=46
  - SIGH is the mispointing in degrees to be specified. If omitted, mispointing is assument to be zero.
- The output of the function is the waveform power (in picowatts (A)



Exercise II – Playing with real waveforms

- A radar altimeter emits a short pulse that is bounced back from the ocean surface and the echo returns to the antenna.
- The recorded power is the convolution of the outgoing pulse with the ocean surface height distribution (i.e. waves), which is well approximated by a Gaussian function.
- The form of the return power is an error function, which is the integral of a Gaussian function.
- A simple model for the expected power versus time is

$$M(t, t_0, \sigma, A) = A\left[1 + \mathrm{erf}\left(\frac{t - t_0}{\sqrt{2}\sigma}\right)\right]$$

- where t is the time since the pulse was transmitted, t_0 is the arrival time of the half power point, σ is the rise time parameter and A is the amplitude of the returned waveform.
- Since the pulse travels from the satellite to the ocean surface and back again, the altitude of the satellite is

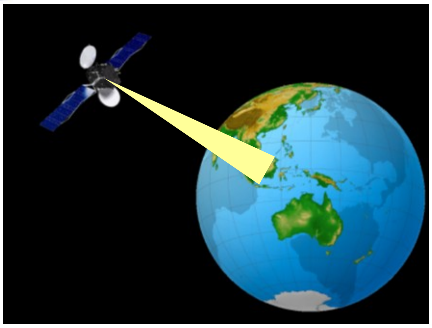
$$r = \frac{ct_0}{2}$$

- where c is the speed of light

Exercise II (cont'd)

- 20 altimeter waveforms collected by an altimeter are available in the file "fitwf.dat"
  - The first column of the file is time in nanoseconds since the altimeter started recording (5.3 x 10^{-3} seconds)
  - The second column is the recorded power.
- The student has to:
  - Load the waveform data
  - Plot waveform data as points (power vs time).
  - Generate a simple model waveform from the function (see previous slide)
  - Plot it over the waveform data
  - Estimate the range in meters
  - Estimate the Significant Wave Height (SWH) in meters

Thank you for your attention!



Reconstruction Sea Level Using CSEOF

Reconstructing Sea Level Using CSEOFs

B.D. Hamlington, R.R. Leben
Colorado Center for Astrodynamics Research
University of Colorado, Boulder

K.-Y. Kim
Seoul National University

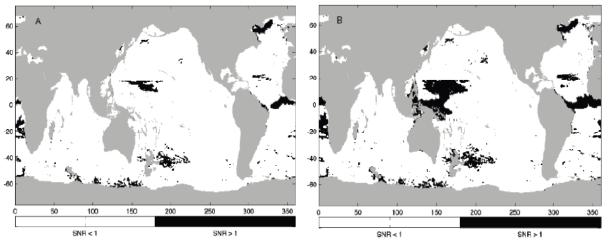
Using CSEOF Analysis to Improve Estimates of the Spatial Variations of Sea Level Trends

Improving Regional Sea Level Trend Estimates: 1993-2009

- By removing the CSEOFs representing the modulated annual cycle (MAC) and ENSO signals from the satellite altimetry data prior to computing the trend, the SNR and standard error of the trend estimate can be improved.
  - Identifying signals not associated with the trend in sea level but are physically interpretable allows us to remove them from the data.
- Compare two methods of computing regional trends:
  1. Fit annual signal, semi-annual signal and trend simultaneously using least squares.
  2. Remove MAC and ENSO CSEOFs from data then compute trend using least squares.
- The remaining signal once the explainable signals are removed is considered to be background noise.
- Power associated with both the linear trend and background noise is estimated by integrating the squared time series for each.
- SNR values are computed by dividing the linear trend power by the background noise power.

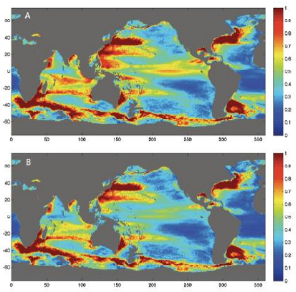
Improving Regional Sea Level Trend Estimates: 1993-2009

- Map of SNR between the linear trend and background noise. A) SNR computed solely using least squares, B) SNR from least squares incorporating CSEOF analysis.



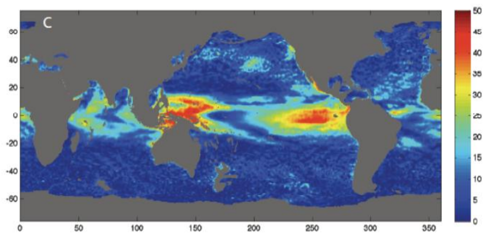
Improving Regional Sea Level Trend Estimates: 1993-2009

- Maps of standard error on the estimated linear trend computed from A) a simple least squares approach and B) least squares incorporating CSEOF analysis to estimate and remove MAC and ENSO signals. Standard error estimates are shown in units of mm/yr.



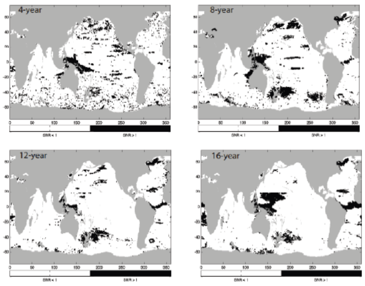
Improving Regional Sea Level Trend Estimates: 1993-2009

- Percentage reduction in the standard error when comparing simple least squares approach to approach using least squares and CSEOF analysis.



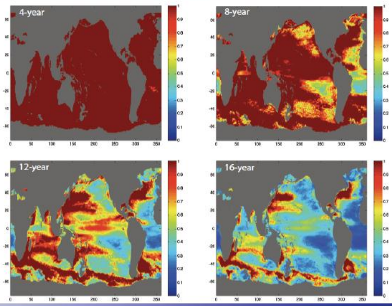
Improving Regional Sea Level Trend Estimates: 1993-2009

- Maps of SNR computed using varying lengths of original time series. Percentages of areas with SNR greater than one are 10.4%, 10.5%, 6.8% and 9.9% respectively.



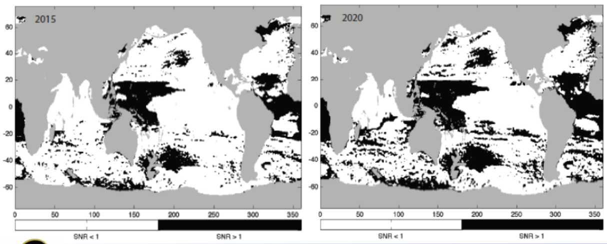
Improving Regional Sea Level Trend Estimates: 1993-2009

- Maps of standard error on the estimated linear trend computed using varying lengths of original time series. Standard error is in units of mm/yr.



Improving Regional Sea Level Trend Estimates: 1993-2009

- SNR maps are created by projecting results to the years 2015 and 2020. The linear portion of the trend is assumed to be stationary and the power associated with the background variability of the signal increases linearly with time. In 2015, the percentage of area with SNR > 1 is 22.4%, while in 2020, the percentage is 32.7%.



Improving Regional Sea Level Trend Estimates: 1993-2009

- The SNR between the secular trend and background noise can be improved by separating the non-secular background variability from the secular trend.
  - Leads to a significant reduction in formal estimates of the standard error on the linear trend computed using least squares.
  - CSEOF analysis is uniquely suited to extracting this background variability.
  - The standard error in the least-squares estimate of the linear trend is reduced across 97.1% of the globe when incorporating CSEOFs.
- Even when including the CSEOF analysis, less than 10% of the ocean has SNR > 1.
  - By varying length of time series, we can see how CSEOF analysis and the SNR changes over time.
  - With longer time series, it is possible another CSEOF will be physically explainable and thus can be removed from data to improve SNR and standard error.
- If another mode is not physically interpretable, only 22.4% of globe will have SNR > 1 in 2015, and 32.7% will have SNR > 1 in 2020.

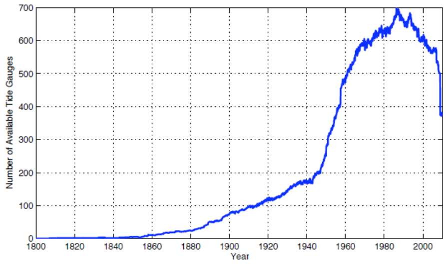
CSEOF Sea Level Reconstruction

What is a 'Sea Level Reconstruction'?

- Creating a sea level climate data record with sufficient duration, consistency and quality that can be used to accurately determine climate variability and change is a challenge.
  - **Tide Gauges**: Long record, but sparsely distributed.
  - **Satellite Altimetry**: Short record, but near-global coverage.
- Sea level is reconstructed by fitting altimetry-derived basis functions to tide gauge data.
  - [e.g. Chambers et al. (2002), Church and White et al. (2004), Ray and Douglas (2011) Hamlington et al. (2011), Meyssignac et al. (2011;2012)].
  - In past sea level and sea surface temperature (SST) reconstructions, generally empirical orthogonal functions (EOFs) have been used as the basis for the reconstruction.
- Here, we refer to a sea level reconstruction as a dataset with spatial coverage of satellite altimetry and length of tide gauge record.

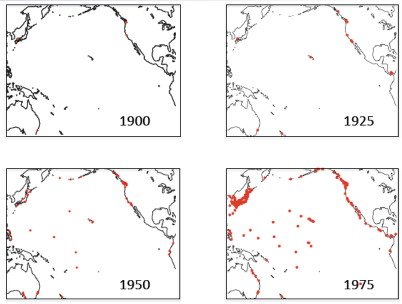
Tide Gauge Availability

- Number of available tide gauges in the Permanent Service for Mean Sea Level (PSMSL) RLR dataset over the period from 1807 to 2010.



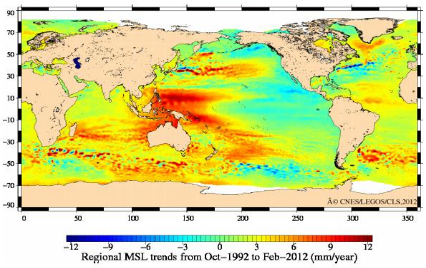
Tide Gauge Availability

- Number of available tide gauges in Permanent Service for Mean Sea Level (PSMSL) RLR dataset between 1900 and 1975.



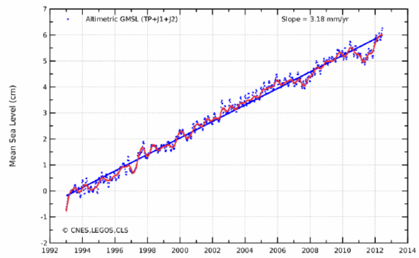
Satellite Altimetry – Regional Trends

- Regional sea level trends computed from the AVISO satellite altimetry dataset from 1992 to 2012.



Satellite Altimetry – Global Mean Sea Level

- Global mean sea level (GMSL) time series computed from the AVISO satellite altimetry dataset.

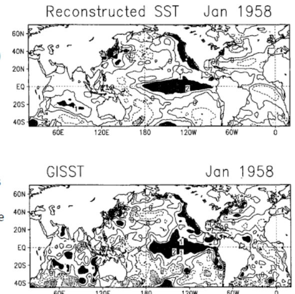


Past Sea Level Reconstructions

- Reconstruction techniques first developed for use with SST.
  - Smith et al. (1996), Kaplan et al. (1998, 2000).
  - Reconstructions extended back into the 19th century.
- Methods were extended to sea level in the last decade.
  - Smith et al. (2000), Chambers et al. (2002).
- Church et al. (2004) performed the most comprehensive reconstruction of sea level and released a dataset covering the period from 1950 to 2001.
  - Reconstruction was updated in Church et al. (2006), and Church et al. (2011).
- Several other papers on reconstructions have since been released.
  - e.g. Berge-Nguyen et al., (2008) Meyssignac et al. (2011, 2012a), Christiansen et al. (2011), Ray and Douglas (2011).

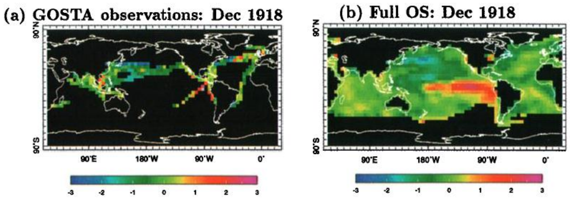
Smith et al. (1996): "Reconstruction of historical sea surface temperatures using empirical orthogonal functions"

- Smith first introduced the idea of reconstructing sea surface temperature by fitting empirical orthogonal functions (EOFs) to *in situ* measurements.
  - Reconstructed SST from 1950 to 1993.
  - Reconstruction was computed using a least-squares fit of EOF basis function to historical SST measurements.
  - EOFs were computed from an OI analysis of combined satellite and *in situ* measurements from 1982 to 1993.
  - By truncating the number of EOFs used in the reconstruction, it was found that smoother maps were produced when compared to simply averaging *in situ observations.*



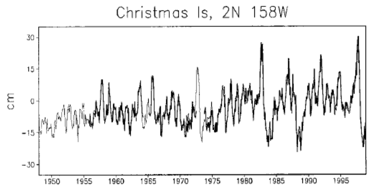
Kaplan et al. (1998): “Analyses of global sea surface temperature 1856–1991”

- *Kaplan et al.* (1998) built on the technique of Smith to reconstruct sea level back to 1856.
  - Used the truncation of the EOFs as well as the error of the historical measurements to perform a weighted least-squares procedure.



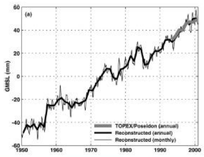
Smith (2000): “Tropical Pacific Sea Level Variations (1948–98)”

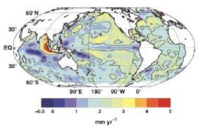
- *Smith* (2000) extended his SST reconstruction technique to reconstruct sea level from 1948-1998.
  - First published paper on performing sea level reconstructions.
  - Fit satellite altimetry-derived EOF basis functions to tide gauge data.
  - Only reconstructed sea level in the tropical Pacific.



Church and White et al. (2004): “Estimates of the Regional Distribution of Sea Level Rise over the 1950–2000 Period ”

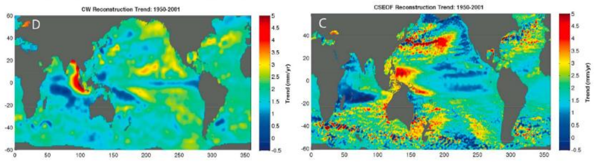
- *Church and White et al.* (2004) used the method of *Kaplan et al.* (1998; 2000) to reconstruct sea level from 1950 to 2000.
  - Again, fit satellite altimetry derived basis functions to tide-gauge measurements.
  - First to account for global mean sea level (GMSL) in reconstruction by introducing a constant EOF basis function (mode of ones) and fitting to differenced tide gauge data to account for lack of global tide gauge datum level.
  - First reconstructed sea level dataset to be made publicly available.





Hamlington et al. (2011) “Reconstructing Sea Level Using Cyclostationary Empirical Orthogonal Functions”

- Using CSEOFs instead of EOFs as the basis for the reconstruction, we found that the reconstruction of climate variability could be improved.
- Hamlington et al. (2011) showed results for a CSEOF sea level reconstruction from 1950 to 2010.
  - Demonstrated reconstruction of ENSO from 1950 to 2010.
  - Reconstruction is publicly available through NASA JPL/PO.DAAC.



EOF Reconstruction Procedure

- Process of solving for the amplitudes of each basis function amounts to a weighted least squares problem (fitting satellite altimetry basis functions to tide gauge data):
- Reconstructed sea level fields (for an EOF reconstruction) are given by:

$$H(r,t) = \sum V_n(r)\alpha_n(t)$$

where V are the LVs and α(t) is the time series of the amplitude of the LV (reconstructed PC time series).

- Chambers et al. (2002) compute the amplitude by minimizing

$$S(\alpha) = (V\alpha - H^0)^T (V\alpha - H^0)$$

EOF Reconstruction Procedure

- Process of solving for the amplitudes of each basis function amounts to a weighted least squares problem (fitting satellite altimetry basis functions to tide gauge data):
- Church and White et al. (2004) added weighting to the cost function and instead minimize

$$S(\alpha) = (V\alpha - H^0)^T M^{-1}(V\alpha - H^0) + \alpha^T \Lambda \alpha$$

- where $M = R + V\Lambda V^T$, R is the variance of the instrumental error and the second term represents the errors introduced by truncating the higher-order EOFs.
- Once the cost function is minimized, the resulting amplitudes are given by

$$\alpha = PV^T M^{-1} H^0$$
$$P = (V^T M^{-1} V + \Lambda^{-1})^{-1}$$

CSEOF Reconstruction Procedure

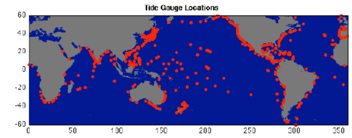
- CSEOF reconstruction technique follows the reconstruction methodology with the significant difference that we use CSEOFs instead of EOFs.
  - All LVs in the nest period are fit simultaneously and the computed reconstructed amplitude is then assigned to the center of the nested period (before fitting, weekly values were interpolated from the monthly tide gauge records).
  - This windowing process leads to the loss of six months of data at either end of the time series.
- The following sea level reconstruction results are obtained using a set of tide gauges similar to that of Church and White et al. (2004).
  - 409 tide gauges in our reconstruction vs. 426 in CW reconstruction.

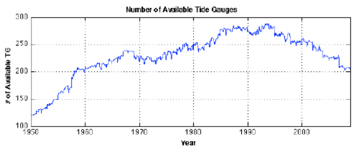
Why use CSEOFs instead of EOFs?

- The motivation for using CSEOFs in place of traditional EOFs as the basis functions for the reconstruction is fourfold:
  1. EOFs are not a good basis for signals in the ocean and are unable to explain the temporal evolution of spatial variability.
  2. CSEOFs account for both the high and low frequency components of the annual cycle in a single mode and do not require the removal of the annual signals from both the altimetry and tide gauge records prior to reconstruction.
  3. Specific signals, such as those relating to the modulated annual cycle and ENSO, can be reconstructed individually with little mixing of variability between modes.
  4. The reconstruction procedure using CSEOFs inherently smoothes the reconstruction, allowing for the use of fewer tide gauges to obtain a meaningful result.

