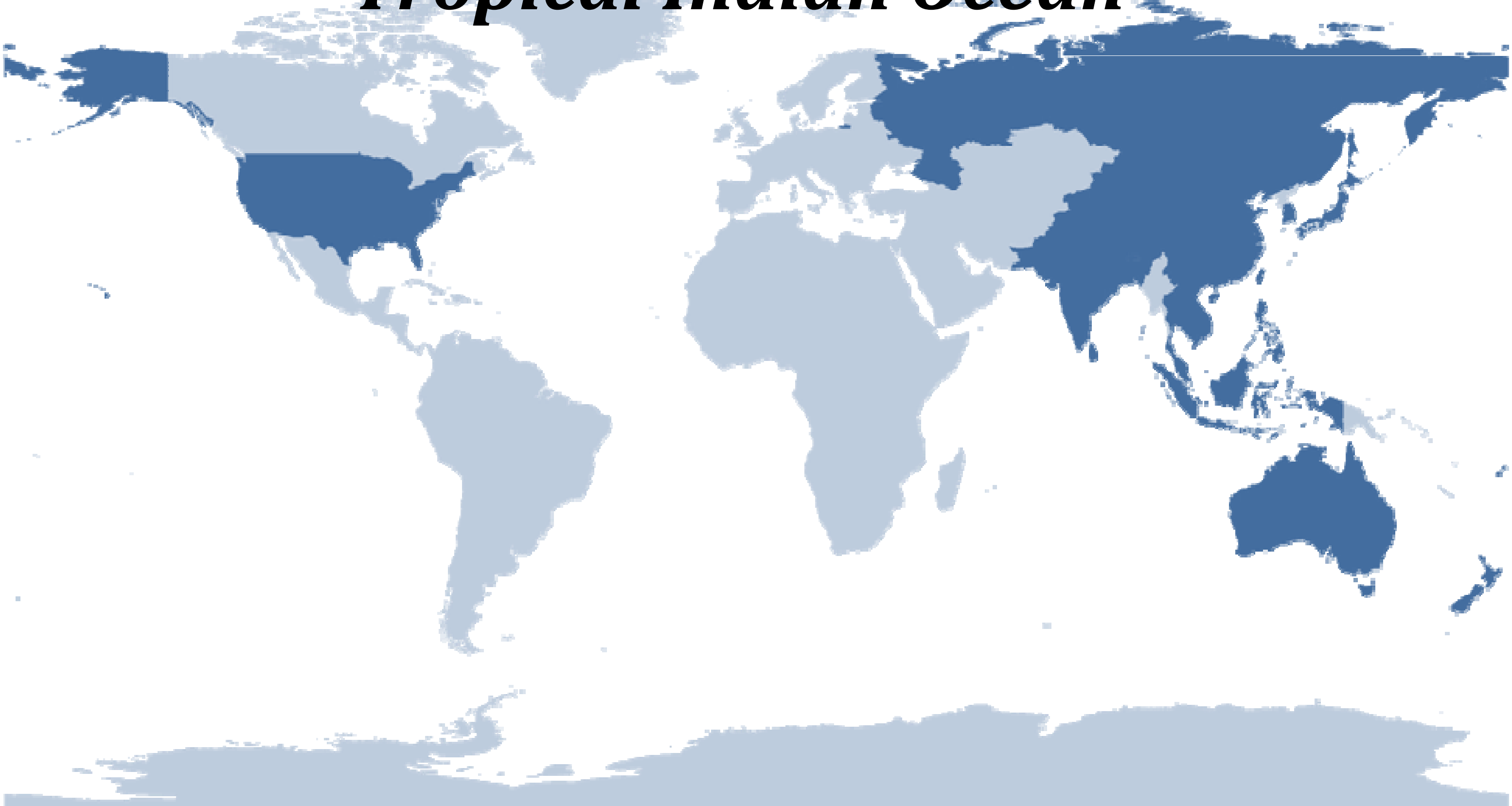
FINAL REPORT for APN PROJECT

Project Reference Number: ARCP2011-22NSG-Liu

# *"Scoping Workshop to Develop Proposal: The Impact of Global Warming Ocean-Atmosphere Feedback Strength in the Tropical Indian Ocean"*



The following collaborators worked on this project:

Lin Liu, First Institute of Oceanography, State Oceanic Administration, China, liul@fio.org.cn

Juneng Liew, National University of Malaysia, Malaysia, jnliew@gmail.com

Tim Li, University of Hawaii/International Pacific Research Centre, U. S., timli@hawaii.edu

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**Final Report submitted to APN**

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# OVERVIEW OF PROJECT WORK AND OUTCOMES

**Minimum 2pages (maximum 4 pages)**

## Non-technical summary

With the scientific and financial help from APN, the current project holds a scoping meeting with the purpose of strengthening the team and country composition in the proposal submitted to the APN for continual funding. After this workshop, an update proposal had been emerged aiming for the next submission. The workshop has been held at the Sophia hotel, Qingdao, China at 26-28 August, 2011. The seven experts from China, Malaysia and Thailand attended the workshop and presented fruitful discussion for the proponents. Based on the suggestion from this workshop, the proponents had modified the proposal named with "The Impact of Global Warming Ocean-Atmosphere Feedback Strength in the Tropical Indian Ocean" for the next submission of ARCP. Except for the modified project contents, more scientists from AP area have been involved in this project. The experts from Global Change Impact Studies Centre, Pakistan and Phuket Marine Biological Center, Thailand were agreed to joint this project. In additional, the project plans to construct a scientific committee (SC) to guarantee the implementation of the project and the experts from Thailand, Malaysia, China and French will be the members of the SC. Moreover, the MOMSEI project, the pilot project of IOC/WESTPAC, has agreed to cooperate with the current project and would provide the chance to disseminate the outcome to others.

## Objectives

The main objectives of the project were:

1. To hold a scoping meeting with the purpose of strengthening the team and country composition in the proposal submitted to the APN for continual funding.
2. To provide the final proposal based on the comments as well as suggestion from the scope meeting for APN's next proposal application.
3. To setup the potential pathway to cooperated with other international project under IOC framework.
4. To introduce the new methodology to evaluate the variability of the dynamic and thermodynamic feedback strength associated with IOD.

## Amount received and number years supported

The Grant awarded to this project was:

US$ 12,000 for Year 1

## Activity undertaken

1. To communicate with APN science office for the clear understanding on the requirement for proposal development.
2. To hold the scope meeting in The Sophia Hotel at Qingdao, China during 26~28 August 2011
3. To disseminate the related work in WCRP open science conference workshop in Denver, U. S. 24-28 Oct. 2011.
4. To take teleconferences and mail exchange for the scope and preparation of proposed project.
5. To discuss with the experts from MOMSEI project, which is the pilot project of IOC/WESTPAC, for the future cooperation.

6. To disseminate such work in CMIP5 workshop in Hawaii, U. S. 3-5 Mar. 2012.
7. To communicate with other international organizations for the their support on cooperation in the proposed project events.

## Results

1. Scope:
a) Well understand to the seed grant requirement from APN has been reached, with a lot of communication and discussion in the project team.
b) Bridge and good communication with IOC/WESTPAC has been taken and IOC/WESTPAC experts in the Asia-Pacific region has involved in this project.
c) Longer term communication with joint international societies is hoped to build for the future cooperation between APN and other international organization.
2. Organization:
a) New partners have been involved in this project. The scientists from Pakistan and Thailand are all interested in this project and have agreed to be the part of proponents.
b) Project team has been reconstructed to fit the new challenge raised in the new proposal.
3. Activities:
a) A scoping workshop has been held with the main aim of strengthening the team and country composition in the proposal.
4. Output and Achievement
a) A new proposal has been rewritten and will be submitted to APN for the next call for proposal of ARCP.
b) Additional financial funds have been fixed to support this proposed events. China has agreed to provide some kind of funding to the event in their countries.

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

Tropical Indian Ocean air-sea coupled event is the most important interannual phenomena, which modulate the variation of Asian summer monsoon system. The influence from global warming to inner air-sea feedback strength of tropical Indian Ocean air-sea coupled event is still unclear and is one of challenge for relevant research. The proposed workshop will benefit to promote the working plan as well as the detailed content of the project. The update proposal has emerged after this scope meeting, which will also give great help to the regional global changing research works.

## Self evaluation

With financial and scientific support from APN, the seed granted project team has realized how to promote the original proposal to well cooperate with other international organization. A well connected and understood working team has been organized and a lot of international professional societies have agreed to setup a scientific committee to guarantee the project execution. A new proposal targeted to enhance the cooperation with IOC/WESTPAC has been proposed as the project main output. The whole team members are pleasure to finish this seed project work and to apply the continual funding.