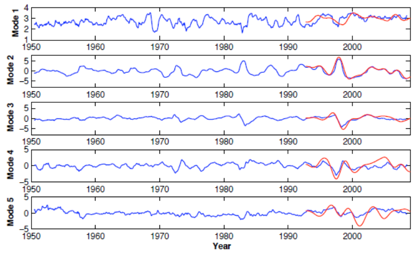
CSEOF Reconstruction Results (Hamlington, *JGR*, 2012)

- The following results were published in *Journal of Geophysical Research.*
- They represent the first attempt at reconstructing sea level using CSEOFs.





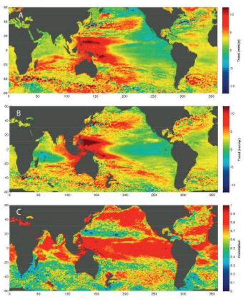
CSEOF Reconstruction Results



- The tide gauge reconstructed PC time series for the first 5 CSEOF modes are shown overlaid with the original altimeter-derived PC time series. The quality of the reconstruction is shown by the agreement between the two.

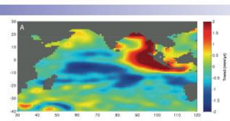
AVISO vs. CSEOF: 1993 to 2009

Regional sea level trends from 1993 to 2009 computed from the AVISO satellite altimetry data (A) and from the CSEOF reconstruction (B). The spatial variation of correlation between the AVISO and CSEOF reconstruction data over the same time period is also shown (C).

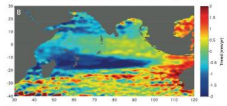


HYCOM Model vs. CSEOF Reconstruction: Regional Trends 1961 to 2008

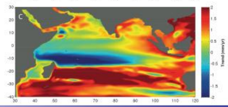
- **Trends from 1961-2001 for the Indian Ocean computed from CW EOF reconstruction.**



- **Trends from 1961-2008 for the Indian Ocean computed from CSEOF reconstruction.**

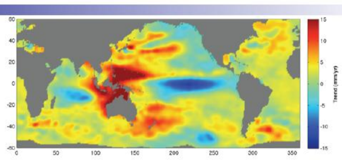


- **Spatial variation of trend for the Indian Ocean from 1961-2008 for HYCOM SLA (Han et al, 2010).**

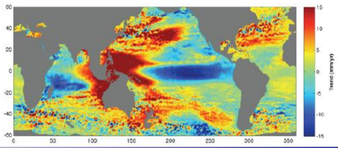


CW vs. CSEOF Reconstruction: Regional Trends 1993 to 2001

- Spatial variation of trend from 1993-2001 computed from **Church and White et al (2004)** (mm/yr).

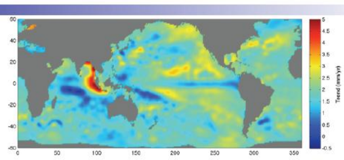


- Spatial variation of trend from 1993-2001 computed from **CSEOF reconstruction** (mm/yr).

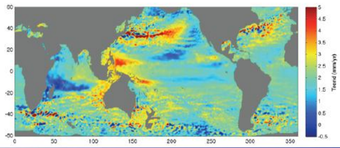


CW vs. CSEOF Reconstruction: Regional Trends 1950 to 2001

- Spatial variation of trend from 1950-2001 computed from **Church and White et al (2004)** (mm/yr).



- Spatial variation of trend from 1950-2001 computed from **CSEOF reconstruction** (mm/yr).



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CSEOF Reconstruction Results: Climate Indices

- CSEOF reconstruction provides SSH-based indices describing well-known climate signals.
  - These indices can be linked to major patterns of climate variability and provide a quick and easy way to talk to the general public about climate change.
- Indices computed strictly from the SSH reconstruction can be used to compare to the indices derived from SST reconstructions.
  - SST reconstructions extend back to the 19th century.
  - SSH reconstruction can be computed back to the first date that tide gauge data is available.
  - Could have advantages over SST computed indices (Giese et al., 2010).

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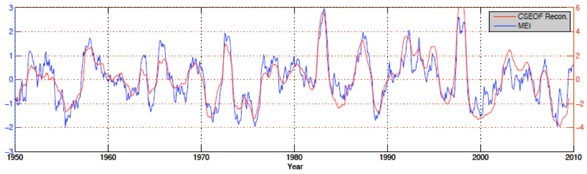
CSEOF Reconstruction Results: EP El Niño



- The Eastern Pacific El Niño is described by CSEOF mode 2 in both the satellite altimetry and reconstructed sea level.
- The correlation between the Multivariate ENSO Index (MEI; Wolter and Timlin, 1998) and the reconstructed EP El Niño amplitude is 0.91 over the period from 1950 to 2010.

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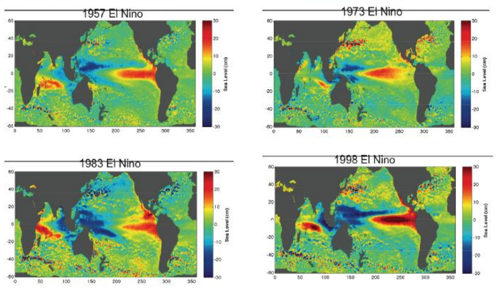
CSEOF Reconstruction Results: ENSO



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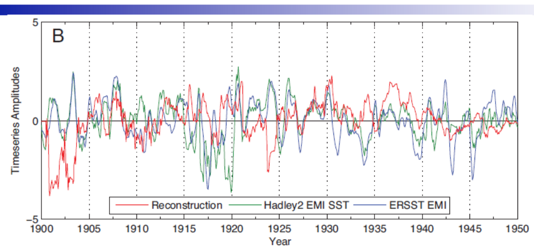
CSEOF Reconstruction Results: CP El Niño



The Central Pacific El Niño or El Niño Modoki Index EMI computed from the reconstructed SSH (red), specifically the third mode of the reconstruction. The EMI computed from the ERSST dataset is also shown, with a correlation of 0.61 between the two over the period from 1950 to 2010.

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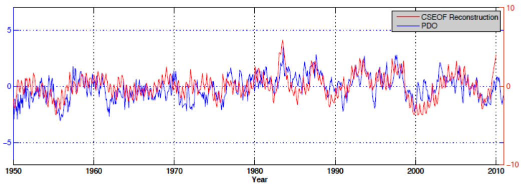
CSEOF Reconstruction Results: PDO



The Pacific Decadal Oscillation (PDO) index is computed from the CSEOF reconstruction (red) and from the SST measurements (http://jisao.washington.edu/pdo/).

CSEOF Reconstruction: GMSL

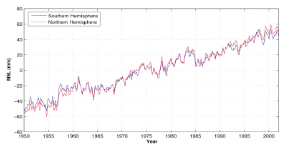
- There is great interest in global mean sea level and it must therefore be accounted for in sea level reconstructions.
  - No basis function from altimetry can describe the change in mean sea level over the reconstructed time period.
- To account for GMSL in their reconstruction, Church and White et al. (2004) introduced a spatially uniform basis function, effectively computing a weighted (using the instrument and truncation errors) mean of the tide gauges.
  - To account for differences in local datum at different tide gauge locations, CW use first differences of tide gauge data.
    - Difficult to do with CSEOFs as a result of temporal dependence of LVs.

$$\frac{dH(r,t)}{dt} = \frac{d\alpha(t)}{dt}V(r) \qquad \frac{dH(r,t)}{dt} = \alpha(t)\frac{dV(r,t)}{dt} + \frac{d\alpha(t)}{dt}V(r,t)$$

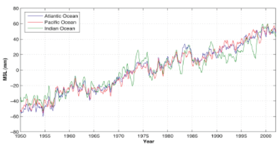
  - As a result of the constant basis function, same mean time series is added to every point across the globe.

CSEOF Reconstruction: GMSL

Mean sea level computed for the southern and northern hemispheres from the sea level reconstruction of Church et al. (2004) over the period from 1950 to 2001.



Mean sea level computed for the Atlantic (Blue), Pacific (Red) and Indian (Green) Oceans from the sea level reconstruction of Church et al. (2004) over the period from 1950 to 2001.



CSEOF Reconstruction: GMSL

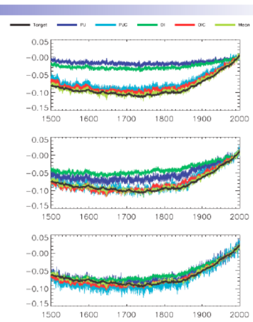
- Christiansen et al. (2010) determined that a spatially uniform mode is absolutely necessary to capture GMSL unless the "calibration" period is close to the length of the actual reconstruction.
  - Worked with pseudo-tide gauges that did not have differences in local datum.
  - Determined more tide gauges and longer calibration period lead to better reconstructions.
  - Results show that GMSL captured by the uniform basis function is similar to a weighted mean of the tide gauges.

CSEOF Reconstruction: GMSL

Results shown by Christiansen et al. (2010) relating length of calibration period to ability to reconstruct GMSL.

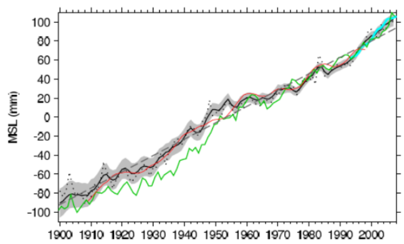
Target → Actual mean sea level
PJ → Chambers et al. (2002)
PJC → PJ with constant basis function
OI → Kaplan et al. (1998)
OIC → Church and White et al. (2004)
Mean → Mean of pseudo-TG data

Conclusions: 1) Until calibration period is long enough to obtain basis function related to mean sea level change, constant basis function must be introduced; 2) Mean of tide gauges is very similar to GMSL computed by other methods.



CSEOF Reconstruction: GMSL

- Ray and Douglas (2011) introduced a technique that estimates a consistent reference level for all tide gauges, thus eliminating the need to work with differenced tide gauge data.
- Very expensive computationally and only really practical with a small number of tide gauges.
- Reconstructed GMSL (solid black line) is very similar to mean of tide gauges (dotted black line).



Ray and Douglas (2011)

CSEOF Reconstruction: GMSL

- Rather than introduce another basis function, GMSL can be calculated separately from the reconstruction of the actual CSEOF modes.
- The following procedure is used to estimate GMSL, including the secular trend.
  1. The full CSEOF reconstruction is computed and then subsampled at each of the tide gauge locations.
  2. Time series from (1) are differenced for each TG location, ensemble averaged at each point in time, and then re-integrated → time series contains ENSO and any other signals the reconstruction captures.
  3. The raw TG data is also differenced, averaged using latitude-band weighting, and then re-integrated to form a GMSL time series associated with the original TG data → time series contains ENSO and any other signals the contained in the TG data.
  4. The time series computed in part (2) is subtracted from the time series computed in part (3) to form an estimate of the GMSL time series with all reconstructed signals removed, including the MAC and ENSO, thus correcting for any trend resulting from the spatial subsampling of signals captured by the reconstruction.

CSEOF Reconstruction: GMSL

$$Trend_{TG} = \overline{TG_{raw}} - \overline{Recon_{TG}}$$

$\overline{TG_{raw}}$ - Mean time series of tide gauge data.

$\overline{Recon_{TG}}$ - Mean time series of reconstruction subsampled at the tide gauge data

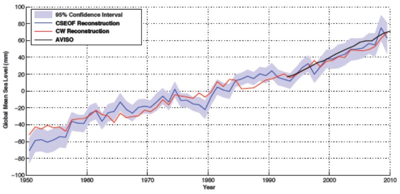
$Trend_{TG}$ - Secular trend time series without any of the signals captured by the reconstruction (eg. Annual cycle, ENSO)

➢ GMSL can then be computed by averaging over the whole reconstructed data set and adding in the secular trend computed above:

$$GMSL = \overline{Recon} + Trend_{TG}$$

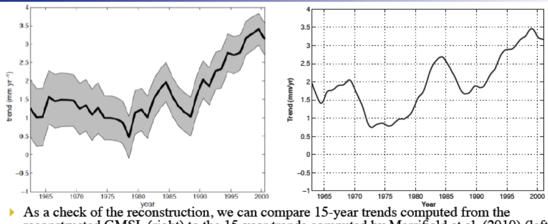
CSEOF Reconstruction: GMSL

A comparison of GMSL derived from satellite altimetry (1993-present; black) from the CSEOF reconstruction (blue) and from the CW EOF reconstruction (red).



- Trend in GMSL from 1950 to 2009 is estimated to be 1.97 mm/yr.
- Trend in GMSL from 1993 to 2009 is 3.22 mm/yr.
- Error is estimated through Monte Carlo simulations in which 70% of tide gauges are selected and used in the reconstruction. 100 trials are conducted → GMSL 1950 to 2009 = 1.95 ± 0.4 mm/yr, GMSL 1993 to 2009 = 3.52 ± 0.6 mm/yr.

CSEOF Reconstruction: 15-year trends



- As a check of the reconstruction, we can compare 15-year trends computed from the reconstructed GMSL (right) to the 15-year trends computed by Merrifield et al. (2010) (left).
  - Relatively **good agreement after 1980**, however generally **trends are higher before 1980** in the reconstructed GMSL.
  - Differences result from a combination of tide gauge dataset (**400+ vs. 120+ tide gauges**) used for the computation and the reconstruction correction for sampling bias.

CSEOF Reconstruction: Tide Gauges

To test sensitivity of the reconstruction to tide gauge editing, seven different tide gauge data sets were created using different editing criteria and a reconstruction was performed with each one.

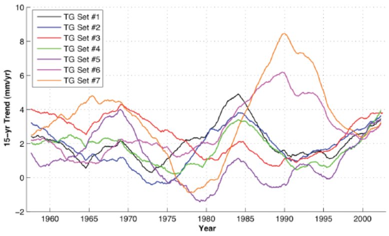
#	Tide Gauge Set	Number of Tide Gauges	Editing Criteria
1	All PSMSL Gauges	1179	GIA Corrected, IB correction Applied
2	Church et al. (2004)	508	GIA Corrected, IB correction Applied, see Church et al. (2004)
3	Merrifield et al. (2009)	122	GIA Corrected, IB correction Applied, see Merrifield et al. (2009)
4	Ray and Douglas (2011)	89	GIA Corrected, IB correction Applied, see Ray and Douglas (2011)
5	40-year minimum	289	GIA Corrected, IB correction Applied, all TGs with < 40 year record length removed
6	5-degree box	268	GIA Corrected, IB correction Applied, longest record in every 5-degree box retained
7	10-degree box	143	GIA Corrected, IB correction Applied, longest record in every 10-degree box retained

CSEOF Reconstruction: Tide Gauges

Reconstruction results from 7 different TG datasets.

TG Set	Trend 1993-2009 (mm/yr)	Trend 1950-2009 (mm/yr)	MEI Correlation	EMI Correlation
1	3.19	1.92	0.92	0.68
2	3.22	1.97	0.91	0.65
3	3.84	2.15	0.86	0.57
4	3.34	1.73	0.85	0.51
5	3.04	1.65	0.80	0.41
6	2.92	2.29	0.82	0.54
7	2.98	1.69	0.83	0.50

CSEOF Reconstruction: Tide Gauges



15-year trends over the period from 1950 to 2010 for each of the seven tide gauge datasets considered. Latitude-band weighting is used for computing the trends.

Application of Satellite Altimetry data for Fisheries

Application of Satellite Altimetry data for Fisheries

Jonson Lumban Gaol
Department of Marine Science &Technology
Bogor Agricultural Univ., Indonesia

Introduction

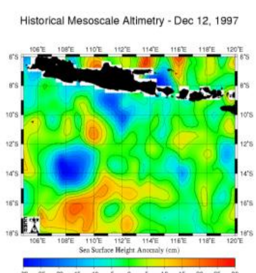
Marine biologists/fishermen are interested in ocean currents, eddies, upwelling, etc for several reasons.

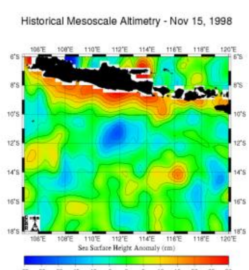
Not only do they transport organisms – particularly their larvae, from place to place, but they also can bring up nutrients from deep in the ocean, fertilizing phytoplankton (who are the foundation of the food chain).

We can derived Ocean Current, Mesoscale eddy, and upwelling, termocline depth from altimetry

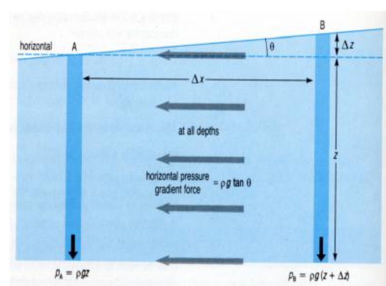
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

These viewers and other regional and global data viewers can be found at: http://www-ccar.colorado.edu/~leben/research.html





- The currents that result when the *horizontal pressure gradient* force is balanced by the Coriolis force are know as *geostrophic currents*.



Gradient surface pressure

Gradient surface pressure (u component)

$$u = -\frac{g}{f}\frac{\delta p}{\delta y}$$

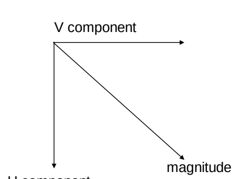
$f = 2\,\Omega \sin \phi$ (parameter coriolis)
ϕ = latitude
$g = 981$ cm/s2,
$\Omega = 7.292\text{e-}5$ rad/s.

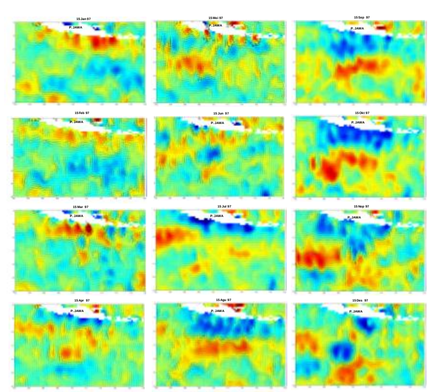
Gradient surface pressure X (v component)

$$v = \frac{g}{f}\frac{\delta p}{\delta x}$$

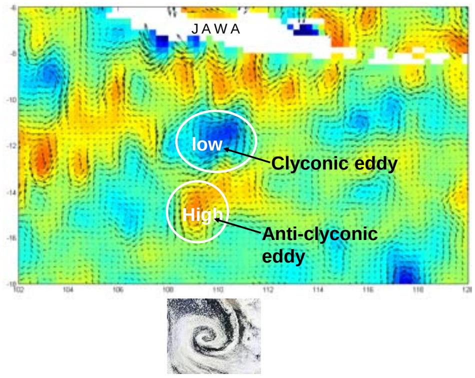
Magnitude of vector u and v:

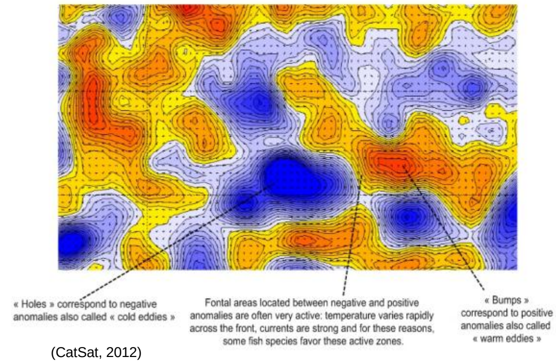
$V_m = (u^2+v^2)^{1/2}$





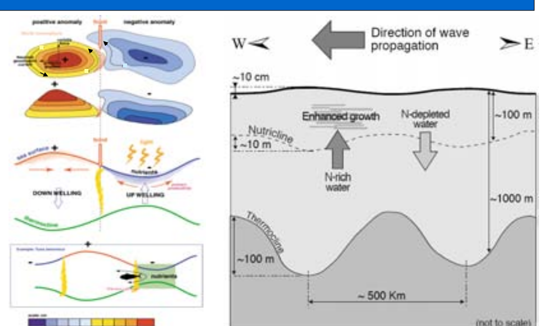
Example data derived from satellite altimeter





(CatSat, 2012)

Schematic of eddy and biological enhancement in the ocean

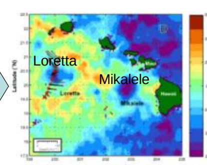


Low (negative) SSH corresponding to sallow (positive) termocline, vice versa

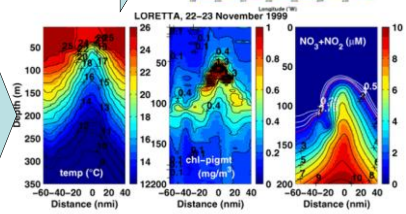
Killoward, (2001)

Example in Hawaii

Satellite remote sensing of cyclonic eddies "*Loretta*" and "*Mikalele*": (Seki et.al, 2001)

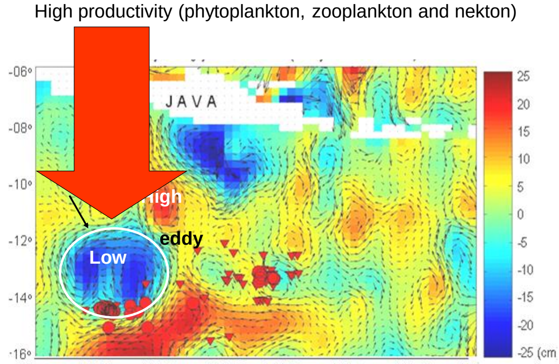


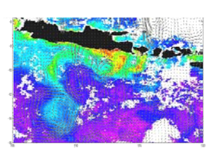
In Situ of cyclonic eddies "*Loretta*" and "*Mikalele*": (Seki et.al, 2001)

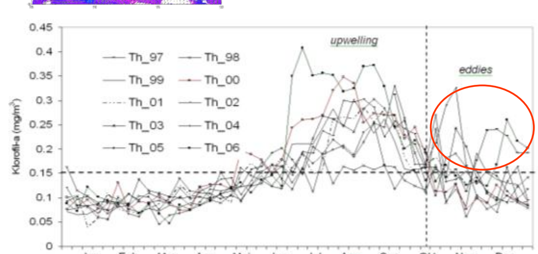


Vertical section of temperature total *in situ* chloropigment (mg m^{-3}), and nitrate+nitrite (N+N, for eddies *Loretta* 22-23 November 1999

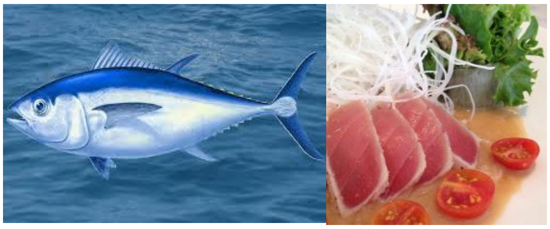
High productivity (phytoplankton, zooplankton and nekton)





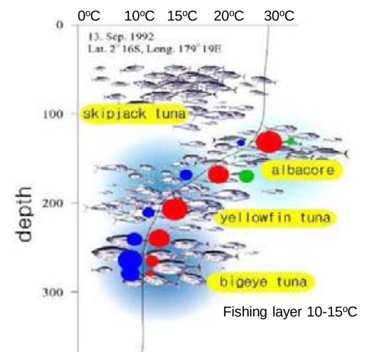


Application for fishing

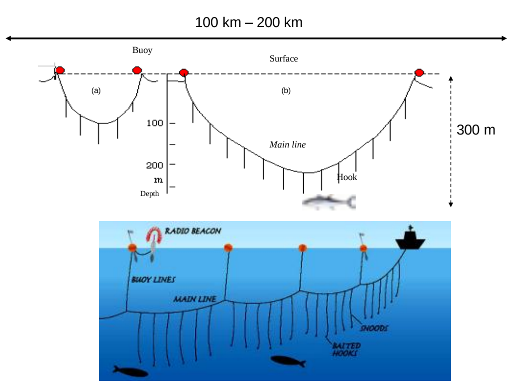


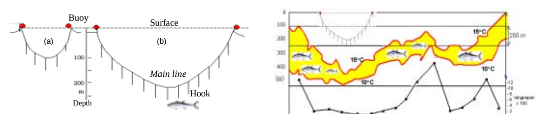
1 kg = Rp 300.000 (US$ 30) → 100 kg -→ 30 juta (US $ = 3000)

Fishing layer of kinds of tuna related to suitable temperature



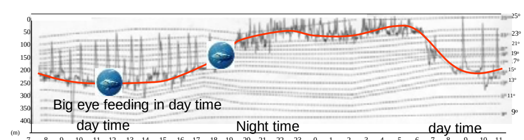
Fishing gear for bigeye tuna → longliner





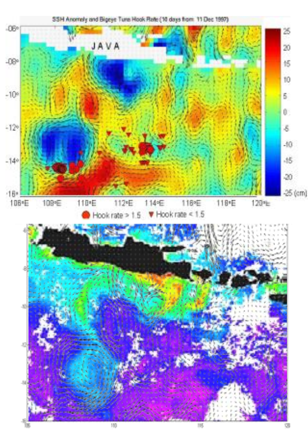
Max depth of hook = 250 meter

Fishing Layer of Big eye tuna (10-15ºC) (180ºE) (Hanamoto, 1986)

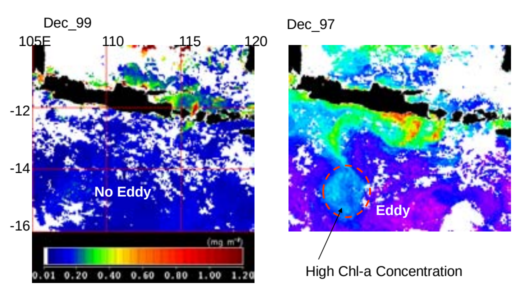


Vertical movement of Big eye tuna by taging (Hollant et al, 1990)

Case study in Eastern Indian Ocean

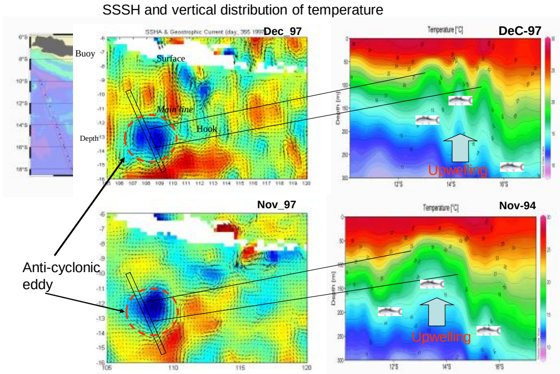


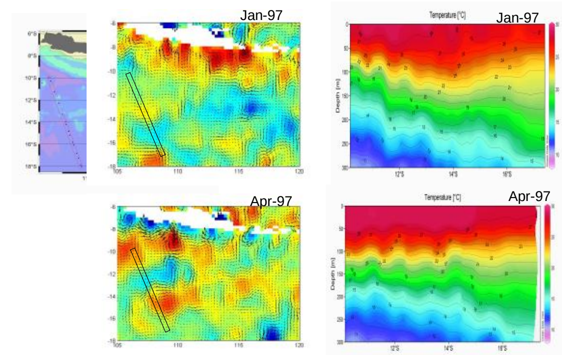
Around eddy → high chlorophyll concentrations

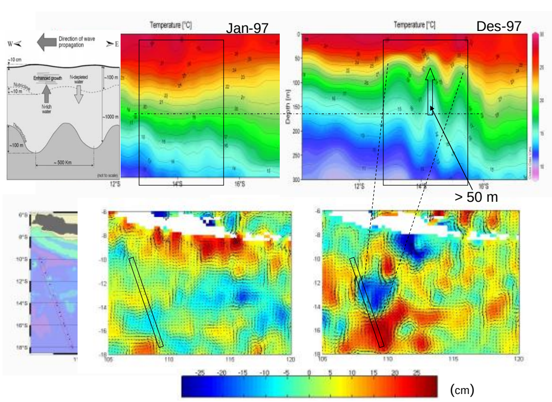


High Chl-a Concentration

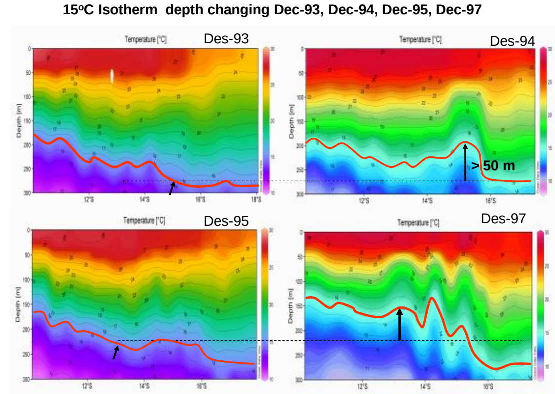
SSSH and vertical distribution of temperature

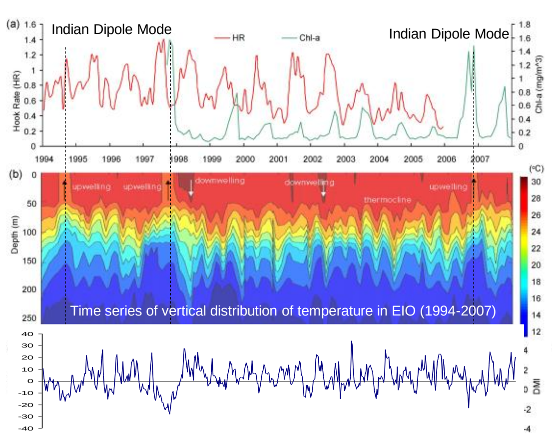




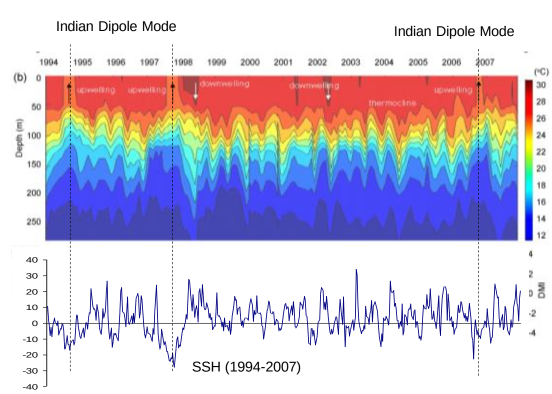


15^{o}C Isotherm depth changing Dec-93, Dec-94, Dec-95, Dec-97



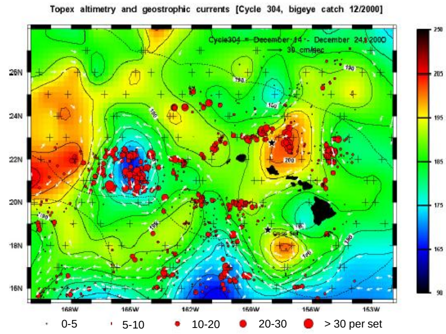


Time series of vertical distribution of temperature in EIO (1994-2007)

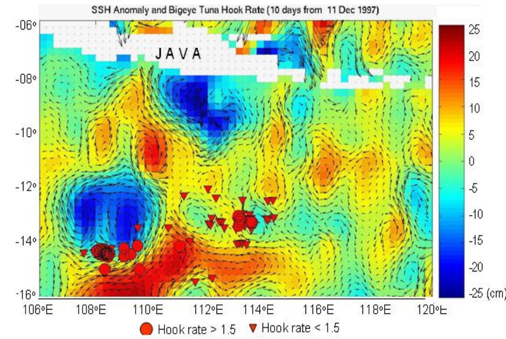


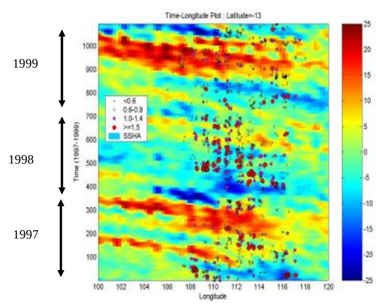
SSH (1994-2007)

Bigeye tuna catch concentrated around anticyclonic eddy (Hawaii)



Sea level, geostrophic current and beigeye catch (Seki, 2002)

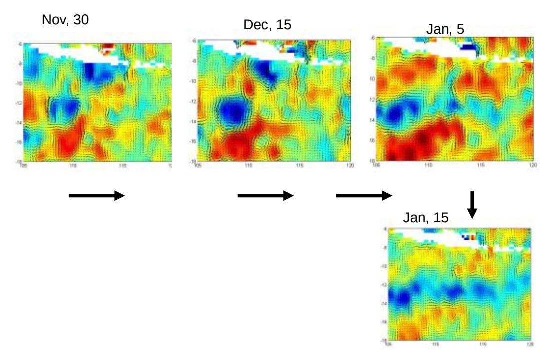




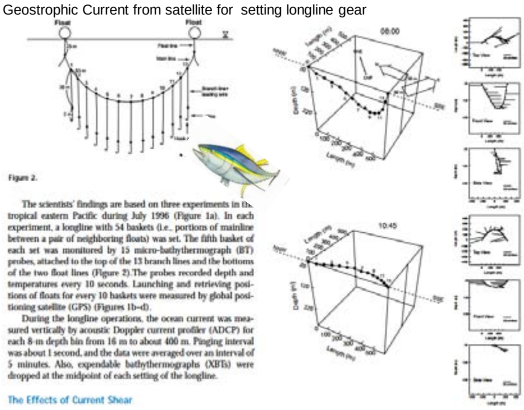
Time-longitude plot of SSHA and bigeye HR in Latitude 13ºS (1997-99)

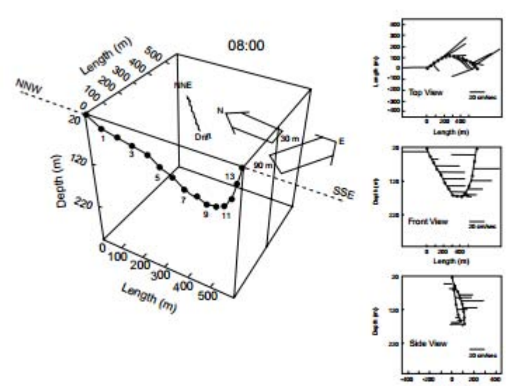
Correlation between SSHA (-) and HR>1.5 is significant around cyclonic eddies (-13º)

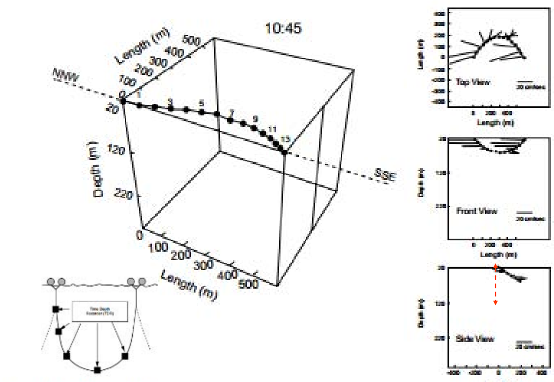
Lifetimes of anticyclonic eddy - more than a month



Geostrophic Current from satellite for setting longline gear





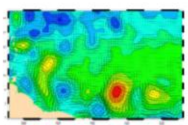


Offshore Operational Support: Gulf of Mexico (B. Leben)

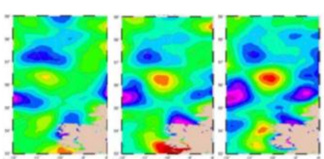
Data User: Capt. Karl Greig, captain of a large anchor handling tug boat owned by Edison Chouest Offshore.
Application: Route finding for towing semi-submersible drilling rigs used in deepwater oil and gas exploration.
Operation: Moving a rig from Mississippi Canyon block 68 to Mustang Island block 68, a total of 425 nautical miles. Typical towing speeds are 3 to 4 knots so avoiding and/or using eddy currents significantly reduces transit times, in this case by over 50 hours.
Altimeter Product Used: Overlays of geostrophic velocity vectors on colored magnitudes values accessed on CCAR website by satellite phone.
Estimated Savings: $650,000 in rig downtime and towing costs.