## Potential for further work

The most important thing in the quite near future is to submit the modified proposal to ARCP program. Based on the suggestion from scoping workshop and the fruitful discussion with relevant experts, the pilot project of IOC/WESTPAC, MOMSEI, has agreed to arrange a joint lecture for this project during its summer training course, 2012, which is a good opportunity for disseminating our project into more persons and organization. At that time, the project participants will also discuss with the experts from IOC/WESTPAC for the further cooperation.

## Publications (please write the complete citation)

Because this seed project is targeted as the proposal promoting and scope enhanced activities, no scientific publication has been taken. However, we will provide one CD-ROM to package the reports, presentations, group photos.

## References

## Acknowledgments

Bedsides the support on both finance and scientific scope from APN, our work also has been supported by MOMSEI project from IOC/WESTPAC. We also appreciate the support from Mr. Weidong YU co-chair of IOC/WESTPAC Indian Ocean Panel.

## TECHNICAL REPORT

**Minimum 15-20 pages (excluding appendix)**

### Preface

Indian Ocean Dipole is a significant ocean-atmosphere coupled event over the tropical Indian Ocean. It is largely controlled by internal air-sea feedback mechanisms and strongly modulating the Asian climate variability, locally and remotely. Global warming is the apparent climatic long term trend over the globe, including the Indian Ocean region. This project examines the impact of global warming on this ocean-atmosphere coupled event using the CMIP5 output. Particularly the output answers the questions 1) to what degree the global warming impacts the IOD event and 2) to explain the physical mechanism on how the IOD is influenced by the global warming.

### Table of Contents

### 1.0 Introduction

The Indian Ocean Dipole (IOD) is a basin-scale ocean-atmosphere coupled mode, characterized by a zonal contrast of a positive and a negative SST anomaly (SSTA) along the equatorial Indian Ocean (IO) and a zonal wind anomaly over the central equatorial IO. During a positive IOD event, the SST is anomalously cool in the southeastern IO (SEIO) off Sumatra) and warm in the western IO (WIO), accompanied with pronounced anomalous southeasterlies along the coast of Sumatra and anomalous easterlies over the central equatorial IO (CEIO). While the IOD rapidly develops in boreal summer, it reaches a mature phase in northern fall. A number of studies showed that the convection associated with IOD exerted a great impact on climate variability in Africa, South Asia, East Asia, and other remote regions. It was suggested that Bjerkness feedback may operate in the equatorial IO. This dynamic feedback involves interactions among the zonal SST gradient, low level wind in the CEIO, and the east-west thermocline displacement. For example, a negative SSTA off Sumatra would induce anomalous low-level easterlies in the CEIO, which depress (lift) the thermocline to the west. The lifted thermocline to the east may enhance the SST cooling through the upwelling of anomalous cold subsurface water. The enhanced surface cooling further amplifies the easterly anomaly. Through this positive dynamic feedback, IOD develops. In addition to the dynamical coupling, the thermodynamical air-sea feedback also played a role during IOD development. Different from the Pacific El Nino during which there is a spatial phase difference between convection and SST anomalies, the SST and cloud anomalies are in general in phase in the tropical IO. This implies a stronger cloudradiation- SST negative feedback in IO. Another notable feature during IOD development is a season-dependent wind-evaporation-SST feedback. A pronounced southeasterly mean flow in boreal summer leads a positive wind-evaporation-SST feedback, that is, a cold SSTA in the SEIO forces a low-level anticyclonic flow to the west of the anomalous heat source, and anomalous southeasterlies along the coast of Sumatra associated with this anticyclone strengthen the surafce evaporation and cool the SST further. As the seasonal prevailing wind switches from southeasterlies in boreal summer to northwesterlies in boreal winter, this SST-wind-evaporation feedback becomes a negative one.

The strength of the dynamic and thermodynamic feedbacks mentioned above depends greatly on the mean state of the tropical IO. For example, the mean thermocline depth and the background upwelling velocity and vertical temperature gradient are critical in determining the effect of the dynamic feedback. A deeper mean thermocline, a smaller mean upwelling velocity, and a weaker upper-ocean vertical temperature gradient may reduce heat exchange between the subsurface and surface. As discussed above, the wind–evaporation–SST feedback also depends on the background monsoon flow. Given the great impact of the IOD on circulation and rainfall variations in various regions, it is crucial to simulate and predict the IOD evolution and amplitude as well as its related climate impact in current state-of-art climate models. Various efforts have been made in evaluating the performance of IOD simulations in coupled general circulation models (CGCMs). Although some researches paid attention to the climate change of Indian Ocean under global warming condition, the issue associated with variability of dynamical and thermodynamical feedback strength during IOD event under global warming condition is largely unknown.

The objective of this project is to conduct a detailed analysis to assess the variability of the dynamic and thermodynamic feedback strength associated with IOD under global warming scenario. This project aims to answer two important questions 1) to what degree global warming could impact IOD event and 2) what is the influence of global warming on dynamical and thermodynamical feedback strength during IOD event.

At 2010, the proponents of the project submitted the proposal named with "The Impact of Global Warming Ocean-Atmosphere Feedback Strength in the Tropical Indian Ocean" to ARCP. It's the great honor for the proponents because the APN has decided to support such project with seed grant titled with "Scoping Workshop to Develop Proposal: The Impact of Global Warming Ocean-Atmosphere Feedback Strength in the Tropical Indian Ocean" at the beginning of 2011. The purpose of the approved project is to give a chance for the leader team to improve the proposal with the suggestions from the experts attending the workshop.

With the scientific and financial help from APN, the current project holds a scoping meeting with the purpose of strengthening the team and country composition in the proposal submitted to the APN for continual funding. After this workshop, an update proposal had been emerged aiming for the next submission. The workshop has been held at the Sophia hotel successfully, Qingdao, China at 26-28 August, 2011. The seven experts from China, Malaysia and Thailand attended the workshop and presented fruitful discussion for the proponents. Based on the suggestion from this workshop, the proponents had modified the proposal named with "The Impact of Global Warming Ocean-Atmosphere Feedback Strength in the Tropical Indian Ocean" for the next submission of ARCP. Except for the modified project contents, more scientists from AP area have been involved in this project. The experts from Global Change Impact Studies Centre, Pakistan and Phuket Marine Biological Center, Thailand were agreed to joint this project.  In additional, the project plans to construct a scientific committee (SC) to guarantee the implementation of the project and the experts from Thailand, Malaysia, China and French will be the members of the SC.  Moreover, the MOMSEI project, the pilot project of IOC/WESTPAC, has agreed to cooperate with the current project and would provide the chance to disseminate the outcome to others.

After the scoping workshop, the proponents started to conduct the preliminary research relevant to the IOD feedback process analysis with CMIP3 and CMIP5 coupled model outputs. The preliminary outcome had been achieved since Aug-2011. At the mean time, the outcome from the current project had been disseminated into other potential users during Oct-2011 and Mar-2012 at international conference.

## 2.0 Methodology

With the support from APN, the current project had applied bellowing activities:

**a. Scoping workshop**

With the support from APN, a scoping meeting has been taken to enhance the team and country composition in the proposal submitted to the APN for continual funding. This workshop has invited experts from IOC/WESTPAC to participant, who gave fruitful comments as well as suggestion for the modified proposal. Through this workshop, the pilot project of IOC/WESTPAC is pleasure to cooperate with this project and is agree to provide chance for our project in his summer training course in order to disseminate the project outcome to public.

**b. Data Acquisition**

Data downloading from the PCMDI server had been performed. The CMIP3 data have already downloaded and the up-to-date CMIP5 multi model outputs are currently underway. The primary datasets used for this study are the outputs of 23 models from the WCRP CMIP3 datasets. The model variables used in the diagnosis include 3D ocean temperature, current, surface wind, cloud fraction, specific humidity, and surface heat flux fields. (further detailed information can be obtained by visiting www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentatioAU4 n). Most of the models are labeled by the name of the institution that performed the run and supplied the data. The particular datasets analyzed here are from the so-called Twentieth-Century Climate in Coupled Model (20C3M). The forcing agents of this experiment include greenhouse gases [CO2, CH4, N2O, and chlorofluorocarbons (CFCs)], sulfate aerosol direct effects, volcanoes, and solar forcing. The results reported in this analysis were only for the period between January 1950 and December 1999. The mean climatological annual cycle was defined based on this 50-yr period. The interannual anomalies were then obtained by subtracting the monthly-mean variables from their respective mean climatological annual cycles. For comparison of the model simulations with the observations, various observed and reanalyzed (assimilated) atmospheric and oceanic datasets were used. Three-dimensional atmospheric wind fields, the surface specific humidity, the surface latent heat flux, cloud cover, and the net surface shortwave radiation (SWR) were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis and 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) products, and threedimensional ocean temperatures were obtained from the Simple Ocean Data Assimilation (SODA) reanalysis. In addition, we used both the Met Office Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) product and the Optimum Interpolation Sea Surface Temperature (OISST) product. Most of the observed or reanalysis datasets were available for the 50-yr period.

CMIP3 model/ institute name:

1) Flexible Global Ocean–Atmosphere–Land System Model gridpoint version 1.0,
2) Geophysical Fluid Dynamics Laboratory Climate Model version 2.1,
3) Parallel Climate Model,
4) ECHAM5/Max Planck Institute Ocean Model,
5) Commonwealth Scientific and Industrial ResearchOrganisationMark version 3.5,
6) Centre National de RecherchesMe´te´orologiques Coupled Global ClimateModel, version 3,
7) MetOffice Hadley CentreGlobal EnvironmentalModel version 1,
8) Istituto Nazionale di Geofisica eAU7 Vulcanologia SINTEX-G,
9) Model for Interdisciplinary Research on Climate 3.2, medium-resolution version,
10) Third climate configuration of theMetOfficeUnifiedModel,
11) CSIROMark version 3.0,
12) Institute of NumericalMathematics Coupled Model, version3.0,
13) Geophysical Fluid Dynamics Laboratory Climate Model version 2.0,
14) Goddard Institute for Space Studies Model E-H,
15) Bjerknes Centre for Climate Research Bergen ClimateModel, version 2.0,
16) Model for Interdisciplinary Research on Climate 3.2, highresolutionversion,
17) Meteorological Research Institute CoupledGeneral CirculationModel, version 2.3.2,
18) Canadian Centre for Climate Modelling and Analysis Coupled General Circulation Model,

version 3.1,

19) Canadian Centre for Climate Modelling and Analysis Coupled General Circulation Model, version 3.1,

20) Community Climate System Model, version 3,

21) L'Institut Pierre-Simon Laplace Coupled Model, version 4,

22) GISS Model E-R,

23) GISS Atmosphere–Ocean Model.

**c. Analysis methodology for the research**

To reveal the cause of the diversity in the model IOD intensity, we first examine the Bjerknes feedback strength in all 23 models. This dynamic ocean–atmosphere feedback consists of the following three key processes: 1) how strong the atmospheric low-level wind responds to a one unit SSTA forcing, 2) how strong the ocean thermocline depth responds to a one unit surface wind forcing, and 3) how strong the ocean subsurface temperature responds to a one unit thermocline depth variation. These three dynamical feedback processes are examined and the respective coupling coefficients are estimated in all 23 models. The overall strength of the Bjerknes dynamic feedback is determined by the product of the three coupling coefficients and the mean upwelling velocity. Two thermodynamic air–sea feedback processes, the wind–evaporation–SST feedback and the cloud–radiation–SST feedback, are specifically examined.

With the help from scoping workshop, the update proposal had emerged and the following includes the future method we will take as well as the relevant activities:

**d. Disseminate the outcome**

Joint lectures with MOMSEI

Preliminary research outcome will be disseminated and shared in joint lectures during MOMSEI summer school workshop to be held in summer 2013. The audience groups are expected from young scientists and also senior researchers from relevant areas e.g. from the numerical models developing groups. The activity aims at sharing new knowledge and foster better interest in understanding the Indian Ocean climate variability.

Another joint session with the MOMSEI summer school will be held in 2014. Through international cooperation and multi-disciplinary information exchange, provide new knowledge for understanding the fundamental regulation and key mechanisms of the air-sea feedback of Indian Ocean under global warming.

## 3.0 Results & Discussion

### (1) The method to measure the IOD feedback strength in coupled models

To reveal the cause of the diversity in the model IOD intensity among CMIP3 coupled models, the proponent has applied new method to measure the simulated IOD strength in numerical model outputs. We first examine the Bjerknes feedback strength in all coupled models. This dynamic ocean-atmosphere feedback consists of the following three key processes, i.e., 1) how strong the atmospheric low-level wind responds to one unit SSTA forcing, 2) how strong the ocean thermocline depth responds to one unit surface wind forcing, and 3) how strong the ocean subsurface temperature responds to one unit thermocline depth variation. These three dynamical feedback processes are examined and the respective coupling coefficients are estimated in all the models. The overall strength of the Bjerknes dynamic feedback is determined by the product of the three coupling coefficients and the mean upwelling velocity. The comparison of the strong and weak composites shows that the former attains a much greater Bjerknes feedback intensity than the latter.

Next we examine the thermodynamic air-sea coupling strength for all the models. Two thermodynamic air-sea feedback processes, the wind-evaporation-SST feedback and the cloud-radiation-SST feedback, are particularly examined. While the observation shows a positive feedback among the wind, evaporation (or surface latent heat flux) and SST during the IOD developing phase, about a half of the CMIP3 models failed to capture such a positive thermodynamic air-sea feedback. The cause of this latent heat flux bias lies in the errors in both the surface wind speed and the sea-air specific humidity difference fields in these models. The composite result shows that a weak positive wind-evaporation-SST feedback occurs in both the strong and weak groups, while a negative feedback appears in the moderate group. As a strong negative feedback process, the cloud-radiation-SST feedback may slow down the IOD development. Most of the CMIP3 models successfully simulated this negative feedback process, even though the feedback intensity varies among the models. The averaged negative feedback coefficient is greater (smaller) in the strong (weak) composite, implying a stronger (weaker) thermodynamic damping.

Through the diagnosis of dynamic and thermodynamic coupling strength of each model during the developing phase in July-August-September (JAS), we will reveal the fundamental causes of the IOD simulation diversity among the models.

**a. Bjerknes feedback intensity**

We examine the Bjerknes feedback strength in all models. This dynamic air-sea coupling consists of three processes. The first is how the atmospheric low-level wind responds to the SSTA forcing in the SEIO. It is well known that during the IOD development period (JAS), the most significant feature of SSTA is the dipole pattern. Such a zonal SSTA gradient causes a zonal wind response in the CEIO through the SST-gradient-induced pressure gradient in the atmospheric planetary boundary layeror the mid-tropospheric heating anomaly.

To quantitatively measure the strength of the zonal wind response to the SSTA, we plot a scatter diagram for each model. Figure 4 shows the relationship between the SSTA in the SEIO (90-110oE, 10oS-0) and the zonal wind anomaly in the CEIO (70-90oE, 5oS-5oN) from the 23 models. For comparison, the observed SST-wind relation is also plotted in the top left corner. Consistent with the observed relationship, all of the models exhibit a positive correlation between the zonal wind and SST anomalies, that is, a negative SSTA in the SEIO (which corresponds to a positive IOD event according to Saji et al. 1999) is accompanied with an easterly anomaly in the CEIO.

We hereby denote a SST-wind coupling coefficient, R(u, T), to represent how strong the low-level wind responds to a unit SSTA forcing at each model. Mathematically, it equals to the linear slope at each of scatter diagrams in Fig. 1. (The linear slope in all scattering diagrams was calculated based on the least square fitting method.) It is interesting to note that the averaged slope in the strong composite is about 2.2 m s-1 K-1, which is a little larger than the averaged slope (1.7 m s-1 K-1) in the weak composite. Compared to the observed R(u, T), the SST-wind coupling coefficient in the strong group appears more realistic.