Offshore applications

SSALTO/DUACS products are tested to plan and monitor operations on offshore drilling sites as part of the EMOFOR project (CLS, Nansen Center and Fugro GEOS)



Real-time monitoring of North Brazil Current Rings



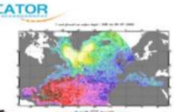
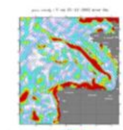
Eddy monitoring West of Ireland for offshore operations

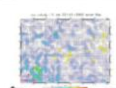
CLS

MERCATOR

Applications

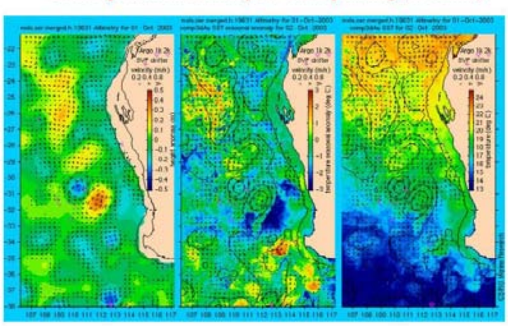
Increasing use of MERCATOR products by ocean service providers



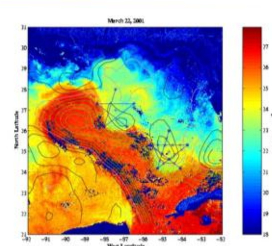

- **Public Service** : strong involvement in oil spill forecasting after the Prestige tanker disaster
  - Ocean bulletins by Mercator forecasters
  - System outputs available for coupling with oil spill dissemination models (Météo-France and Met.No)
- **Nautical Events** : Ocean races such as Route du Rhum or (now) Transat race Jacques Vabre ; etc
- **Research** (cruise planning)
- **Commercial** : fisheries (Catsat service)

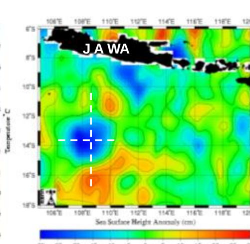
Use of operational altimetry for cruise planning (D. Griffin)



Large-scale situation at the beginning of the cruise. Used to decide which eddies to study, and where they were at the moment.

Sample Survey Design for Whale Survey





Research Professor Robert R. Leben
Colorado Center for Astrodynamics Research
University of Colorado at Boulder

APN Training: Satellite Altimetry
Lecture #3

Multivariate Sea Level Reconstruction

Multivariate Sea Level Reconstruction

B.D. Hamlington, R.R. Leben
Colorado Center for Astrodynamics Research
University of Colorado, Boulder

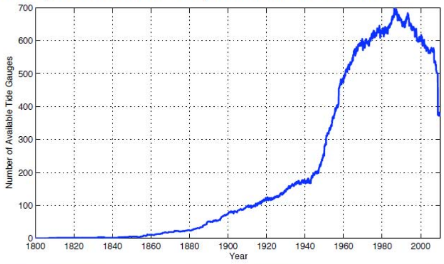
K.-Y. Kim
Seoul National University

What is a 'Sea Level Reconstruction'?

- Creating a sea level climate data record with sufficient duration, consistency and quality that can be used to accurately determine climate variability and change is a challenge.
  - **Tide Gauges**: Long record, but sparsely distributed.
  - **Satellite Altimetry**: Short record, but near-global coverage.
- Sea level is reconstructed by fitting altimetry-derived basis functions to tide gauge data.
  - [e.g. Chambers et al. (2002), Church and White et al. (2004), Ray and Douglas (2011) Hamlington et al. (2011), Meyssignac et al. (2011;2012)].
  - In past sea level and sea surface temperature (SST) reconstructions, generally empirical orthogonal functions (EOFs) have been used as the basis for the reconstruction.
- Here, we refer to a sea level reconstruction as a dataset with spatial coverage of satellite altimetry and length of tide gauge record.

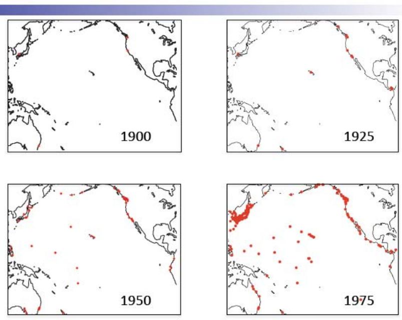
Tide Gauge Availability

- Number of available tide gauges in the Permanent Service for Mean Sea Level (PSMSL) RLR dataset over the period from 1807 to 2010.



Tide Gauge Availability

- Number of available tide gauges in Permanent Service for Mean Sea Level (PSMSL) RLR dataset between 1900 and 1975.

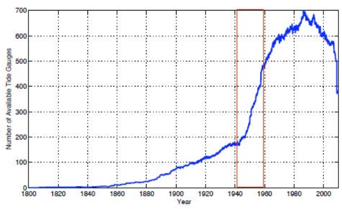


Reconstructing Sea Level Before 1950

- Gridded, globally reconstructed SST datasets extending back to 1850 are publicly available: why is a similar product not available for sea level?

Reconstructing Sea Level Before 1950

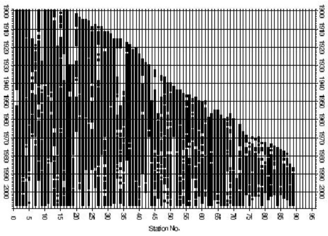
- **Previous reconstructions have primarily been used to study global mean sea level (GMSL) before 1950.**
  - Very limited discussion in literature regarding a sea level reconstruction of large-scale climate variability back to 1900.
  - Limits possibilities for climate monitoring and sea level studies.
- **Prior to 1950, the number of available tide gauges decreases rapidly.**
  - Difficult to reconstruct even the largest climate signals like ENSO, PDO etc.
  - Few or no tide gauges are available in the regions of high variability for signals like the EP and CP ENSO.



- Tide gauge availability in PSMSL from 1800 to 2011.

Ray and Douglas (2011)

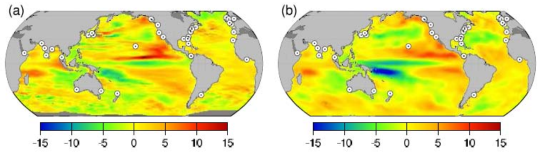
- Ray and Douglas (2011) provide one of the only discussions of sea level reconstruction prior to 1950.
  - Demonstrate difficulty in reconstructing climate variability prior to 1950.
  - Used fewer than 100 tide gauges in their reconstruction.



Ray and Douglas (2011)

Ray and Douglas (2011)

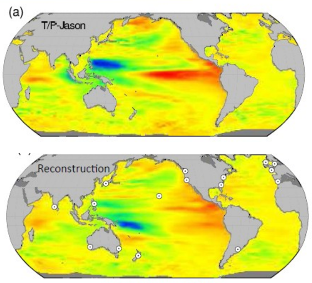
- Reconstruction of 1940/1941 ENSO using basis functions from (a) satellite altimetry, and (b) ocean model.



Ray and Douglas (2011)

Ray and Douglas (2011)

- Reconstruction of 1997/1998 ENSO using tide gauge sampling of 1920.
  - T/P-Jason satellite altimetry data (top), sea level reconstruction (bottom).
- Suggests limited number of tide gauges can not be used to reconstruct climate signals prior to 1950.



Ray and Douglas (2011)

Using SST to Reconstruct Sea Level

- Reconstructions are limited by the historical data that is available and and can be included in the procedure.
- Finding a way to include other climate variables can provide for a more accurate sea level reconstruction back to the turn of the century.
  - Here, satellite and historical sea surface temperature (SST) measurements are used to create an improved sea level reconstruction from 1900 to present.
  - Motivation: many more SST measurements than tide gauge measurements prior to 1950.
- This reconstruction technique relies on cyclostationary empirical orthogonal functions (CSEOFs) and a simple regression analysis (Kim et al., 1997; Kim et al, 2003).

Cyclostationary Empirical Orthogonal Functions

- Most SST and sea level reconstructions have relied on EOFs as basis functions.
  - EOFs are prone to mode mixing, particularly with regards to the annual signal.
- To address this and other problems, Kim et al. (1996; 1997; 2001) introduced the concept of cyclostationary empirical orthogonal function (CSEOF) analysis.
- EOFs decompose data into a temporal component (principal component time series – PCTS), and a spatial component (loading vector – LV).
- In contrast to EOFs, CSEOFs have time-dependent LVs that are periodic with a nested period, *d*.

$$T(r,t) = \sum_n P_n(t) LV_n(r,t)$$

$$LV_n(r,t) = LV_n(r,t+d)$$

  - When studying the annual cycle, for example, the LVs would represent the one-year nested periodicity, while the PC time series would describe the change in amplitude of the annual cycle over time.

Incorporating SST Into A Sea Level Reconstruction

- By performing a regression on the CSEOF PC time series, SST patterns can be created that have the same PC time series as corresponding SSH patterns.

1. Perform CSEOF analysis on satellite-measured SSH and SST data.
2. Regress all SST PC time series on each SSH PC time series:

$$PCTS_{SSH,n}(t) = \sum_i \alpha_i PCTS_{SST,i}(t) + \varepsilon(t)$$

3. Use regression coefficients to form SST spatial patterns, LVR(r,t) with amplitude fluctuations described by $PCTS_{SSH}(t)$:

$$LVR_{SST,n}(r,t) = \sum_i \alpha_i LV_{SST,i}(r,t)$$

4. Goal of reconstruction is to reproduce PCTS back through time → Use LVR_{SST} and LV_{SSH} fit to historical SST and sea level measurements, respectively, to reconstruct PC time series.

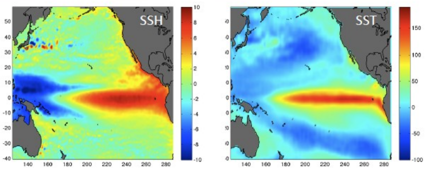
Data – Sea Level and SST

- **Sea Level Basis Functions**: ¼° resolution multiple altimeter AVISO dataset spanning 1993 to 2011.
  - CSEOF decomposition using 1-year nested period.
  - Used 11 modes in the reconstruction explaining 80% of the variability in the AVISO dataset.
- **Sea Level Historical Data**: Permanent Service for Mean Sea Level (PSMSL) tide gauges spanning 1900 to 2011.
  - Used over 400 tide gauges for reconstruction of Pacific Ocean region.
  - CSEOF reconstruction technique has been found to be relatively insensitive to poor tide gauge measurements.
- **SST Basis Functions**: 1° resolution NOAA Optimum Interpolation Sea Surface Temperature (OISST) spanning 1993 to 2011.
  - CSEOF decomposition using 1-year nested period.
- **SST Historical Data**: ICOADS 2° resolution SST anomalies spanning 1900 to 2011.
  - A monthly climatology was computed from 1960 to 1980 and removed from the data covering the period from 1900 to present in order to remove the seasonal signal from the observations.
  - All available observations in a 2°x2° bin were averaged together to form "super-observations".

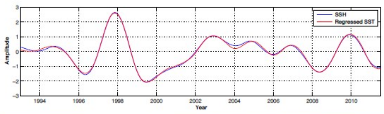
Reconstruction Procedure

- Sea Level and SST basis functions are fit simultaneously to reconstruct PC time series from 1900 to 2011.
  - Must assume that regression relationship holds over entire period of reconstruction.
  - Reconstruction of the Pacific Ocean is presented here.
  - The trend in GMSL has not been included, so all subsequent regional trends are shown relative to the background mean trend.
  - Reconstructions have also been computed for comparison using only TG measurements and using only SST measurements.
  - Seasonal signal is not used in the reconstruction, but could/should be included in the future.
  - Sea level and SST components of the reconstruction are weighted equally over the full time period from 1900 to 2011.
    - In general, leads to an individual tide gauge measurement being weighted more heavily than an individual SST measurement.

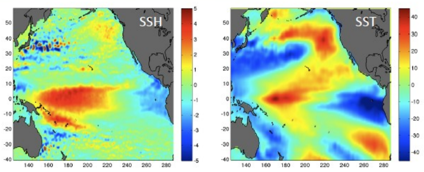
Regression: CSEOF Mode 1



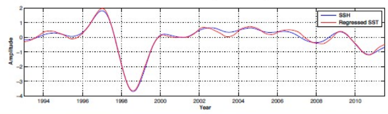
*(Only 1 of 52 maps shown)



Regression: CSEOF Mode 2

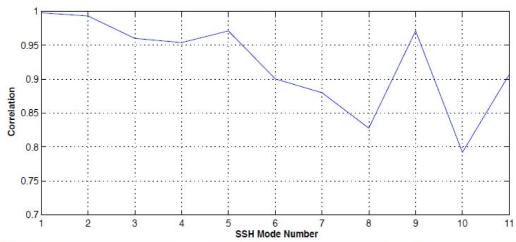


*(Only 1 of 52 maps shown)



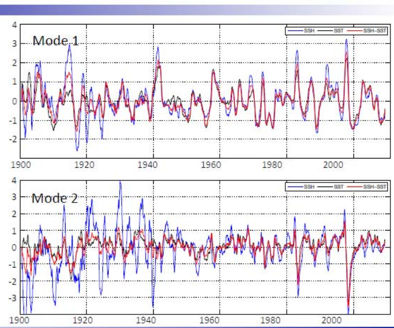
SSH vs. Regressed SST PCTS Correlation

- Correlation between SSH PC time series and regressed SST PC time series for first 11 modes from 1993 to 2011.



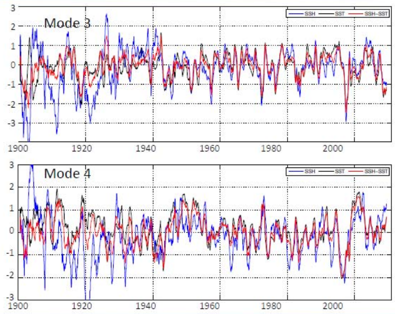
Reconstructed PC Time Series

- Reconstruction of first two PCTS from 1900 to 2010 for the Pacific Ocean region.
- Three reconstructions are shown, one using only sea level measurements (blue), one using only SST measurements (black), and a bivariate reconstruction (red) that incorporates both.



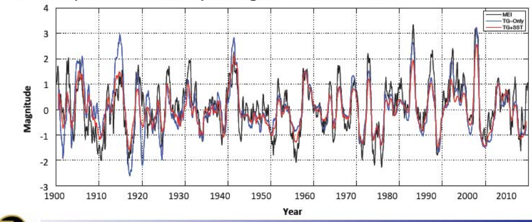
Reconstructed PC Time Series (cont.)

- Reconstruction of PCTS for modes 3 and 4 from 1900 to 2010 for the Pacific Ocean region.
- Three reconstructions are shown, one using only sea level measurements (blue), one using only SST measurements (black), and a bivariate reconstruction (red) that incorporates both.



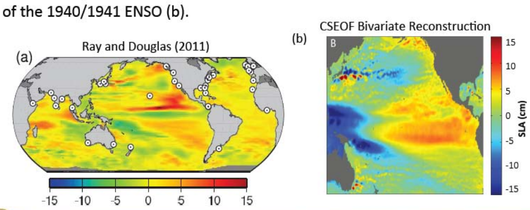
Eastern-Pacific ENSO

- Comparison between Multivariate ENSO Index (MEI) and reconstructed mode 1 PCTS from TG-only (blue) and TG-SST (red) reconstructions.
- TG-only reconstruction captures EP ENSO signal well over full time period.
- Some improvement seen by adding SST measurements.



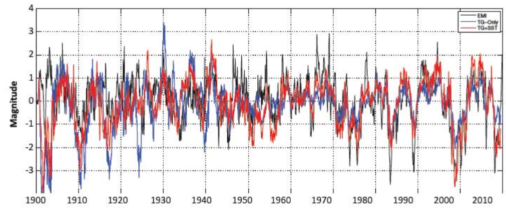
Comparison of 1940/1941 ENSO

- While the goal of their reconstruction was not to capture specific climate signals, Ray and Douglas (2011) show results for the reconstruction of the 1940/1941 ENSO event (a).
- The bivariate (TG+SST) reconstruction shows the improved representation of the 1940/1941 ENSO (b).



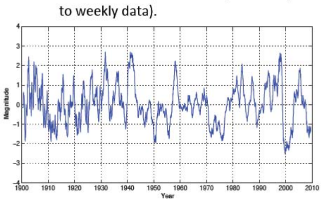
Central-Pacific ENSO

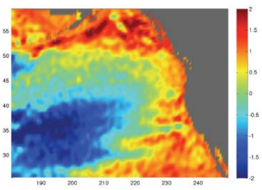
- Comparison between EMI from HadSST2 reconstruction and EMI from TG and TG-SST reconstructions.
- Agreement improved prior to 1950 by incorporating SST measurements.



Pacific Decadal Oscillation

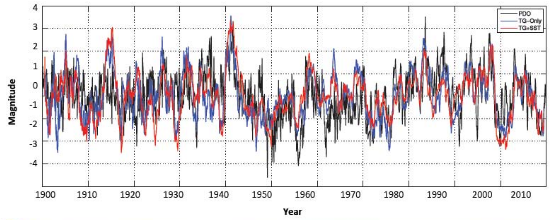
- We can compute an index for the Pacific Decadal Oscillation by performing an EOF decomposition of the north Pacific.
  - PDO index is represented by the first (leading) EOF (no smoothing has been applied to weekly data).





Pacific Decadal Oscillation

- Comparison between PDO from long time series SST (Mantua et al. 1997) and PDO from TG and TG-SST reconstructions.
  - Computed as PCTS of first EOF in the north Pacific.



Correlation with Climate Indices

Reconstruction	TG-only	SST-only	TG-SST
MEI 1950-2010	**0.92** (0.95)	**0.92** (0.94)	**0.95** (0.97)
MEI 1900-2010	**0.77** (0.80)	**0.84** (0.89)	**0.86** (0.91)
EMI 1950-2010	**0.72** (0.84)	**0.75** (0.87)	**0.82** (0.91)
EMI 1900-2010	**0.34** (0.48)	**0.58** (0.75)	**0.64** (0.80)
PDO 1950-2010	**0.62** (0.73)	**0.54** (0.66)	**0.67** (0.77)
PDO 1900-2010	**0.49** (0.60)	**0.55** (0.60)	**0.59** (0.68)

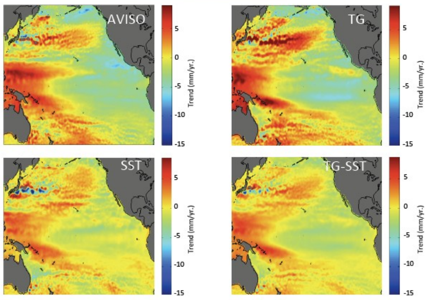
(*Numbers in parentheses represent correlations after 1 year smoothing is applied)

Regional Sea Level Trends

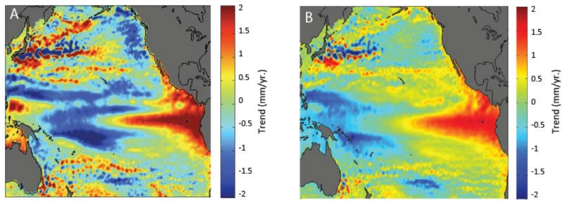
- Reconstructions can also be used to compute regional trends in sea level change.
- Regional sea level trends have found to be very sensitive to the basis functions and reconstruction technique employed [Meyssignac et al. (2012); Hamlington et al. (2012)].
- Reconstructions have generally shown very different trend patterns over the time period from 1950 to present.
  - Most have avoided computing and presenting regional trends back to 1900.
- Comparison to satellite altimetry trends also provides another way to evaluate the quality of the reconstruction.