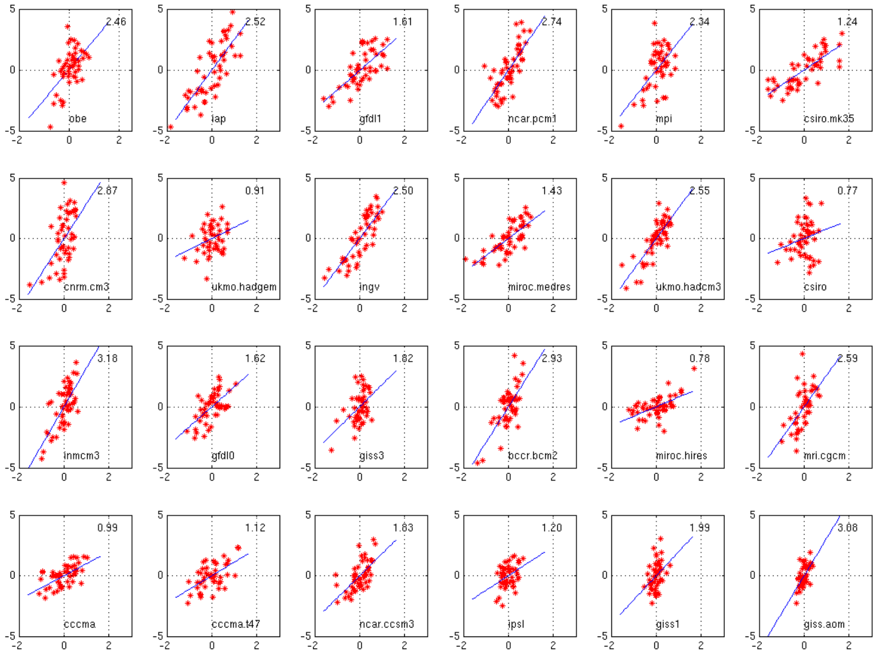


Fig. 1. Scatter diagrams revealing relationships between 850-hPa zonal wind anomaly (unit: m s-1) in the CEIO and SSTA (unit: K) in the SEIO during the IOD developing phase (JAS) for the observation (top left) and each of the 23 models. The horizontal axis is SSTA, and the vertical axis is the zonal wind anomaly. At each panel, the name of each model is shown in the bottom, and the number at the top indicates the slope of each fitted line.

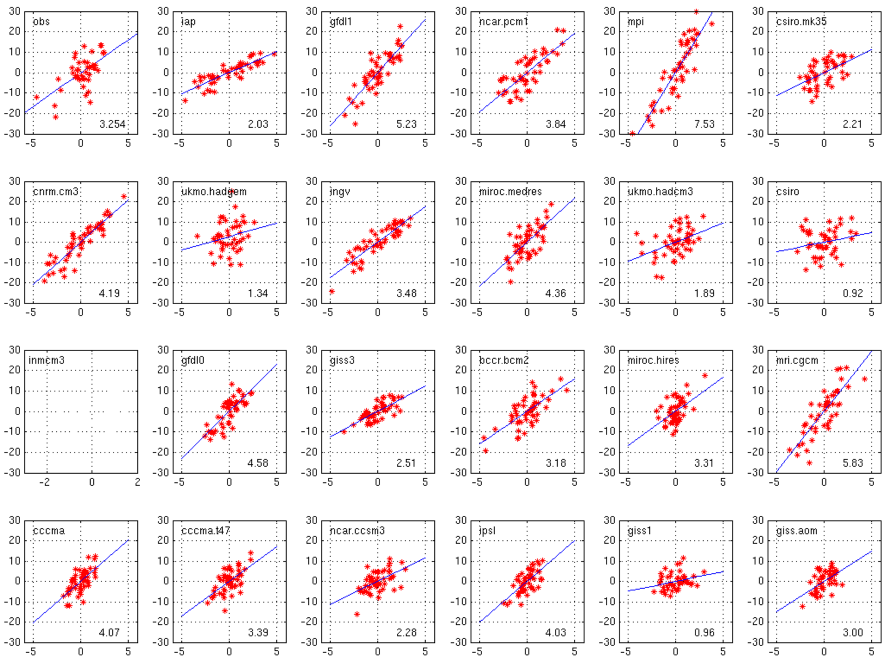


Fig. 2. Same as in Fig. 1 except for the relationship between the thermocline depth anomaly (unit: m) in the SEIO and the 850-hPa zonal wind anomaly (unit: m s-1) in the CEIO.

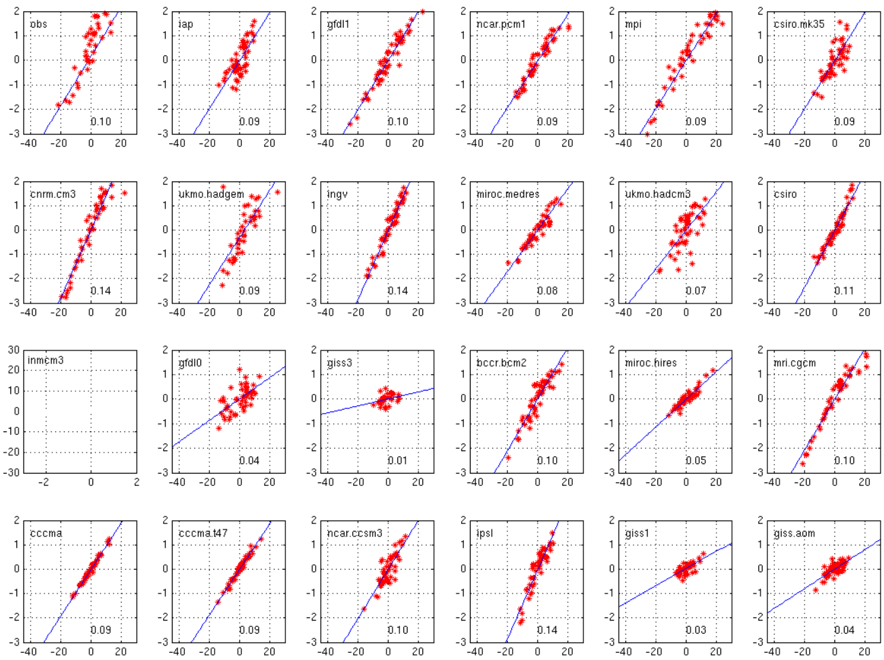


Fig. 3. Same as in Fig. 1 except for the relationship between the subsurface temperature anomaly (unit: K) and the thermocline depth anomaly (unit: m) in the SEIO.

The second process involves how the ocean thermocline responds to the equatorial surface wind forcing. The zonal wind anomaly in the CEIO in general forces two types of the ocean thermocline response, a fast adjustment in which the thermocline depth anomaly is approximately in a Sverdrup balance with the zonal wind stress anomaly, similar to that in the Pacific, and a slow evolution that involves the propagation of oceanic Rossby and Kelvin waves.

Figure 2 shows the scatter diagrams between the zonal wind anomaly in the CEIO and the thermocline depth anomaly in the SEIO for each model. The observed feedback relation between the wind and SEIO thermocline depth anomaly is positive because an easterly wind anomaly in the CEIO may lift (suppress) the thermocline in the eastern (western) part of the basin. Such a positive relationship is captured by all of the coupled models.

We hereby denote a wind-thermocline coupling coefficient R(D, u) to measure the strength of thermocline depth change for a given unit zonal wind forcing. It can be represented by the slope in Fig. 2. The averaged R(D, u) for the strong composite is 4.2 m per ms-1, while it is about 2.9 m per ms-1 for the weak composite. The observed R(D, u) is somewhere between the values of the strong and weak composites.

The third process involves how the ocean subsurface temperature responds to the ocean thermocline variation. In the SEIO, a shoaling (deepening) of the thermocline leads to a negative (positive) temperature anomaly at a fixed subsurface level. The change of the subsurface temperature may further affect SST through the anomalous vertical temperature advection by the mean upwelling. In the region of deep climatological mean thermocline, the subsurface temperature variation is small, and so is the SST variability.

Figure 3 shows the observed and the model simulated relationship between the thermocline depth anomaly and the temperature anomaly at 70 m (where the subsurface temperature variability is largest) in the SEIO. A positive correlation appears between the observed thermocline depth and subsurface temperature. We hereby denote R(Te, D) as a thermocline-subsurface temperature coupling coefficient, which can be measured by the slope in Fig. 6. The observed slope is 0.1 K m-1, implying that one meter thermocline change would lead to a SST change of 0.1K. Most of the CMIP3 models reproduce such a positive relationship, even though the slope is markedly different.

The overall Bjerknes dynamic feedback strength should be determined by the combined effect of the three processes above. To quantitatively measure the Bjerknes feedback intensity and to compare it with the thermodynamic feedback intensity, we introduce a simplified SST tendency equation as below:

$$\frac{\partial T'}{\partial t} = \overline{w}\frac{T_e'}{h} + \frac{Q'}{\rho C_w h} \tag{1}$$

where $T'$ and $T_e'$ denote the surface and subsurface ocean temperature anomalies respectively, $\overline{w}$ denotes the climatological mean vertical velocity at the base of the ocean mixed layer, $Q'$ is the net surface heat flux anomaly, $\rho$ and $C_w$ are the sea water density and specific heat, and $h$ is the ocean mixed layer depth. In Eq. (1), we only show the thermocline feedback and heat flux terms and have neglected other advection terms for simplicity. Assuming $T' = \delta T e^{\sigma t}$, Eq. (1) may be rewritten as:

$$\rho C_w h\sigma = \rho C_w \overline{w}\frac{T_e'}{T'} + \frac{Q'}{T'} \tag{2}$$

Here the left hand side of Eq. (2) is proportional to the growth rate ($\sigma$) of the SSTA. The second term in the right hand side of Eq. (2) represents how strong the surface heat flux anomaly is in response to a unit SSTA change. Thus it reflects the strength of the thermodynamic air-sea feedback. The first term in the right hand side of Eq. (2) represents the vertical advection of anomalous subsurface temperature by the mean upwelling velocity, thus reflecting the strength of the Bjerknes dynamic air-sea feedback. We hereby define the first term in the right hand side of Eq. (2) as the Bjerknes feedback intensity index (BFI) and the second term as the thermodynamic feedback intensity index (TFI). The BFI may be written as:

$$BFI = \rho C_w \overline{w} R(u,T) R(D,u) R(Te,D) \tag{3}$$

Equation (3) states that the BFI depends on the mean vertical velocity and a product of the SST-wind, wind-thermocline and thermocline-subsurface temperature coupling coefficients during the IOD developing phase. It measures the overall strength of the Bjerknes feedback in each model. Figure 4 shows the averaged values of the SST-wind, wind-thermocline and thermocline-subsurface temperature coupling coefficients and BFI respectively for the strong, moderate and weak composites. For comparison, the observed coupling coefficients and BFI are also shown in the figure. Note that the BFI is consistent with the overall strength of the IOD simulations, with the greatest (smallest) value occurring in the strong (weak) composite.

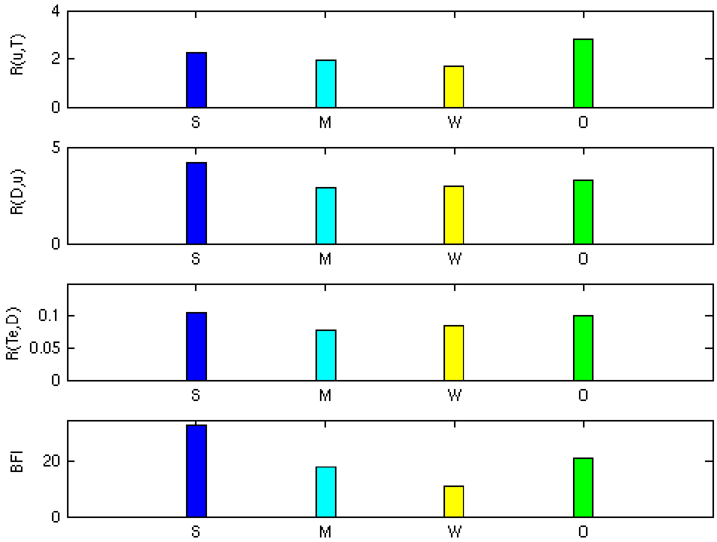


Fig. 4. R(u,T) (unit: m s-1 k-1), R(D,u) (unit: s), R(Te,D) (unit: K m-1) and BFI (unit: W m-2 K-1) in JAS season for the strong (denoted by 'S'), moderate (denoted by 'M'), and weak (denoted by 'W') composites and from the observational data (denoted by 'O').

The above analysis points out the important role of the dynamic air-sea coupling in determining the strength of the model IODs. Given that the IOD is also affected by the thermodynamic air-sea coupling, in the following we will examine the wind-evaporation-SST feedback and the cloud-radiation-SST feedback in the SEIO from the 23 models.

**b. Thermodynamic air-sea feedback strength**

Two types of thermodynamic air-sea feedback processes were involved during the IOD developing phase. One is a positive feedback among the SST, surface wind, and evaporation. This positive feedback is attributed to the background southeasterly in the SEIO, under which an anomalous southeasterly induced by a cold SSTA may further enhance the cold SSTA through increased surface evaporation. Another is a negative feedback among the SST, cloud, and shortwave radiation anomalies, that is, a cold SSTA leads to the decrease of clouds, which further increases the downward shortwave radiation and decreases the cold SSTA.

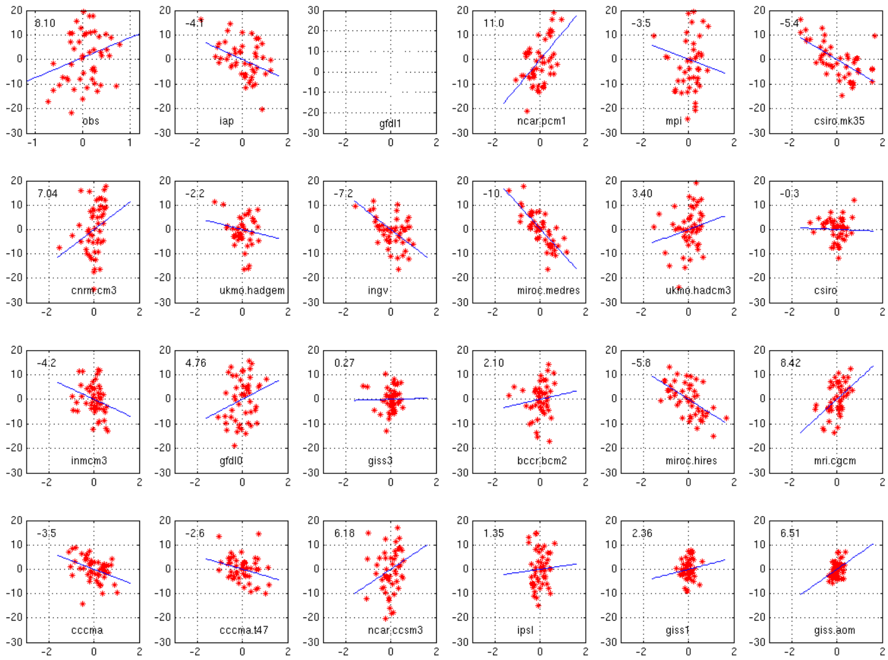


Fig. 5. Same as in Fig. 1 except for the relationship between the surface latent heat flux anomaly (unit: W m-2) and SSTA in the SEIO. The latent heat flux is defined positive downward.

How well do the CMIP3 models simulate such a positive wind-evaporation-SST feedback? To quantitatively measure the feedback strength, we plot the scatter diagram (Fig. 5) to illustrate the relationship between the surface latent heat flux (LHF) anomaly and the SSTA in the SEIO in JAS. For the comparison, the observed counterpart is also plotted.

We hereby denote R(LHF, T) to represent the SST-evaporation feedback coefficient, which can be measured by the slope at each panel of Fig. 8. The observed feedback coefficient is 8.1W m-2 K-1, which implies that for given 1K SST cooling, the resulting latent heat flux anomaly is 8.1 W m-2. This amount of anomalous heat flux could be used to further enhance the local SST cooling. Surprisingly, many CMIP3 models (including these in the strong simulation group) fail to reproduce such a positive feedback process. The large bias in the wind-evaporation-SST feedback poses a great challenge to many state-of-art coupled GCMs.

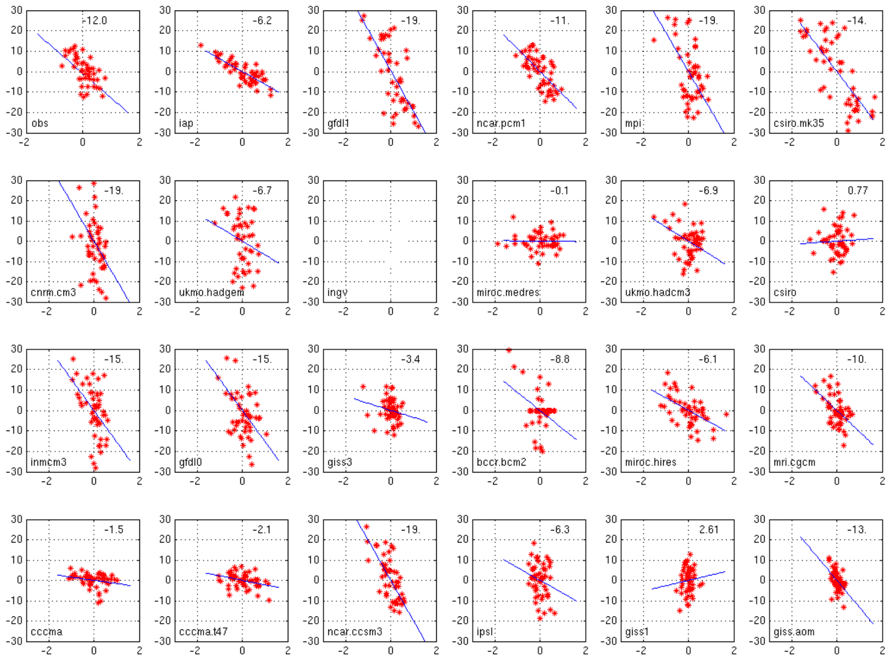


Fig. 6. Same as in Fig. 1 except for the relationship between the surface net shortwave radiation anomaly (unit: W m-2) and SSTA in the SEIO.