Regional Trends 1993-2011

- Regional trends from 1993 to 2011 computed for three different sea level reconstructions (TG-only, SST-only, and TG+SST) and compared to AVISO.
- All three reconstructions agree reasonably well.
- Able to reconstruct sea level trends using only SST.



Regional Trends 1900-2011



- Good agreement between the regional trends estimated from the two different reconstructions [(A) TG-only and (B) TG+SST] over the full time period of the reconstruction, although greater magnitude for TG-only reconstruction.

Historical Sampling Tests

- To test whether or not the historical data is sufficient to capture sea level variability, we perform sampling tests.
  - The distribution of historical sea level and SST measurements in 1920, 1940, 1960 and 1980 is used during the altimeter time period from 1993 to 2010 to reconstruct sea level from coincident tide gauge sea level and in situ SST measurements.
  - In other words, use only the handful of tide gauges and SST measurements at that were available during past decades to perform the 1993 to 2010 reconstruction and subsequently compare to the AVISO data.
  - Results are shown as a percentage given by the formula:

$$\%Difference = 100(\frac{RMSE_{sub} - RMSE_{full}}{RMSE_{full}})$$

  - RMSE is computed using the difference between the reconstructed sea level from 1993 to 2010 and the AVISO satellite altimetry data over the same period.

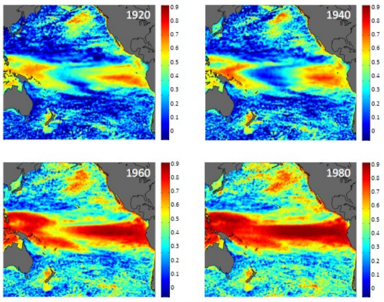
Historical Sampling Tests

	Year Specifying Spatial Sampling			
Reconstruction Type	**1920**	**1940**	**1960**	**1980**
CSEOF TG-Only Recon.	58.8	42.4	10.3	2.62
CSEOF SST-Only Recon.	3.15	2.18	1.15	1.12
Combined TG + SST Recon.	2.22	2.08	0.81	0.38

- Reconstruction is significantly improved by using both TGs and SST measurements, particularly before 1950.
- Reconstruction of sea level using SST is superior to the reconstruction using only sea level for all time periods considered.

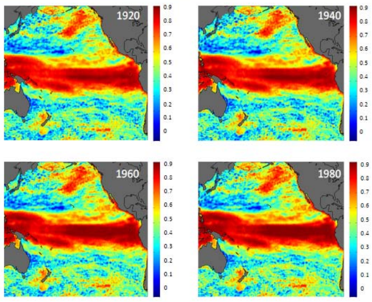
Historical Sampling Tests– TG-only

- Correlation between TG-only weekly reconstruction and AVISO from 1993 to 2011 using historical sampling from 1920, 1940, 1960, and 1980 (seasonal signal removed prior to computing correlations).



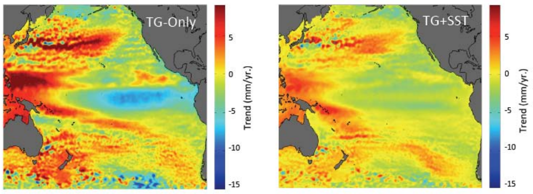
Historical Sampling Tests – TG + SST

- Correlation between bivariate (TG+SST) weekly reconstruction and AVISO from 1993 to 2011 using historical sampling from 1920, 1940, 1960, and 1980 (seasonal signal removed prior to computing correlations).
- Significant improvement in past compared to TG-only reconstruction.
- Little variation between correlation maps as sampling changes.



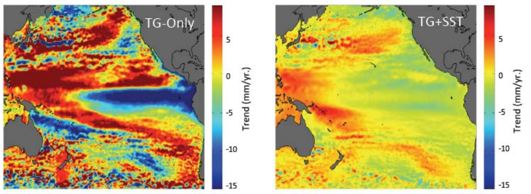
Historical Sampling Tests – Trends

- Reconstruction of trends from 1993 to 2010 using historical sampling from 1980.



Historical Sampling Tests – Trends

- Reconstruction of trends from 1993 to 2010 using historical sampling from 1920.



What does the bivariate reconstruction mean for regional and global trends?

- Improved reconstruction back to 1900 allows for better understanding of regional trend patterns.
- While we do not directly estimate GMSL from 1900 to 2011 here, improved reconstruction of climate signals can improve estimates of GMSL.
  - GMSL can not be computed using SST measurements.
  - Must rely only on tide gauges to estimate GMSL in the past.
  - With a longer record, we can better understand contributions of signals like ENSO and PDO to GMSL trends on both short and longer timescales.
  - Removing known climate signals from tide gauges prior to the computation of GMSL can improve estimates of trend on GMSL.

Summary

- Tide gauge distribution is very sparse prior to 1950.
  - Difficult to reconstruct specific climate signals.
  - Past reconstructions have primarily focused on GMSL prior to 1950.
- Including SST measurements allows for the reconstruction of signals like ENSO and the PDO in sea level back to 1900.
  - Reconstructed sea level dataset from 1900 to 2011 has been produced and is available for a variety of applications.
  - Historical grid testing has shown the importance of using the bivariate approach in reconstructing sea level, particularly before 1950.
  - An accurate sea level record spanning the period from 1900 to 2011 will allow for improved climate monitoring.
- Future Work:
  - Perform reconstruction in other regions of the ocean.
  - Include additional observations (e.g. sea level pressure, winds).
  - Study how climate signals contribute to regional and global sea level trends.

Multivariate Exercise

Tuesday, November 13th, 2012
Exercise: Reconstruction of Sea Level Change in SE Asia

In this exercise, we will look at reconstructed sea level data in SE Asia using two different approaches: 1) univariate approach that uses only tide gauge data, and 2) bivariate approach that incorporates sea surface temperature in the reconstruction.

1. Load the file **seas_multivariate_data.mat.** This file contains the variables **time**, **lat**, **lon**, and **seas_multi_data**, which contains the reconstructed sea level data for SE Asia using the multivariate CSEOF approach. Use pcolor to visualize some of the reconstructed sea level fields.

2. Load the .mat file **tg_monthly.mat.** This contains the tide gauge data used to compute each reconstruction. Using the data in **tg_monthly.mat**, find all the tide gauge data found in the SE Asia region as defined by the variables lat and lon. How many tide gauges were available and providing data in the region before 1990? Before 1980? Plot the time series for some of these tide gauges.

3. Compute the linear trend at each point in the data field for **seas_multi_data**, to form a map of the reconstructed sea level trends. Plot this using pcolor.

4. Compute the mean sea level time series from the variable **seas_multi_data** for the region. Save the linear trend map created in question 3 and the mean sea level time series created in question 4 to a .mat file. This will be used for comparison later.

5. Clear your workspace. Then, load the file **seas_tgonly_data.mat.** This file contains the variables **time**, **lat**, **lon**, and **seas_tgonly_data**, which contains the reconstructed sea level data for SE Asia using the univariate CSEOF approach. Use pcolor to visualize some of the reconstructed sea level fields.

6. Compute the linear trend at each point in the data field found in **seas_tgonly_data**, to form a map of the reconstructed sea level trends. Plot this using pcolor.

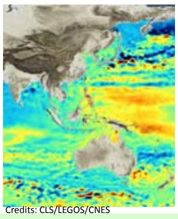
7. Compute the mean sea level time series from the variable **seas_tgonly_data** for the region. Plot the mean sea level time series computed in question 3 simultaneously with the data computed in question 6.

8. Again, load the file **tg_monthly.mat**. This contains the tide gauge data used to compute each reconstruction. Find the tide gauge time series for the Guam tide gauge, located at **lattg = 13.5** and **lontg = 144.5**. Find the corresponding time series in **seas_tgonly_data** and in **seas_multi_data**. Plot all three time series simultaneously. Which reconstruction appears to match the tide gauge data better? Do this for some of the other tide gauges in the region.

9. Using the **seas_multi_data** reconstructed sea level, compute a linear trend map using only the data from 1976 to 1992. Then compute the linear trend map using only the data from 1993 to 2009. Compare the two trend maps.

Capturing the coastal zone:
a newfrontier for satellite altimetry

Capturing the coastal zone: a new frontier for satellite altimetry



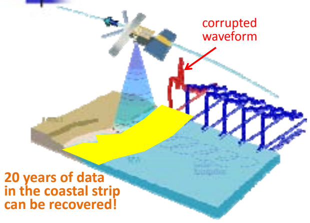
Stefano Vignudelli
Consiglio Nazionale delle Ricerche, Italy
On behalf of
COASTALT project team
+ the coastal altimetry community

A community contribution

- from the Organizers and session chairs of 5th and 6th Coastal Altimetry Workshop (CAW-5 and CAW-6):
  - J. Benveniste (ESA), L. Miller (NOAA), N. Picot (CNES), R. Scharroo (NOAA/Altimetrics), T. Strub (OSU), D. Vandemark (UNH), S. Vignudelli (CNR), S. Zoffoli (ASI), O. Andersen (DTU), L. Bao (Chinese Acad. Sci), F. Birol (CTOH/LEGOS), E. Coelho (Stennis), X. Deng (U Newcastle). W. Emery (U Colorado), L. Fenoglio-Marc (TU Darmstadt), J. Fernandes (U. Porto), J. Gòmez-Enri (U Cadiz), D. Griffin (CSIRO), G. Han (Fisheries and Oceans), J. Hausman (JPL), K. Ichikawa (Kyushu U), A. Kostianoy (P.P. Shirshov), V. Kourafalou (U Miami), S. Labroue (CLS), R. Ray (NASA/GSFC), M. Saraceno (U Buenos Aires), W.H.F. Smith (NOAA), P. Thibaut (CLS), J. Wilkin (Rutgers U), S. Yenamandra (NIO)
- and from the many scientists who have presented their results at the Workshops

Satellite altimetry: from global to regional

Why do coastal altimetry?



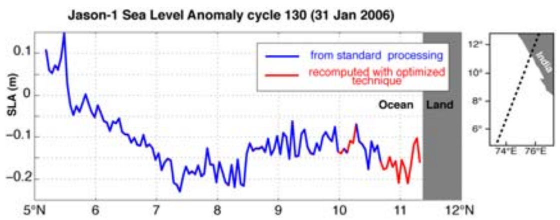
Traditionally, data in the coastal zone are flagged as bad and left unused

(coastal zone: as a rule of thumb 0-50 km from coastline, but in practice, **any place where standard altimetry gets into trouble** as waveforms are non-Brown and/or corrections become inaccurate)

In recent years a vibrant community of researchers has started to believe that
most of those coastal data can be recovered
and that coastal altimetry can be **a legitimate component of coastal observing systems!** *(see OceanObs'09 Community White Paper on coastal altimetry)*

Also important for **SAR & Ka-band altimetry, having good coastal performance !**

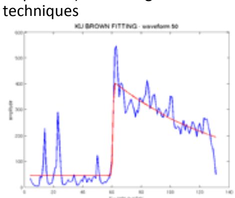
Example of coastal altimetry



How we recover more data

0-10 km

A. Specialized **retracking**
   - Use better waveform models, accounting for change of shape in coastal environment
   - Use specialized (2-D or sequential) retracking techniques



0-50 km

B. Improved **Corrections**
   - Most crucial is the correction of path delay due to **water vapour** ("wet tropospheric" correction)
   - Some applications require correction of **tidal** and **high-frequency** signals, which are also difficult to model in the coastal zone

Both validation and applications require **exploitation of coastal models & in situ measurements**

…the history bit…

- **Some early studies**
  - Manzella , Vignudelli et al. 1997 – custom wet tropospheric correction
  - Crout 1998 - could recover data when coastal topography is flat
  - Anzenhofer et al. 1999 – retracking coastal waveforms
  - Vignudelli et al. 2000 - Signal recovered consistent with in situ data

ALBICOCCA
France-Italy-UK 2001/04
Feasibility

ALTICORE-EU
EU/INTAS 2006/08
Capacity building

MAP/XTRACK/MARINA
CNES/LEGOS/CTOH ongoing
Integrated approach to data editing filtering, multimission, dissemination

DATA available

ALTICORE-India
ALTICORE-Africa

PRODUCT DEVELOPMENT STUDIES INCLUDING WAVEFORM RETRACKING

PISTACH
CNES 2007-present
For Jason-2

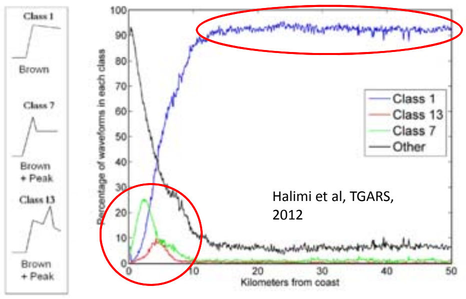
COASTALT
ESA 2008-2011
For Envisat

→ now following with **eSurge** *(multimission, 2011-2014)*

…plus several OSTST Projects funded by NASA and CNES

Recent improvements - retracking

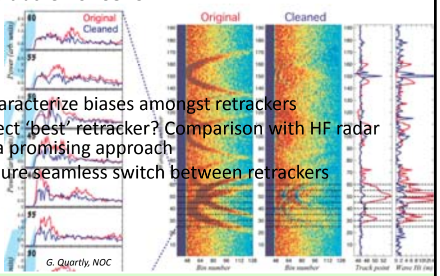
- modified models: "reduced waveform", Brown+peaks



Halimi et al, TGARS, 2012

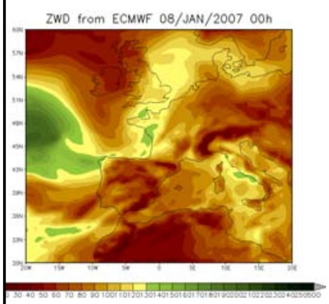
Recent improvements - retracking

- Treating waveforms sequentially
  - Truncated SVD filtering for noise reduction – OCE3 retracker for PISTACH
  - Hyperbolic Pre-tracker for COASTALT



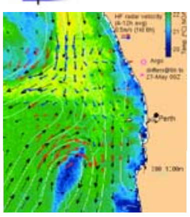
- Issues
  - Need to characterize biases amongst retrackers
  - How to select 'best' retracker? Comparison with HF radar (Emery) is a promising approach
  - How to ensure seamless switch between retrackers

Recent improvements - corrections



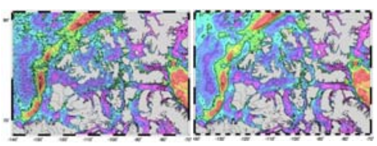
- the wet tropo varies rapidly especially in the coastal environment models like this from ECMWF (ZWD=Zenith Wet Delay) may not capture its dynamics and short-scale variability.
- Wet Tropospheric: crucial improvements
  - **Mixed-Pixel Algorithm** (S. Brown)
  - **Land Proportion Algorithm** (PISTACH group)
  - **GPD**: GNSS-derived Path Delay (J. Fernandes for COASTALT)
  - **CNN** – Coastal Neural Network wet tropo for Envisat (CLS), from $T_{brightness}$, Land Proportion and sigma0

Applications



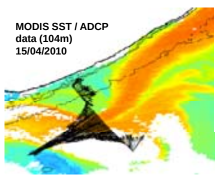
Comparison of Cryosat with Sub-mesoscale currents from HF-radar (D. Griffin)

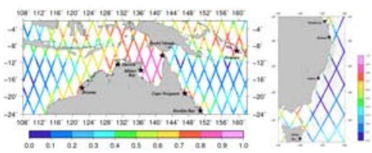
J-1 geodetic and Cryosat novel gravity data → improved gravity maps (O. Andersen)



Applications

Successful identification of sub-mesoscale Natal pulses in comparison PISTACH 5Hz velocity vs in situ (from ACT campaign) (M. Cancet)

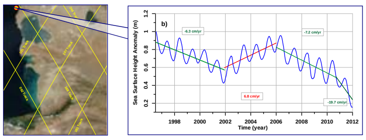




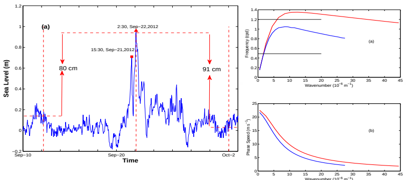
Statistical regression model to predict coastal sea level extreme events (X. Deng)

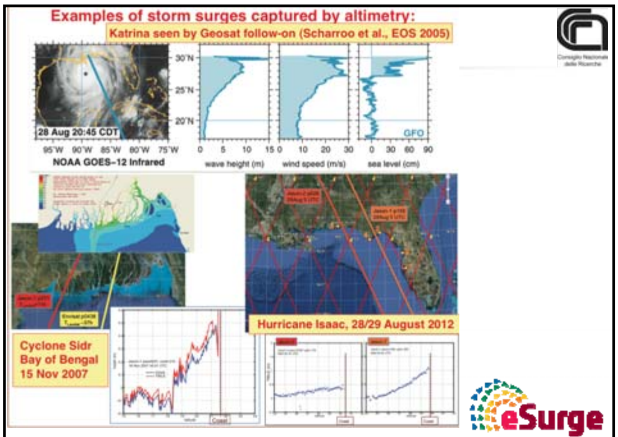
Applications

Inter-annual, seasonal variability in Caspian Sea, bay and lake levels (A. Kostianoy)



Storm Surges: Hurricane Igor storm surge and ensuing free Coastally Trapped Waves; propagation and dispersion agree with CTW theory





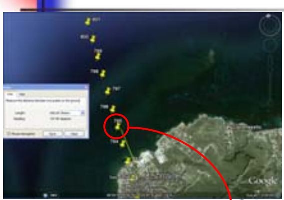
Issues for cal/val and sea level

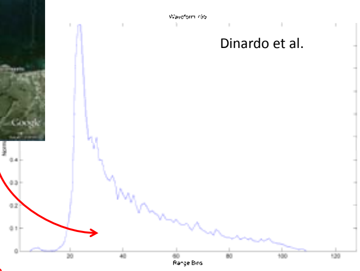
- Coastal altimetry is needed to link the open ocean with tide gauges
  - 'fills a gap' in the cal/val process
- And then, is sea level rising faster at the coast?