To illustrate how different the cloud-radiation-SST feedback is among the 23 models, we show in Fig. 6 the simultaneous relation between the shortwave radiation and SST anomalies averaged in JAS over the SEIO. Different from the positive wind-evaporation-SST feedback, a negative feedback between the observed SST and shortwave radiation anomalies exists in the SEIO. While most of the coupled models reproduce such a negative feedback process, two models (csiro, giss1), surprisingly, exhibit a weak positive feedback.

We hereby denote R(SWR, T) to measure the strength of the negative cloud-radiation-SST feedback. The averaged slope for the strong composite is -14 W m-2 K-1, which is about twice as large as that (-7 W m-2 K-1) in the weak composite.

The overall thermodynamic feedback intensity (TFI) may be measured by the sum of the wind-evaporation-SST feedback and the cloud-radiation-SST feedback, that is,

$$TFI = R(LHF, T) + R(SWR, T) \tag{4}$$

Figure 7 shows the diagrams of R(LHF, T), R(SWR, T) and TFI for the strong, moderate and weak composites and for the observation. The major bias appears in the latent heat flux-SST relationship. Consequently, the overall thermodynamic damping in all the three groups is overestimated, compared to the observation. The strongest (weakest) thermodynamic damping appears in the strong (weak) group.

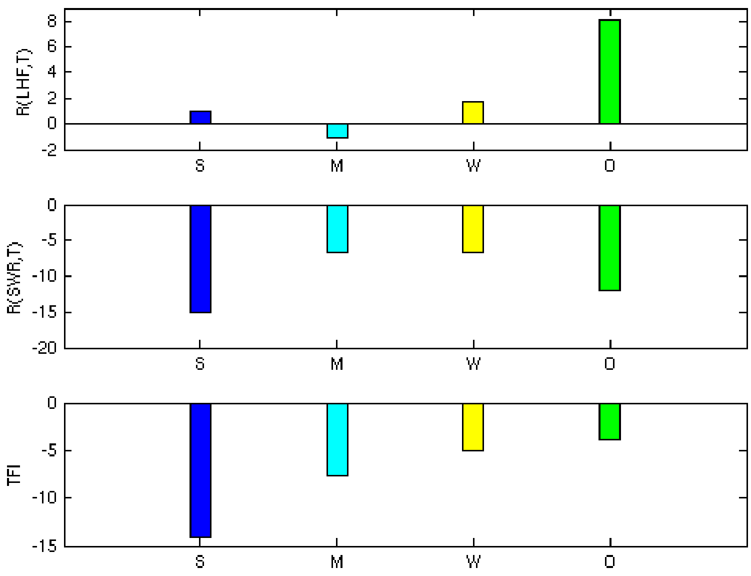


Fig. 7. R(LHF,T), R(SWR,T) and TFI (unit: W m-2 K-1) averaged during JAS season for the strong, moderate and weak composites (denoted as 'S', 'M' and 'W' respectively) and from the observation (denoted as 'O').

We examine the detailed dynamic and thermodynamic air-sea feedback processes in 23 CMIP3 models and reveal their possible roles in the diversity of IOD simulations and the connection to the model mean state. The methodology applied here may be readily extended to other climate phenomena such as ENSO and may provide general guidance for coupled model assessment and improvement. For instance, a comparison of scatter diagrams of the SST-wind, wind-thermocline, thermocline-subsurface temperature, SST-latent heat flux and SST-shortwave radiation relations with the observations may provide the model developers about what parts of air-sea feedback processes or model physics might be inaccurate and need to be further improved.

**(2) The performance of IOD event in CMIP5**

Following the update working plan, the proponents have performed preliminary research on the CMIP5 multi-model outputs. The performance of 17 WCRP CMIP5 models in the simulation of the Indian Ocean Dipole (IOD) is evaluated and the results show large diversity in the simulated IOD intensity as well as the consistent IOD spatial pattern in sea surface temperature field among models. Fig8 lists the standard deviation of IOD index at each month among models and observation. The result is quite applausive because all of the numerical coupled models have ability to simulated IOD event successfully. This conclusion lays on the basis for the further analysis and research. Considering the aforementioned method, we will perform the more detailed research on this issue.

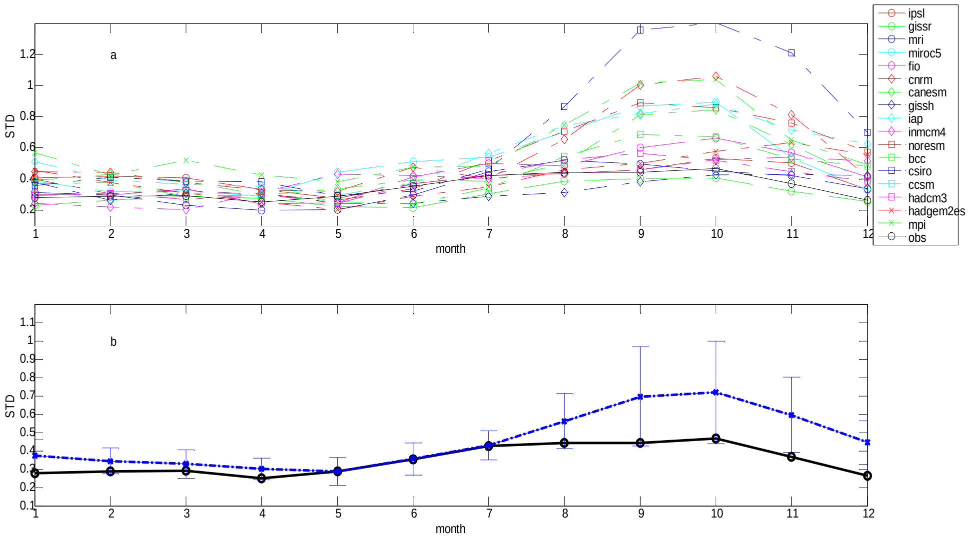


Fig. 8. The standard deviation of Indian Ocean Dipole mode index at each calendar month(a) and the ensemble averaged result(b) from CMIP5 model outputs.

**(3) What is the contribution for capacity building for global change research?**

In this project, the characteristics of IOD associated air-sea interaction and feedback strength in the CMIP5 models will be assessed. The result of this analysis will greatly assist the modeling communities to validate and improve their coupled models for climate change projections as well as for short term climate prediction. The projected changes of Indian Ocean feedback and climate states are also important for the mitigation and adaptation research communities. The publication of the result will contribute to the on going 5th IPCC assessment.

The multi lateral collaboration between APN project researchers and those from the MOMSEI program allow sharing of latest knowledge regarding the Indian Ocean climate variability. Through participating and contributing in the MOSMEI summer school (2012, 2013) lectures, which is to be held annually, result and the data analysis techniques will be shared and communicated to the relevant participating stakeholders. The participants will be introduced to available climate data and take part in the data processing and analysis. This allows them to learn about the impact of climate change to the Indian Ocean climate variability and its potential implication in adaptation strategies. This increases their capacities in dealing with climate change issues in the impacted area. In addition, this introduces the summer school participants to APN and promotes future networking with the involved researchers.

**(4) How to guarantee the implementation of the project?**

This project involved researcher from different countries and the successful collaboration between members of distinct countries would rely on the each member effort and hardly work. In order to facilitate the implement of the proposed work plan, a scientific advisory committee is setup to provide advisory support to the relatively junior researchers involved in current project. As of current writing, the committee consists of senior scientists from China, Malaysia, French and U. S.

## 4.0 Conclusions

Tropical Indian Ocean air-sea coupled event is the most important interannual phenomena, which modulate the variation of Asian summer monsoon system. The influence from global warming to inner air-sea feedback strength of tropical Indian Ocean air-sea coupled event is still unclear and is one of challenge for the relevant research. The proposed workshop will benefit to promote the working plan as well as the detailed content of the project. The update proposal has emerged after this scope meeting, which will also give great help to the regional global changing research works.

With financial and scientific support from APN, the seed granted project team has realized how to promote the original proposal to well cooperate with other international organization. A well connected and understood working team has been organized and a lot of international professional societies have agreed to setup a scientific committee to guarantee the project execution. A new proposal targeted to enhance the cooperation with IOC/WESTPAC has been proposed as the project main output. The whole team members are pleasure to finish this seed project work and to apply the continual one.

With the hard work of the whole team, we have achieved progresses related with the project:

**The method to measure the IOD strength in coupled models**

A detailed diagnosis is carried out to understand the role of the Bjerknes dynamic air-sea feedback and the thermodynamic air-sea coupling in shaping the different model behaviors. The Bjerknes feedback processes include the equatorial zonal wind response to SST, the thermocline response to the equatorial zonal wind, and the ocean subsurface temperature response to the thermocline variation. The thermodynamic feedback examined includes the wind-evaporation-SST and cloud-radiation-SST feedback. We examine the detailed dynamic and thermodynamic air-sea feedback processes in 23 CMIP3 models and reveal their possible roles in the diversity of IOD simulations and the connection to the model mean state. The methodology applied here may be readily extended to other climate phenomena such as ENSO and may provide general guidance for coupled model assessment and improvement. For instance, a comparison of scatter diagrams of the SST-wind, wind-thermocline, thermocline-subsurface temperature, SST-latent heat flux and SST-shortwave radiation relations with the observations may provide the model developers about what parts of air-sea feedback processes or model physics might be inaccurate and need to be further improved.

**The performance of IOD event in CMIP5**

Following the update working plan, the proponents have performed preliminary research on the CMIP5 multi-model outputs. The performance of 17 WCRP CMIP5 models in the simulation of the Indian Ocean Dipole (IOD) is evaluated and the results show large diversity in the simulated IOD intensity as well as the consistent IOD spatial pattern in sea surface temperature field among models. Fig1 lists the standard deviation of IOD index at each month among models and observation. The result is quite applausive because all of the numerical coupled models have ability to simulated IOD event successfully. This conclusion lays on the basis for the further analysis and research. Considering the aforementioned method, we will perform the more detailed research on this issue.

**What is the contribution for capacity building for global change research?**

In this project, the characteristics of IOD associated air-sea interaction and feedback strength in the CMIP5 models will be assessed. The result of this analysis will greatly assist the modeling communities to validate and improve their coupled models for climate change projections as well as for short term climate prediction. The projected changes of Indian Ocean feedback and climate states are also important for the mitigation and adaptation research communities. The publication of the result will contribute to the on going 5th IPCC assessment.

The multi lateral collaboration between APN project researchers and those from the MOMSEI program allow sharing of latest knowledge regarding the Indian Ocean climate variability. Through participating and contributing in the MOSMEI summer school (2012, 2013) lectures, which is to be held annually, result and the data analysis techniques will be shared and communicated to the relevant participating stakeholders. The participants will be introduced to available climate data and take part in the data processing and analysis. This allows them to learn about the impact of climate change to the Indian Ocean climate variability and its potential implication in adaptation strategies. This increases their capacities in dealing with climate change issues in the impacted area. In addition, this introduces the summer school participants to APN and promotes future networking with the involved researchers.

**How to guarantee the implementation of the project?**

This project involved researcher from different countries and the successful collaboration between members of distinct countries would rely on the each member effort and hardly work. In order to facilitate the implement of the proposed work plan, a scientific advisory committee is setup to provide advisory support to the relatively junior researchers involved in current project. As of current writing, the committee consists of senior scientists from China, Malaysia, French and U. S.

The most important thing in the quite near future is to submit the modified proposal to ARCP program. Based on the suggestion from scoping workshop and the fruitful discussion with relevant experts, the pilot project of IOC/WESTPAC, MOMSEI, has agreed to arrange a joint lecture for this project during its summer training course, 2012, which is a good opportunity for disseminating our project into more persons and organization. At that time, the project participants will also discuss with the experts from IOC/WESTPAC for the further cooperation.

## 5.0 Future Directions

The new submitting the modified proposal to ARCP program is the most important thing in the quite near future. Based on the suggestion from scoping workshop and the fruitful discussion with relevant experts, the pilot project of IOC/WESTPAC, MOMSEI, has agreed to arrange a joint lecture for this project during its summer training course, 2012, which is a good opportunity for disseminating our project into more persons and organization. The proponents will try the best to enhance the communication with IOC/WESTPAC for the further cooperation. Also, we will build the connection with numerical model developer in order to improve their coupled models based on our research.

## References

## Appendix

Annex 1 Scope Meeting Agenda

# Agenda for Scoping Workshop

# Developing Proposal: The Impact of Global Warming Ocean-Atmosphere Feedback Strength in the Tropical Indian Ocean

## Qingdao, China

## August 26-28, 2011

**The venue:**

No. 5 Conference Room of Sophia International Hotel, Qingdao

**Agenda:**

**August 26, 2011**

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**14:00 – 14:10: Agenda review**

**14:10 – 14:40: Project overview**

**14:40 – 15:30: Discussion**

**15:30 – 15:40: Coffee break**

**15:40 – 18:00: Discussion (cont.)**

**18:00: Reception dinner**

**August 27, 2011**

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**9:00 - 12:00: Discussion (cont.)**

**13:00 – 16:00: Discussion (cont.)**

**August 28, 2011**

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**9:00 - 10:00: Review of modified chapter**

**10:00 – 10:10: Meeting summary**

**10:10: Close**

## Key Contacts:

Dr Lin LIU

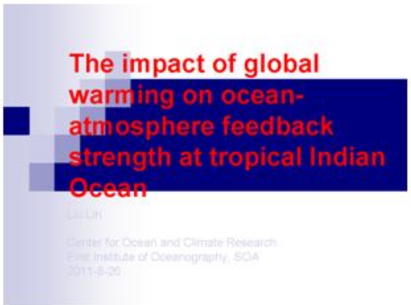
Center for Ocean and Climate Research
The First Institute of Oceanography, State Oceanic Administration
No.6 Xian-Xia-Ling Road, High-Tech Park
Qingdao 266061, P.R.CHINA
Tel : +86-(0)532-88961173
Fax: +86-(0)532-88961173
Email : liul@fio.org.cn;

Miss Duxin JIAO

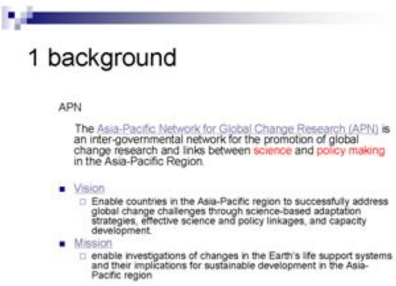
Center for Ocean and Climate Research
The First Institute of Oceanography, State Oceanic Administration
No.6 Xian-Xia-Ling Road, High-Tech Park
Qingdao 266061, P.R.CHINA
Qingdao 266061, P.R.CHINA
Tel : +86-(0)532-88962331
Fax: +86-(0)532-88962331
Email : jiaodx@fio.org.cn;

## Annex 2 Scope Meeting presentations

### (1) Dr Lin Liu's presentation on the proposal








The Annual Regional Call for Research Proposal (ARCP)

ARCP is one of the scientific pillars of the APN to encourage and promote global change research in the Asia-Pacific region that has potential, in addition to improving the understanding of global change and its implications in the region, to contribute to the establishment of a sound scientific basis for policy-making with regard to issues for which global change is an important factor.

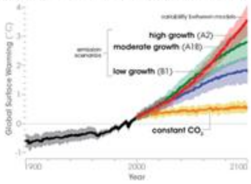
- New research which addresses knowledge gaps in key scientific areas
- Synthesis and analysis of existing research
- Research planning/scoping activities
- The development of policy products such as integrated assessments, impact assessments, climate models, etc.

## 2 The activity at 2010

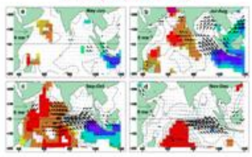
- The proposal titled as "The impact of global warming on ocean-atmosphere feedback strength at tropical Indian Ocean " has been submitted to the ARCP
- Proponents from China, Malaysia and U.S.

## Motivation of the project

- Global warming is the apparent phenomenon




- Indian Ocean is the key area for the climate variability of Asian Countries.