The SAR data revolution

- delay-Doppler (SAR altimeter) allows a much better characterization of short scales
- This is not only useful at the coast: think of areas of strong submesoscale activities, (filaments, very intense fronts across storms), major oil slicks, etc
  - cross-fertilization of ideas with open-ocean scientists (and also inland, ice margins); technical improvements will benefit altimetry in general
- We need to work closely with the in situ community (**for cal/val**) and modelling community (**for data assimilation**)
- *Is Sentinel-3 going to be the first operational coastal altimetry mission?*

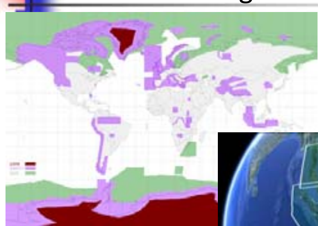
Cryosat-2 data in the coastal zone





When the track approaches the coast almost orthogonally, the waveforms conform well to the delay-Doppler Altimetry model (and give sensible results when retracked), up to 500m from the coast or even closer.

Cryosat-2 collects data over the Indonesian region

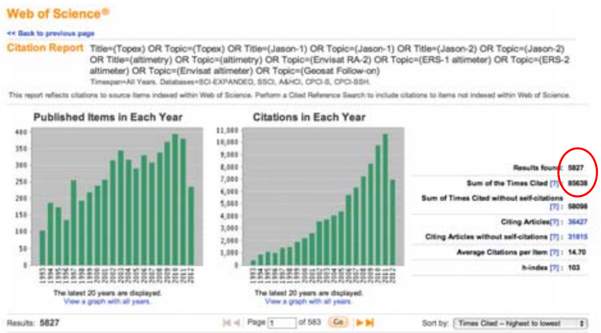


- Several low-lying and densed-populated coastal areas
- Prone to sea level rise and surges

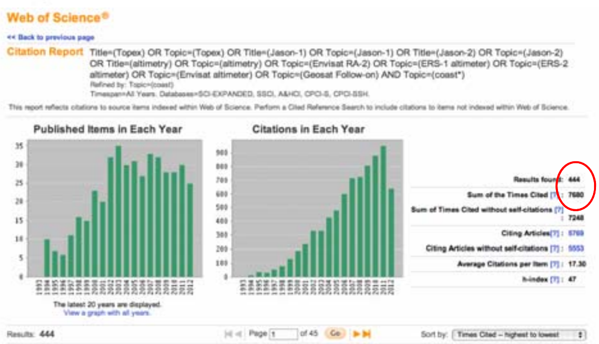
- Satellite altimetry is one piece of the puzzle
- Conceptually simple, but challenged by specific processing
- In situ sea level measurements critical for the generation of accurate altimeter-derived estimates

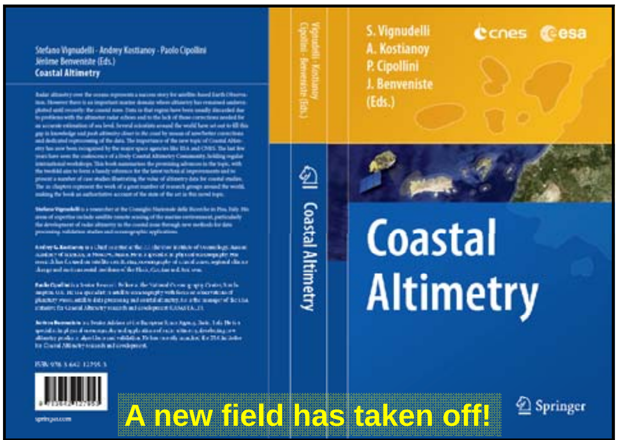
6th Coastal Altimetry Workshop, Riva del Garda 20/21 September 2012
- Community review of science and applications
- Recommendations to OSTST (see them at www.coastalt.eu)

Altimetry: exceptional impact…



…but we must do better at the coast!





A new field has taken off!

Recommendations from the 6th Coastal Altimetry Workshop

The Coastal Altimetry Community

"The community of coastal altimetry scientists and users who convened in Riva del Garda for the 6th Coastal Altimetry Workshop on 20/21 September 2012 recommends that…"

1. coordinated efforts for products

"…coordinated effort should be put into generating and distributing a harmonized, well-documented multi-mission coastal altimetry product calibrated to common standards and tailored to end-users, to foster the uptake of those data for improved analysis and prediction of coastal ocean circulation. This effort should include a reprocessing of the existing ~20 year record from past missions, a portal for data access and information sharing."

[this objective sounds very ambitious – but we will get there step by step!]

2. continued R&D

"…further R&D should be invested towards improving the techniques for processing, interpretation and cal/val of altimetry data in the coastal zone, including a full exploitation of the new opportunities offered by SAR altimetry and Ka-band altimetry. The in situ and modelling community need to be engaged in this process"

[This follows on the experience gathered in 20 years of open-ocean altimetry, where the support by Space Agencies has proved crucial to achieve the current, climate-level maturity of the field]

3. easy access to level 1 data

"…level 1 data should be made easily available as the foundation of further R&D and the basis for reprocessing since significant progress can only be made by going back to full bit rate data"

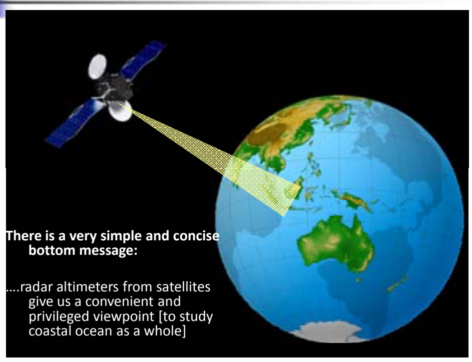
4. planning future missions

"…every effort should be made to maximize the sampling and information content of future altimetric missions, which is particularly important for coastal zone applications. To this purpose, the adoption of the interleaved mode for Jason-CS is strongly recommended as it will also benefit retrospectively previous SAR missions."

5. and, finally, SAR for Sentinel-3!

- "… in order to improve the precision and resolution of the data for all ocean applications, the area of Sentinel-3 SAR altimeter acquisition over the ocean should be maximized.

Thank you for your attention!



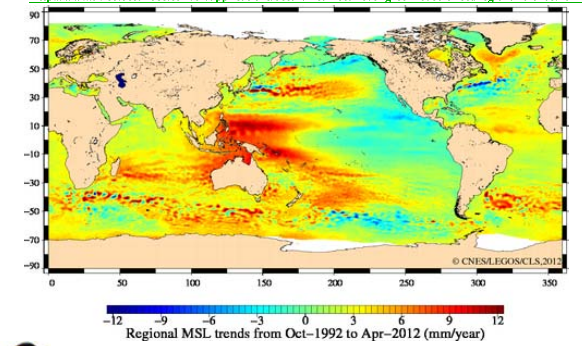
Sea Level Trends in Southeast Asian Seas

Sea Level Trends in Southeast Asian Seas

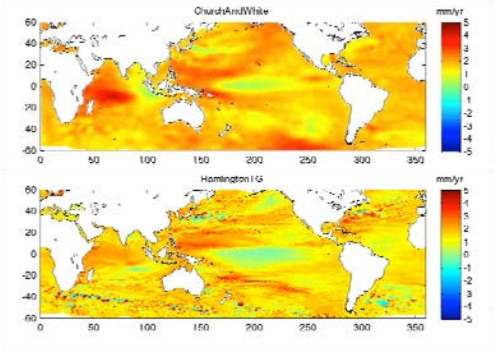
Research Prof. Robert Leben
Colorado Center for Astrodynamics Research
Dept. of Aerospace Engineering Sciences
University of Colorado, Boulder

~20-year AVISO Regional Mean Sea Level (MSL) Trends

http://www.aviso.oceanobs.com/en/applications/ocean/mean-sea-level-greenhouse-effect/regional-trends.html



Sample 60-year MSL Trends: 1950 through 2009 from Sea Level "Reconstructions"



Open Questions

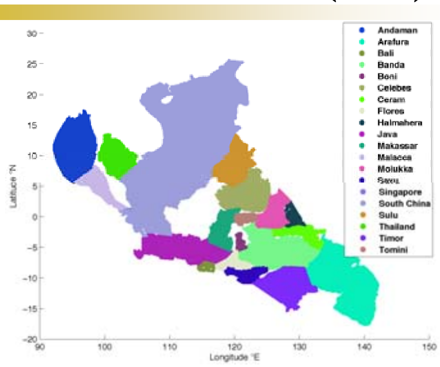
1. **How accurate are regional MSL trends computed from sea level reconstructions?**
2. **At what time and space scales can MSL trends be relied upon by scientists and decision makers interested in past, present, and future sea level rise?**

This study is funded in part by the Asian Pacific Network for Global Change Research project ARCP2011-21NSY-Manurung:

"Reconstruction of Sea Level Change in Southeast Asia (RESELECASEA) Waters Using Combined Coastal Sea Level Data and Satellite Altimetry Data"

Thus, we focus on the South East Asian Seas (SEAS) ....

Southeast Asian Seas (SEAS)



SEAS Region

The SEAS region is comprised of a total of 20 bodies of water including sea, straits and gulfs according to the *Limits of the Oceans and Seas* (1953).

- **The region has many low lying and densely populated coastal areas including large urban and rural river deltas and thousands of small inhabited islands.**
- **The region is one of the most biodiverse oceanographic regions on our planet.**
  - **Southeast Asia's coral reefs have the highest degree of biodiversity of all the world's coral reefs.**
  - **It is estimated that only 10 percent of marine species associated with coral reefs have been identified and described.**
- **The region is increasingly impacted by sea level rise and warming climate.**

"Pros and Cons" of Sea Level Reconstructions in the SEAS

"Pros and Cons" is from Latin "pro et contra" which in English means "for and against"

The "Pros"

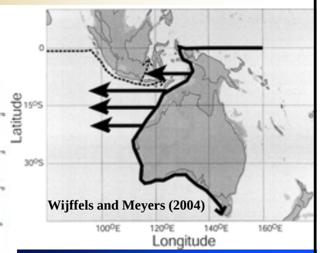
- SEAS mean sea level trends are controlled to a large degree by Pacific and Indian ocean variability.
- Strong "signal to noise" in the region increases accuracy of sea level reconstruction and trend detection.

The "Cons"

- Historical tide gauge coverage is very limited.
- Tide gauge spatial coverage is extremely sparse, probably the sparsest of any densely populated coastal area on the globe.
- Much of the region is coastal and shallow seas, which limits the accuracy of mapped altimetry. AVISO maps are based on along-track data edited within ~75 km of the coast.

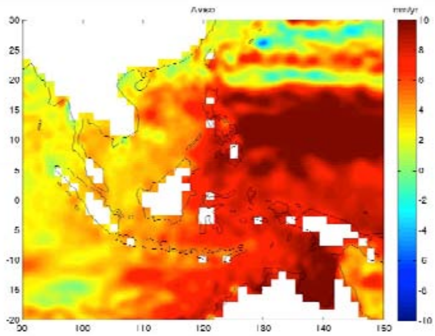
Controlling Physics

Indonesian throughflow and thus sea level ...

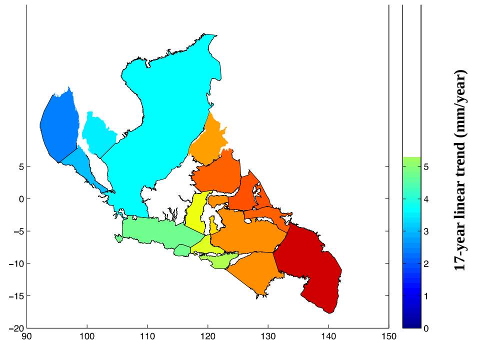


...is driven primarily by free equatorial Kelvin and Rossby waves originating along the Indian and Pacific equatorial waveguides.

17-year AVISO MSL Trends



17-year AVISO SEAS MSL Trends



Outline of Presentation

1. Global sea level reconstructions
2. SEAS tide gauge observations of sea level
3. Bivariate sea level reconstructions
4. SEAS *in situ* observations of SST
5. Global sea level trends and analysis
6. SEAS sea level trends and analysis.
7. Summary and conclusions

Global Sea Level Reconstructions

Global Sea Level Reconstructions

Church et al. (2004) Church and White (2006)
- Tide Gauge - CW

Hamlington, Leben & Kim (2012)
- Tide Gauge - HLK/TG
- Bivariate – HLK/BV

Meyssignac et al. (2011)
- Tide Gauge – M/Alt
- Mean (Alti, SODA, DRAKKAR) – M/Mean

What is a "reconstruction"?

A "reconstruction" is a reduced state space optimal interpolation first described by Kaplan et al. (1998).

Basic procedure:
- Compute basis functions from a "training" data set such as gridded satellite observations or model simulations.
- Truncate to a reduced set of basis functions.
- Optimally interpolate historical observations using the selected basis functions.

NOTE: Special procedures much be used to account for lack of knowledge of the mean to reconstruct sea level using altimeter observations and tide gauge measurements.

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University of Colorado, Boulder, CO USA
International Workshop on Coastal Altimetry
The RESELECASEA Project – Bogor – 14 November 2012

TG/Altimetry Trained: Church and White

Basis Functions: EOFs

Training Data: Custom 1° by 1° monthly SSHA maps derived from TOPEX/ Poseidon, Jason-1 and OSTM (Jason-2) 10-day repeat altimetry using a 300 km Gaussian filter

Training Data Time Period: Jan 1993 through Dec 2009

Number of Modes: 20

Percent of Variance: 84% of the non-annual signal

Observations: Monthly sea level observations from 426 PSMSL tide gauge stations

Reconstructed Time Period: 1950 through 2009

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TG/Alt Trained: Meyssignac et al. (2011)

Basis Functions: EOFs

Training Data: Annual Averaged AVISO

Training Data Time Period: 1993 through 2009

Number of Modes: 15

Percent of Variance: ?? > 88% for white noise (15/17)

Observations: Annual averaged sea level observations from 91 PSMSL tide gauge stations

Reconstructed Time Period: 1950 through 2009

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TG/Model Trained: Meyssignac et al. (2011)

Basis Functions: EOFs

Training Data: SODA 2.0 and DRAKKAR/NEMO model data

Training Data Time Period: 1958 through 2007 (50 years)

Number of Modes: 15

Percent of Variance: ??

Observations: Annual averaged sea level observations from 91 PSMSL tide gauge stations

Reconstructed Time Period: 1950 through 2009

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TG/Alt Trained: Hamlington et al. (2012)

Basis Functions: Cyclostationary EOFs (CSEOFs)

Training Data: AVISO weekly SSHA subsampled to ½° by ½°

Training Data Time Period: 1993 through 2009 (17 years)

Number of Modes: 11

Percent of Variance: 80% of the non-annual signal

Observations: Monthly sea level from 377 PSMSL tide gauge stations upsampled to weekly observations

Reconstructed Time Period: 1900 through 2009

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SEAS Tide Gauge Observations

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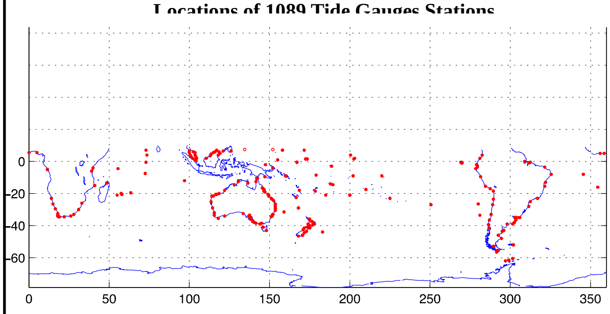
PSMSL Gauges Used by Hamlington, Leben and Kim



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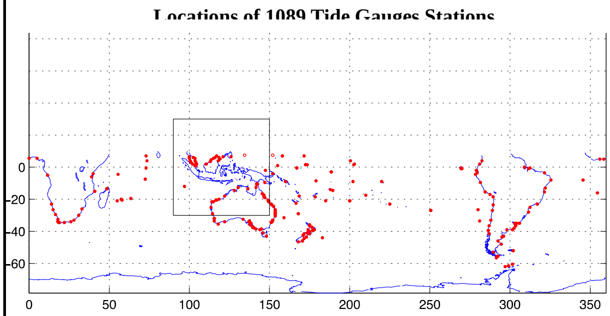

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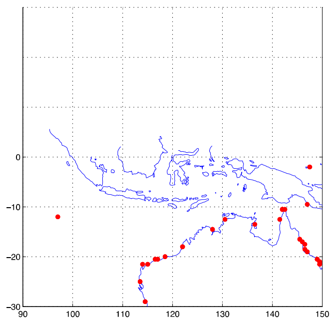
SEAS Region Tide Gauges



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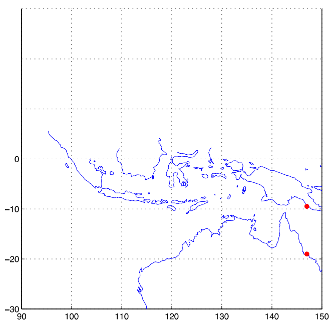
Station Coverage in the 1950s



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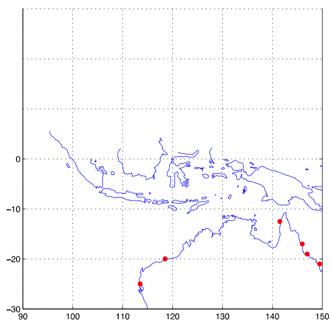
Station Coverage in the 1960s



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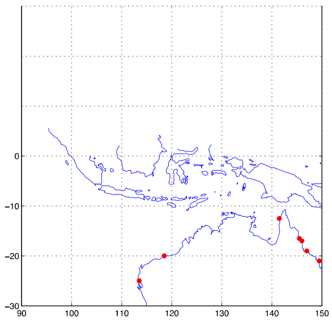
Station Coverage in the 1970s



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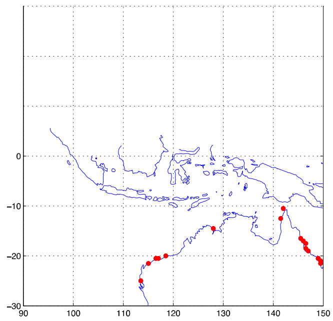
Station Coverage in the 1980s