Relevant working of the proponent on this issue

Dynamical response
- Surface wind to SST
- Thermocline to Wind
- SST to Thermocline

} Positive feedback

Thermodynamical response
- Latent heat flux to SST → Positive feedback
- Shortwave flux to SST → Negative feedback

Feedback mechanisms during IOD evolution

$$\frac{\partial T'}{\partial t} = \bar{w}\frac{T_e'}{h} + \frac{Q'}{\rho C_w h}$$

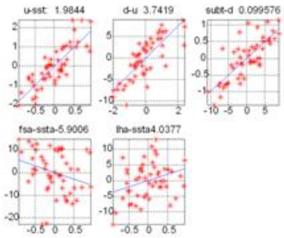
$$T' = \delta T e^{\sigma t}$$

$$\rho C_w h\sigma = \rho C_w \bar{w}\frac{T_e'}{T'} + \frac{Q'}{T'}$$

$$BFI = \rho C_w \bar{w} R(u,T) R(D,u) R(Te,D)$$

$$TFI = R(LHF,T) + R(SWR,T)$$

**CFI = BFI + TFI**




- Public focal point
- Policy maker's concern
- Scientific research basis
- Cooperation experience among proponents

| Stages | Action | Date | Status |
| --- | --- | --- | --- |
| Advisory Service (Voluntary) | Potential proponents can consult with the APN Secretariat with cc to nFP and SPG member by sending a Letter of Intent | Deadline: Friday, 11 June 2010 | COMPLETED |
| Stage 1: Submission & Review of Summary Proposal | Submission of Summary Proposals to the APN Secretariat<br>Preliminary screening process to shortlist proposals for funding and notification of successful proponents. | Deadline: 30 July 2010<br>August/September 2010 | COMPLETED |
| Stage 2: Submission & 2-Step Review of Full Proposal | Submission of Full Proposals to the APN Secretariat by the successful Stage 1 proponents | Deadline: Tuesday, 12 October 2010 | COMPLETED |
| Step One | Step 1 Review by the SPG members and External Reviewers.<br>Proponents are sent questions and comments from the SPG members.<br>COMPULSORY: Proponents respond in writing to SPG reviewers' questions and comments. | October/December 2010<br>December 2010<br>10 January 2011 | COMPLETED |
| Step Two | Step 2 Review. SPG members submit revised ratings based on responses of the proponents at Stage 1. | January/February 2011 | |
| Stage 3 | The APN's 16th Inter-governmental Meeting (IGM) approves which proposals to fund, following the recommendations made from the SPG. The APN Secretariat then communicates the final decisions | 4-8 April 2011 | |

## The purpose of the workshop

Help to develop and improve the proposal for the next stage application

## 3 Proposed action

- 3.1 Working plan
- 3.2 Capacity Building for Global Change Research
- 3.3 Relevance to Policy Processes and Sustainable Development
- 3.4 Relationship between Global Change Research Programmes and Networks
- 3.5 Communications, Publications and Open Access to Data

3.1 Working plan

- 1. Scientific Research
  - Analysis for the observational data.
  - Designing the proper numerical experiment and model data output analysis.
  - Analysis for CMIP3 and CMIP5 data
- 2. Workshop
  - Spread the update research progress.
  - Expand the potential international cooperation
  - Communication with police-maker via meeting

3.2 Capacity Building for Global Change Research

- It is a bridge for China, Malaysia and US scientists as well as other relevant countries working together for critical scientific issue, which will deepen the cooperation between participated countries definitely on Indian Ocean are climate change research.
- The cooperation and communication among members will do good at increasing the research ability of members within the project and understanding for Indian Ocean climate variability as well as the final outcomes.

3.3 Relevance to Policy Processes and Sustainable Development

- The final results would provide the concrete information for the influence from global warming on the interannual variability of tropical Indian Ocean, which would modulate the local summer monsoon at Indian Ocean area.
- The project would provide concrete information for the policy designers and make them realize that to what extent the global warming affects natural ocean-atmosphere coupled phenomena in Indian Ocean.
- The result of this project would be published and sent to local policy makers for their reference.

3.4 Relationship between Global Change Research Programmes and Networks

- CLIVAR/GOOS Indian Ocean Panel is an international association, working to design and implement an integrated observing system for the Indian Ocean.
- This project will share the data from ongoing observing system and conduct co-working on data analysis activities with CLIVAR/GOOS Indian Ocean Panel experts.
- The proponent had worked with experts from CLIVAR/GOOS Indian Ocean Panel before and the good relationship between each had been built. This project would stimulate the further cooperation between APN and CLIVAR/GOOS Indian Ocean Panel.

3.5 Communications, Publications and Open Access to Data

- This project will publish papers on peer-reviewed journals.
- The relevant results will be uploaded into website, which is designed to publish up-to-date information to the public.

### Response from the reviewers

- 1. The analysis methodology is well described, but the focus of the resources is on communication as opposed to analysis.
- 2. Not fully convinced of the real competence of the team to actually make a difference. Provide more information.
- 3. More details of coupled model experiments should have been provided. Further, since APS results become available by the time this proposal goes for execution, I recommend use of APS results.
- 4. The interactions between scientists are addressed, but the linkages to policy-makers are not addressed. Apart from a "workshop" there is no attempt to disseminate results appropriately to policy makers and decision makers using policy briefs in local languages. Linkages to CLIVAR/GCOS may assist in further dissemination.

- 5. The project requires major financial support to travel and limited for scientific forum. The things to be carried out or discussed during the forum are not emphasized and well explained.
- 6. Type of data to be collected is not clearly defined. Would there be any cost for collection of that data? The project may seek the collaboration with the CLIVAR / GOOS or CMIP3 data centre to carry out the project effectively.
- 7. This topic is an important one. The PI proposes to examine the impact from global warming on ocean-atmosphere coupled event at tropical Indian Ocean through numerical modeling efforts and analysis of observational data. However, it is not clear how the proposed activities of participating in relevant conferences and discussion among project members can contribute significantly to achieving the proposed goal.

***Thanks***

### Topics for discussion

- Working plan
- Capacity Building for Global Change Research
- Relevance to Policy Processes and Sustainable Development
- Relationship between Global Change Research Programmes and Networks
- Communications, Publications and Open Access to Data

**Annex 3 Scope Meeting Participants Name list**

**Prof. Wenjie DONG**
Member of Scientific Steering Committee, APN,
Member of Scientific Steering Committee ,CLIVAR/WCRP;
College of Global Change and Earth System Science,
Beijing Normal University, China

**Prof. Somkiat Khokiattiwong**
IndianOcean GOOS (Officer, North Eastern)
SEA-GOOS (Chair)
Chairs of GRAs (SEA GOOS)
Phuket Marine Biological Center, Thailand

**Prof. Laurent LI**
Laboratoire de Météorologie Dynamique (LMD)
Centre National de la Recherche Scientifique (CNRS)
Ecole Normale Supérieure
Ecole Polytechnique
Université Pierre et Marie Curie (Paris 6)
Paris, France

**Prof. Qinyu Liu**
Ocean University of China
Shandong, China

**Prof. Yue FANG**
Center for Ocean and Climate Research
First Institute of Oceanography, State Oceanic Administration
Qingdao, China

**Dr. Juneng LIEW**
Faculty of Science and Technology
Universiti Kebangsaan Malaysia.
Bangi, Selangor, Malaysia

**Dr. Lin LIU**
Center for Ocean and Climate Research
First Institute of Oceanography, State Oceanic Administration
Qingdao, China

**Annex 4 Qingdao meeting Photos**


**Presentation by Lin LIU**


**Discussion**


**Discussion**


**Group Photo**

**Annex 5 Dissemination Report in CMIP5 Workshop, 8 March, 2012**

**Dr. Lin LIU(1st from right side) presented the poster on APN project preliminary result during CMIP5 workshop hold at Hawaii.**

## Annex 6 List of Young Scientists

Dr. Juneng LIEW
Faculty of Science and Technology
Universiti Kebangsaan Malaysia.
Bangi, Selangor, Malaysia
jnliew@gmail.com

The project activity will provide the change to cooperate with international researcher and he will perform the study focused on the mean state change of Indian Ocean.

Dr. Lin LIU
Center for Ocean and Climate Research
First Institute of Oceanography, State Oceanic Administration
Qingdao, China
liul@fio.org.cn

His work is mainly develop the methodology for the model outputs evaluation.

Dr. Shahbaz Mehmood
Scientific Officer (Climate Section)
Global Change Impact Studies Center (GCISC)
Quaid-i-Azam University Campus
Islamabad, Pakistan
shahbaz.mehmood@gcisc.org.pk

The project activity will provide the change to cooperate with international researcher and he will perform the thermodynamical feedback analysis.

## Annex 7 Glossary of Terms

Intergovernmental Oceanographic Commission Sub-Commission for the Western Pacific (IOC/WESTPAC)

Monsoon Onset Monitoring and its Social & Ecosystem Impacts (MOMSEI)
Indian Ocean Dipole (IOD)
Coupled Model Intercomparison Project (CMIP)