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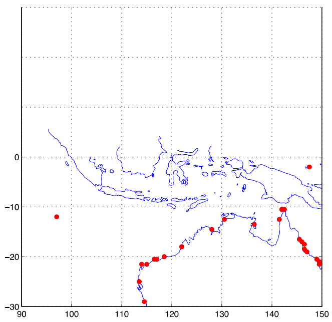
Station Coverage in the 1990s



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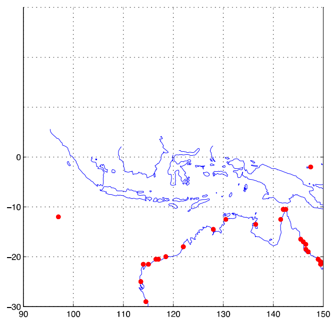
Station Coverage in the 2000s



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Bivariate Sea Level Reconstruction

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Tandem TG & SST: Hamlington et al. (2012)

"First Bivariate Reconstruction of Sea Level"

Basis Functions: Cyclostationary EOFs (CSEOFs)

Training Data:

- AVISO weekly SSHA subsampled to ½° by ½°
- NOAA OISST weekly 1° by 1° SST

Training Data Time Period: 1993 through 2009 (17 years)

Number of Modes: 11

Percent of Variance: 80% of the non-annual signal

Observations:

- Monthly sea level from 377 PSMSL tide gauge stations
- Monthly SST ICOADS 2° by 2° "super observations"

Reconstructed Time Period: 1900 through 2009

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SEAS SST Observations

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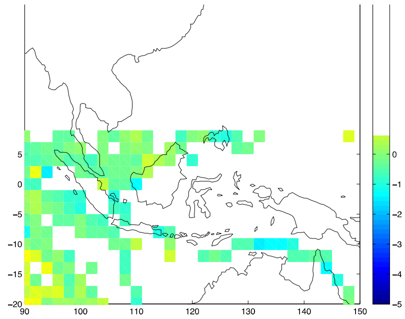
ICOADS SST Observations Week 1 1950



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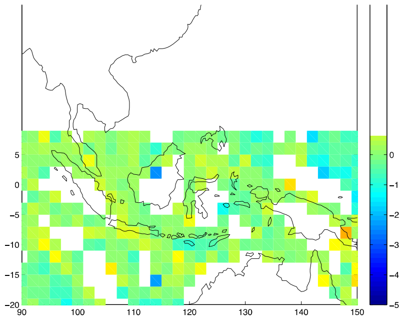
ICOADS SST Observations Week 1 1960



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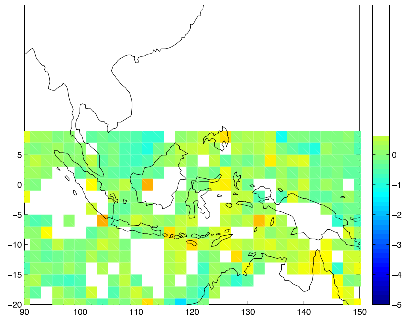
ICOADS SST Observations Week 1 1970



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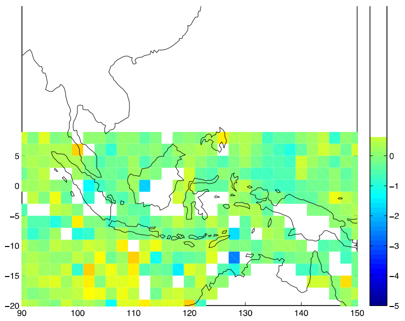
ICOADS SST Observations Week 1 1980



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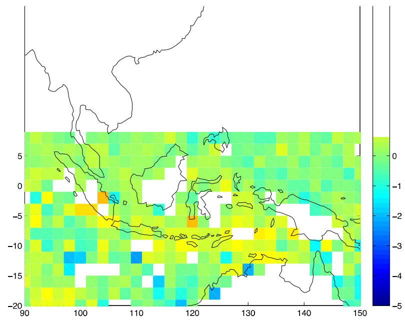
ICOADS SST Observations Week 1 1990



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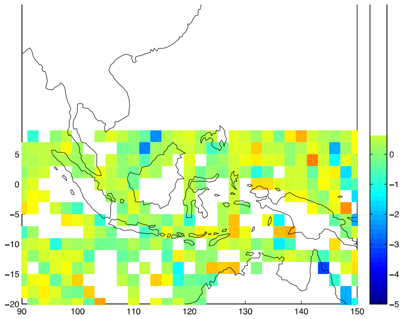
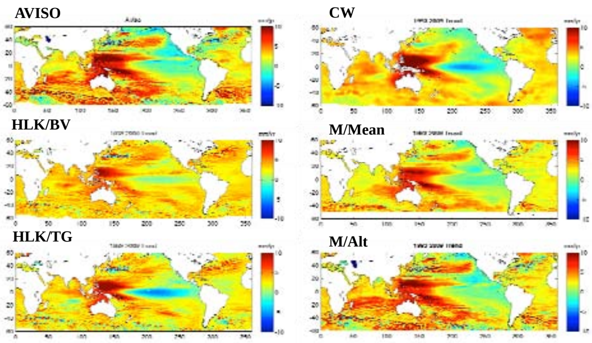
ICOADS SST Observations Week 1 2000

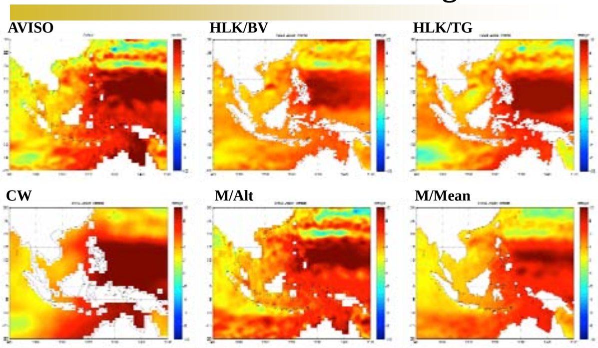


Global Sea Level Results

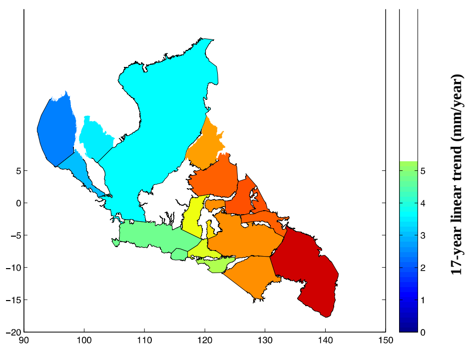
AVISO vs. Reconstructed 17-year Trends



Sea Level Trends: 1993 through 2009

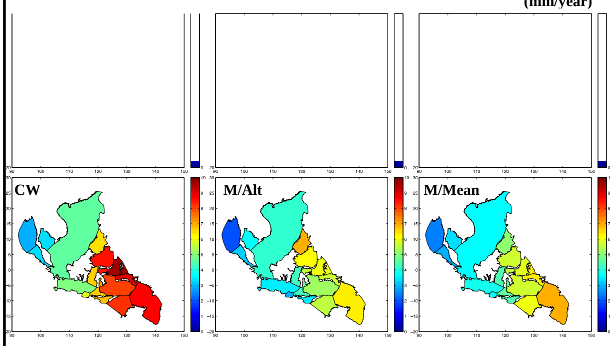


17-year AVISO SEAS MSL Trends

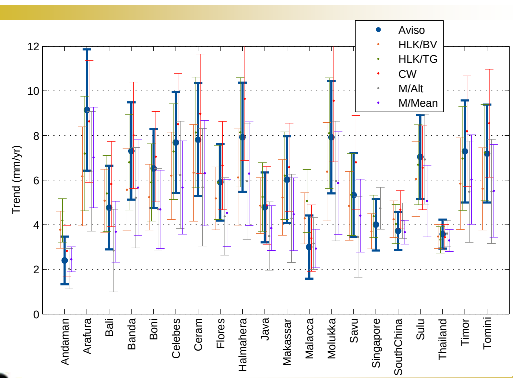


SEAS Sea Level Trends: 1993 through 2009

(mm/year)



1993-2009



Correlation Analysis of 17-year Trend Maps

To highlight the trend variability at the time scales observed over the current altimetric record we performed the following analysis:

- Averaged all reconstructed data sets to form annual averages over the 1950 through 2009 record.
- Calculated 17-year linear trends from the annual averaged data sets to produce 44 17-year trend maps from 1958 through 2001.
- Performed a lagged correlation analysis (present versu past) of the 17-year trend time series for each data set.

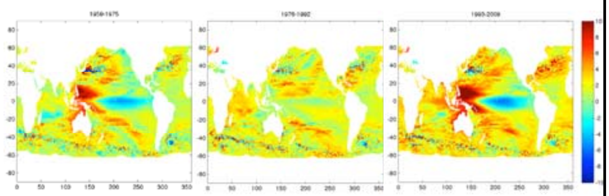
Results

There are roughly three extrema in the 17-year trend variability of the global sea level reconstructions associated with independent 17-year time periods in the 60-year record:

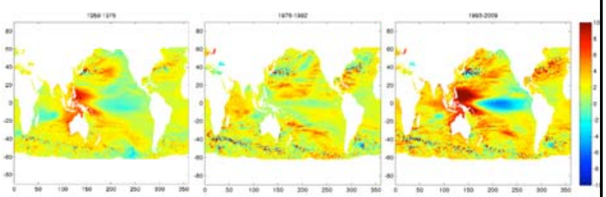
1. 1959-1975 – 17-year trend centered on 1967
2. 1976-1992 – 17-year trend centered on 1984
3. 1993-2009 – 17-year trend centered on 2001

We will use these time periods to assess the agreement of the global regional and SEAS sea level trends in the sea level reconstructions.

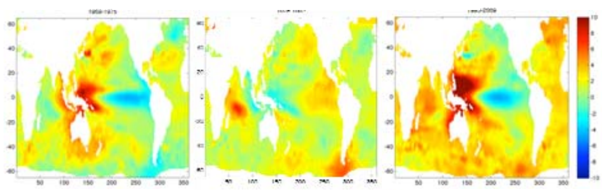
17-year Trend Correlation HLK/TG



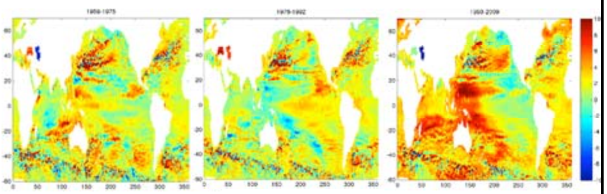
17-year Trend Correlation HLK/BV



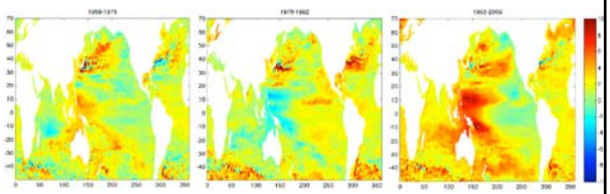
17-year Trend Correlation CW



17-year Trend Correlation M/Alt



17-year Trend Correlation M/Mean



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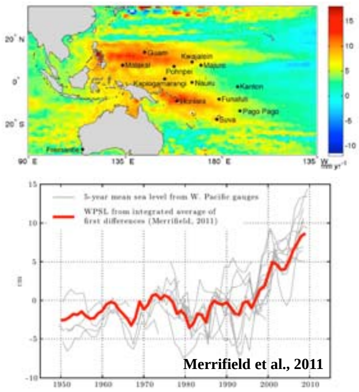
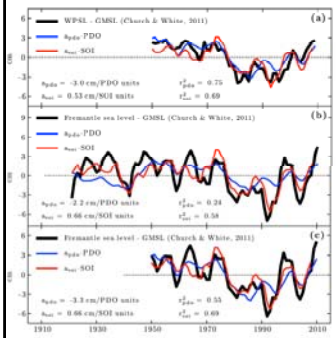
What is driving Western Pacific Sea Level Trends?



Merrifield et al., 2011

Low-frequency variability related to PDO and SOI

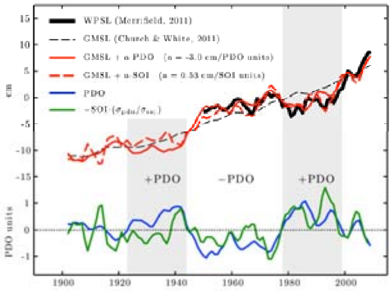


Merrifield et al., 2012

When detrended by Global Mean Sea Level (GMSL), the Western Pacific Sea Level (WPSL) is correlated with the low-frequency variability of the Pacific Decadal Oscillation(PDO) and the Southern Oscillation Index (SOI).

This sea level signal is driven by anomalous decadal wind variability over the equatorial Pacific and propagates along the waveguide through the archipelago reaching as far south as Fremantle on the western Australian coast.

"Reconstruction" of WPSL using SOI and PDO



Merrifield et al, 2012

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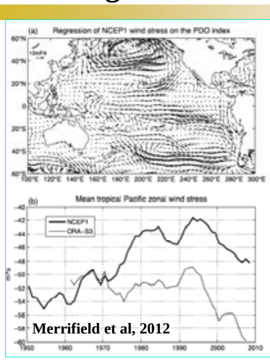
Regression of wind stress on PDO



Merrifield et al, 2012

(a) Regression coefficient for the PDO index regressed on NCEP1 wind stress.

(b) Mean zonal wind stress of two wind stress products regressed on the PDO and averaged over the tropical Pacific within the boxed region shown by dashed line in (a).

Note: Large discrepancy in mean zonal wind stress trends.

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SEAS Comparisons

Comparisons

We will use these time periods to assess the agreement of the SEAS sea level trends in the sea level reconstructions.

1. 1959-1975 – 17-year trend centered on 1967
2. 1976-1992 – 17-year trend centered on 1984
3. 1993-2009 – 17-year trend centered on 2001

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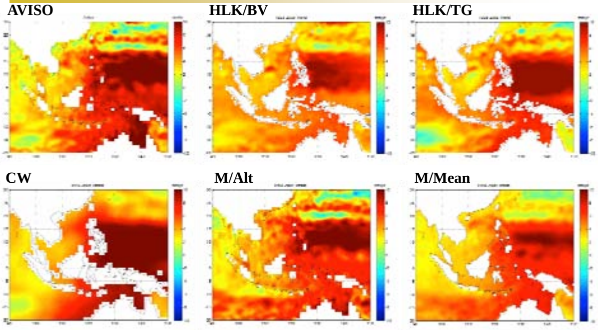
Sea Level Trends: 1993 through 2009



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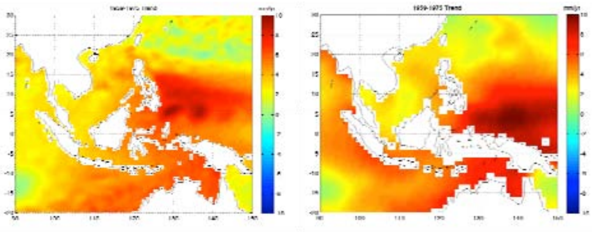
HLK/BV vs. CW

SEAS 17-year Regional Trend Map: 1959-1975



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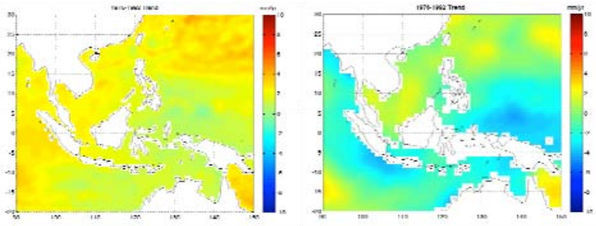
HLK/BV vs. CW

SEAS 17-year Regional Trend Map: 1976-1992



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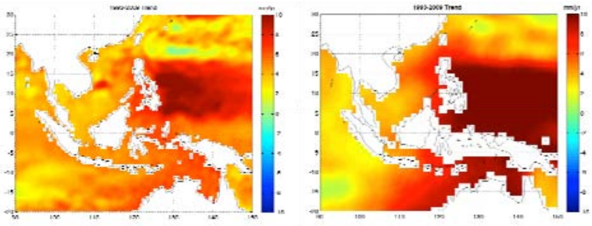
HLK/BV vs. CW

SEAS 17-year Regional Trend Map: 1993-2009



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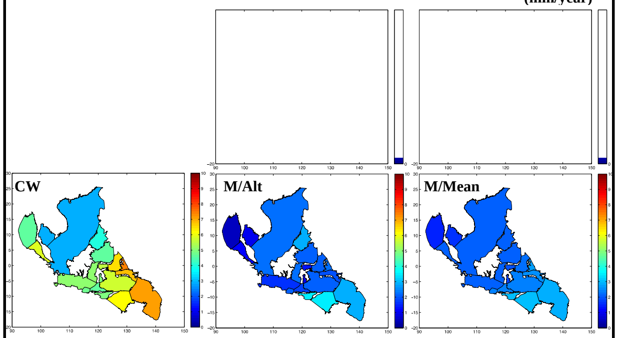
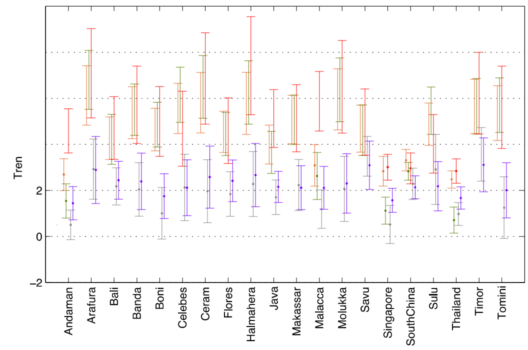
SEAS Sea Level Trends: 1959 through 1975

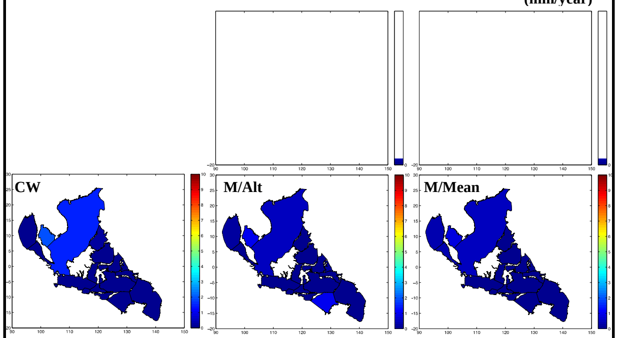
(mm/year)





SEAS Sea Level Trends: 1976 through 1992

(mm/year)



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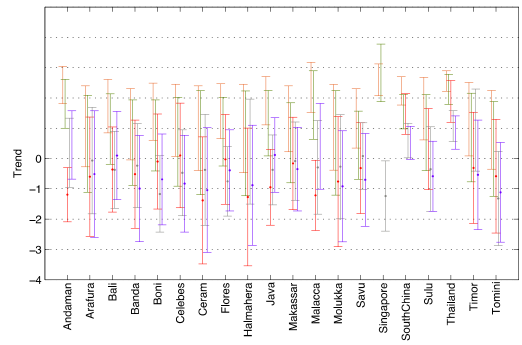
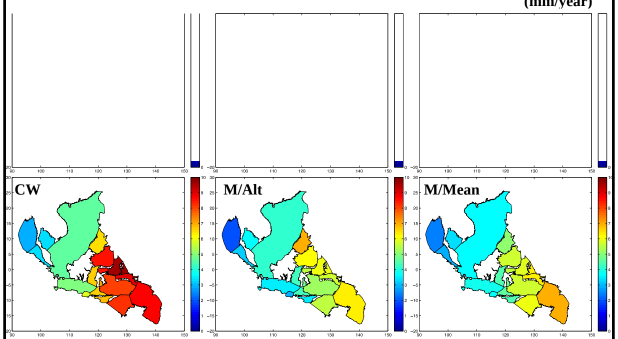


SEAS Sea Level Trends: 1993 through 2009

(mm/year)



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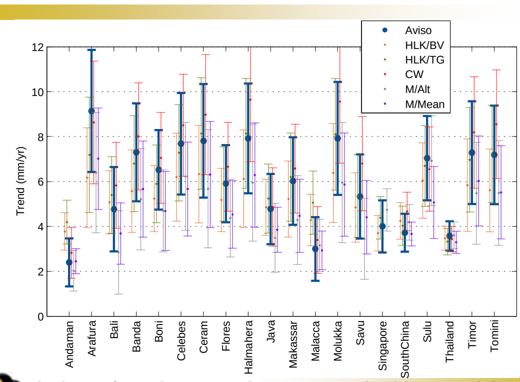
SEAS Sea Level Trends 1993-2009



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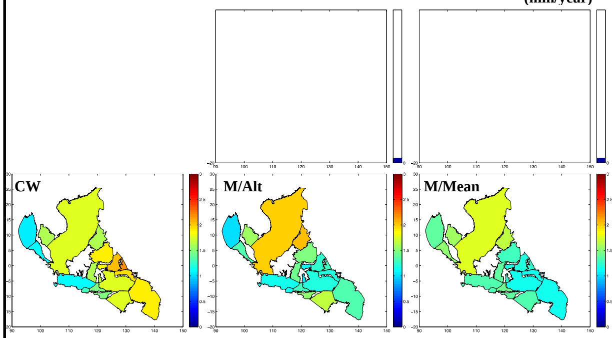
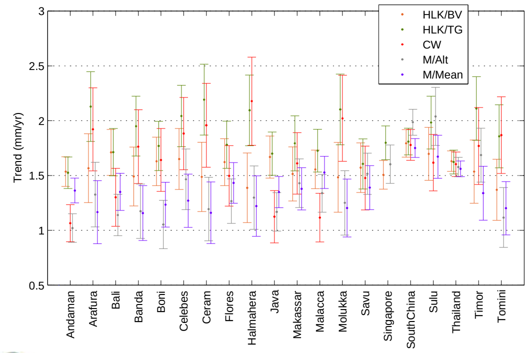
SEAS Sea Level Trends: 1950 through 2009

(mm/year)



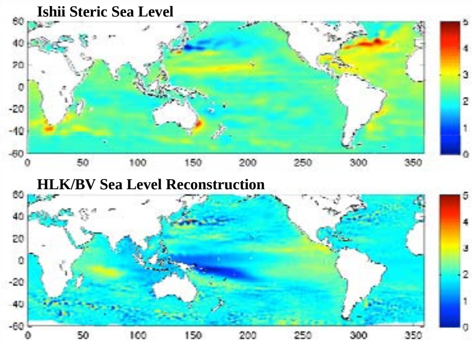
SEAS Sea Level Trends 1950-2009



Summary

- Our initial comparisons of sea level trends show good agreement between global sea level reconstructions in areas and times of larger signal to noise associated with strong decadal sea level variability forced by low frequency wind forcing.
- SEAS regions along the deep-water Kelvin/Rossby waveguide connecting the Pacific and Indian Oceans are most affected by this variability.
- The good news for the SEAS region is the likelihood that recent strong sea level trends observed during the altimetry record will abate as trade winds fluctuate on decadal and multi-decadal time scales.
- SEAS regional sea level trends during the 2010s and 2020s, thus, are likely to be less than the GMSL trend, similar to smaller sea level trends observed during in the 1976-1992 time period relative to GMSL.
- Nevertheless, long-term sea level trends in the SEAS regions will continue to be affected by GMSL rise occurring now and and in the future.
- Sea level reconstruction techniques provide a useful tool for understanding sea level changes in the past, present, and future.

Future Work: Comparisons to Ishii Steric Sea Level Trends 1950-2009



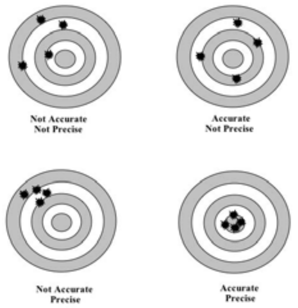
Acknowledgements

Thanks to the following people for contributions of time and data sets to this presentation:

- Mathew Strassburg
- Ben Hamlington
- John Church and Neil White
- Benoit Meyssignac
- Masayoshi Ishii

Thank you!

Accuracy vs. Precision



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Tsunami Detection

Using Satellite Altimetry

Tsunami Detection Using Satellite Altimetry

Ben Hamlington[1], Robert Leben[1], Oleg Godin[2], Edison Gica[3], Vasily Titov[3], Bruce Haines[4], Shailen Desai[4]

1. Colorado Center for Astrodynamics Research
2. NOAA/Earth System Research Laboratory
3. NOAA Center for Tsunami Research
4. Jet Propulsion Laboratory

Early Warning and Detection of Tsunami

- Early warning of an impending tsunami is heavily dependent on the detection of the tsunami away from the shore.
  – Wave amplitude in the open ocean is small (generally < 1 meter).
  – Difficult to distinguish tsunami signal from other ocean variability until tsunami approaches the shore.
  – Detection must occur with enough lead-time to allow coastal populations to move to safety.
- Models have generally been used to provide early assessment of an impending tsunami threat.
  – Without actual observations in the open ocean, it is difficult to definitively determine the presence of a tsunami in the ocean.
  – Open ocean observations could also be used to hone model predictions and improve representation of the earthquake source (Geist et al. 2007; Yamakazi et al. 2011).

Detection of Tsunami by Satellite Altimetry

- In recent years, tsunami detection has been demonstrated in the open ocean using measurements from satellite altimeters.
  – Detection using sea surface height measurements:
    - **1992 Nicaragua Tsunami** (Okal et al. 1999)
    - **1995 Chile Tsunami** (Okal et al. 1999)
    - **2004 Sumatra-Andaman Tsunami** (e.g. Smith et al., 2005; Song et al., 2005; Ablain et al., 2006; Hirata et al., 2006; Geist et al., 2007; Gower, 2007; Hayashi, 2008; Hoechner et al., 2008)
    - **2010 Chile Tsunami** (Hamlington et al. 2010)
  – Detection using sea surface roughness measurements
    - **2004 Sumatra-Andaman Tsunami** (Godin et al. 2004)
    - **2010 Chile Tsunami** (Hamlington et al. 2010)

Can Satellite Altimeters Help With Early Warning and Detection of Tsunamis?

"Unfortunately, satellite altimetry bears little promise of useful contribution to future tsunami warning systems, as it requires intensive and time- consuming data processing, and above all, the presence of a satellite at the right place at the right time." (Okal, 2011).

– Statement has frequently been made that there is only a small chance of observing a tsunami with along-track measurement system of satellite altimetry.
  - May be true for smaller-scale events, but does not hold true for larger events.

– Relevant questions:

1. Not if, but how soon after the tsunamigenic event will a satellite altimeter sample the tsunami?
2. How can satellite altimeter measurements be used for improving tsunami early warning and detection?

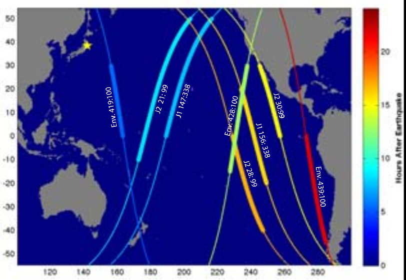
To better answer these questions, we study the 2011 Tohoku tsunami.

2011 Tohoku Tsunami

- Tohoku tsunami generated by Mw 9.0 earthquake at 5:46 UTC on March 10th, 2011, approximately 130 km east of Sendai, Honshu, Japan.
  – Caused over 19,000 casualties in northeastern Japan and affected more than 57 cities (Ando et al. 2011).
- **Important to emphasize that we do not suggest that satellite altimetry could have helped for the warning of coastal populations of Japan.**
  – Time between earthquake and arrival of tsunami was measured in minutes rather than hours.
  – Quickest and best warning for coastal populations in such close proximity to the location where the tsunami was the earthquake itself.
  – Here, we focus on improving far-field tsunami detection and warning (time-lag between tsunami generation and arrival on the order of hours).

Satellite Altimeter Coverage of 2011 Tohoku Tsunami

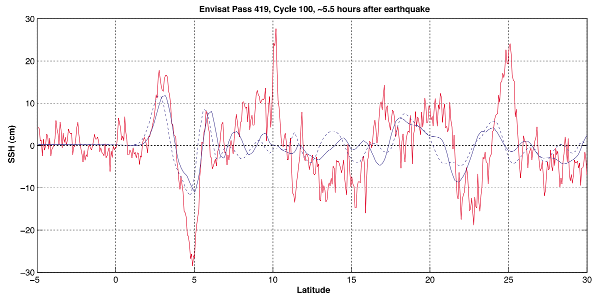
Envisat:
Pass 419 of cycle 100 (5.5 hours)
Pass 428 of cycle 100 (13 hours)
Pass 439 of cycle 100 (22 hours)
Jason-1:
Pass 147 of cycle 338 (7.5 hours)
Pass 156 of cycle 338 (16 hours)
Jason-2:
Pass 21 of cycle 99 (8.5 hours)
Pass 28 of cycle 99 (15 hours)
Pass 30 of cycle 99 (17 hours)



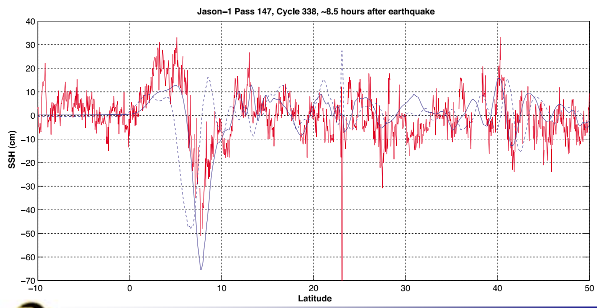
Data

- Jason-1 and Jason-2 Near Real Time SSH anomaly data was obtained from the Physical Oceanography Distributed Archive Center (PO.DAAC) at NASA JPL.
  - For Envisat and for historical Jason-1 data used in randomization tests, SSH measurements were obtained from the Radar Altimeter Database System (RADS).
  - At time of study, Jason-1 and Envisat NRT SSH data had average latency of roughly 7 hours, with Jason-2 having latency closer to 4 hours.
- For comparison and to verify time and location of tsunami leading edge, we used the Method of Splitting Tsunami (MOST) model SSH data produced by NOAA Center for Tsunami Research (Titov et al. 2005).

Model vs. NRT Data: Envisat



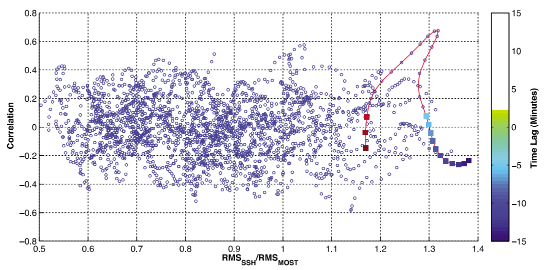
Model vs. NRT Data: Jason-1



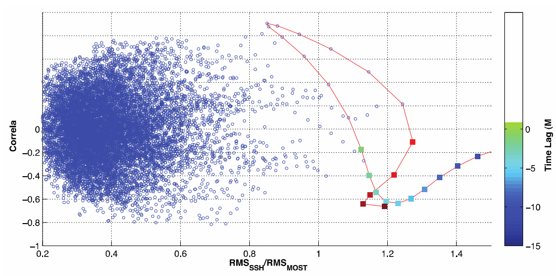
Historical Randomization Tests

- Using historical data, it is possible to determine if the correlation and amplitude between observations and model data for a given pass are exceptional (containing tsunami signal).
  - Using the Envisat pass as an example the test is completed as follows:
  1. Pass 419 (tsunami pass) from every previous Envisat cycle is collected using RADS, and the correlation and RMS amplitude ratio between the MOST model and filtered SSH data is computed.
  2. MOST model is adjusted +/- 15 minutes, leading to 31 data points for each cycle.
  3. Locations with **high correlation**, and **RMS amplitude ratio of ~1**, suggest the presence of a tsunami.

Historical Randomization Tests: Envisat



Historical Randomization Tests: Jason-1

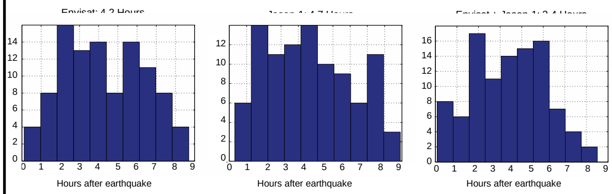


NRT Tsunami Monitoring Using Satellite Altimetry

- Deep-Ocean Assessment and Report of Tsunamis (DART) buoys and tide gauges are generally used to detect tsunamis shortly after generation.
- However, Recent advances in processing of altimeter data have opened up the possibility of using satellite altimeters to improve assessments of the propagating tsunami.
  - Latencies could be reduced further by using less accurate orbit altitude estimates, or the addition of ground terminals for reception of telemetry from satellites.
- For Tohoku tsunami:
  - Envisat first measured tsunami 5.5 hours after earthquake → with current latencies, could have improved warnings and predictions in Central and South America.
  - A Jason-2 pass within 5.5 hours of earthquake → with current latencies, could have improved warnings and predictions for Hawaii.

How soon after tsunami should we expect satellite altimeter sampling?

- Using a simple randomization test and setting the start time of the Tohoku tsunami at random times in the past, we can determine the expected time for a satellite altimeter overflight.



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Could satellite altimetry have improved early warning and detection of the 2011 Tohoku Tsunami?

1. MOST model results are computed very quickly from a set of pre-computed runs for locations where tsunamis have occurred in the past.
   - Model is adjusted with DART buoy data, which is primarily located near coastlines.
   - No observations in the open ocean are currently used to improve the model estimate.
2. Comparison between NRT altimetry data and initial MOST model can be made and altimetry passes coincident with the tsunami signal could be identified.
3. NRT satellite altimetry data containing the tsunami signal would then be used to refine and improve model estimates.
4. Additionally, satellite altimetry data could be used directly to confirm the presence and size of a tsunami in the open ocean.

We now have a software system in place at CCAR to retrieve and analyze JPL/PO.DAAC NRT Jason-2 altimeter data as soon as a potential tsunamigenic earthquake occurs.

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Summary and Conclusions

- Satellite altimetry cannot currently provide improved warning for locations in the near-field of the tsunami, such as for Japan in the 2011 Tohoku tsunami.
- However, satellite altimetry should not be dismissed when considering the early warning and detection of tsunamis.
  - Far-field events can still be large and result in significant damage to property and potential loss of life.
  - Satellite altimetry should be seen as a supplement to existing systems.
  - Open ocean observations of the tsunami provide the opportunity for additional model refinement.
  - Satellite altimeters cover areas of the ocean where no DART buoy or tide gauge is present.
  - Results depend heavily on data latencies and satellite altimeter availability at the time of the tsunami.

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Thank You!

Additional details and analysis can be found in "Could Satellite Altimetry have Improved Early Detection and Warning of the 2011 Tohoku Tsunami?" Hamlington et al., GRL, 2012.

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Satellite Altimetry Web Database

SATELLITE ALTIMETRI WEB DATABASE

Parluhutan Manurung
Dewangga Rahardian

Objective

- Website for research and practical community interested in Altimetry
- Exchange of altimetry data in Indonesia
- Exchange of software and codes
- Media for communicating research results
- Information on publication, meeting, seminar, training, etc.

Web design

Home
- General info
- Vision dan Mision
- Objectives

What is altimetry
- Introduction
- Product Handbook
- Publications: national and international published papers
- Tutorial

Web Design (2)

DATA
- Data altimetri Level 1 dan 2 Aviso dan PODAAC Products with tracks along accros Indonesia
- Data Base of retracked altimetry data accross Indonesia
- RelatedData:
  - Tidal data for calibration
  - Bathymetric data
  - Etopo
  - Satelite based weather data
  - Satellite image

Project
- Press release : photoes and videos
- Activities and agenda
  - Workshop agenda
  - Training agenda
  - Meetings etc

Web Design (3)

FORUM:
- Forum for communities
- Mailing list and blog

Contact:
- Secretariate address
- Office

Closing Remarks

- It is time to build altimetry data base for Indonesia
- We need to build a community interested in research altimetry
- This is a forum for data exchange accessible to researchers

Workshop Recomendation

Recommendation of the Coastal Satellite AltimetryWorkshop

Bogor, 14 November 2012

1) to promote “sea level” as a major research topic in Indonesia;
2) to continue study of long-term sea level variability in Indonesian seas to quantify past regional sea level change so that the risk of current and potential future sea level rise can be accurately assessed;
3) to sustain research and product development of deepwater and coastal satellite altimetry in Indonesia, as crucial to progress in this very interdisciplinary field, including the opportunities offered by new SAR and Ka-band altimeter technologies ;
4) to enable national and international collaborations by continuation of this series of workshops and specific outreach/capacity building activities, in order to provide more complete understanding of the capabilities of altimeter data, both alone and in combination with other types of satellite and in situ data and ocean models;
5) to encourage the development of an Indonesian satellite altimetry mission.