Project Final

(2022)

Project Reference Number: CBA2020-06SY-Yoo

Project Title: WCRP Workshop on Extremes in Climate Prediction Ensembles (ExCPEns)

WCRP Workshop on Extremes in Climate Prediction Ensembles (ExCPEns)

1. Project information

1.1 Project duration

- Project Duration: 1 year (April 2021 – March 2022)

The project involved preparing and organizing the World Climate Research Programme (WCRP) Workhop on Extremes in Climate Prediction Ensembles, which was held on October 25 – 28, 2-21. Based on the workshop presentations, invited lectures, and discussions, the project team worked on extracting key research results and recommendations for furthering scientific advancements, in addition to creating a priority list of proposed research topics in the field of subseasonal-to-multidecadal climate prediction and its application, particularly over the Asia-Pacific region.

1.2 Funding, collaborators and key organizations

1.2.1 Funding

- Initial funding: $40,000 USD
- Changed funding: $14,600 USD

The project fund requested to APN (Asia-Pacific Network for Global Change Research) was originally $40,000 USD including travel expenses of early career scientists from developing countries in the case of hosting an offline workshop; however the global spread of COVID-19 forced the workshop to be held online only. Accordingly, the project team requested revised budget of $14,600 USD.

1.2.2 Collaborators

- June-Yi Lee, Pusan National University/ICCP (IBS Center for Climate Physics), Co-chair of WCRP /WGSIP (Working Group on Subseasonal to Interdecadal Prediction)
- William Merryfield, Environment and Climate Change Canada, Co-chair of WCRP/WGSIP
- Doug Smith, UK Met Office, WCRP/Explaining and Predicting Earth System Change
- Frederic Vitart, ECMWF (European Centre for Medium-Range Weather Forecasts), Co-chair of WCRP/WWRP (World Weather Research Programme)/S2S (Sub-seasonal to Seasonal Prediction Project)
- Xuebin Zhang, Environment and Climate Change, Co-chair of WCRP/GC-Extremes
- Arun Kumar, National Oceanic and Atmospheric Administration, WCRP/WWRP/S2S
- Hong-Li Ren, China Meteorological Administration, WCRP/WGSIP
- Catherine Michaut, IPSL (Institute Pierre-Simon Laplace)/UVSQ University of Versailles Saint-Quentin-en-Yvelines), WCRP
- Yun-Young Lee, APEC Climate Center
- Jin-Ho Yoo, APEC Climate Center
- Sangwon Moon, APEC Climate Center

1.2.3 Key organizations

- World Climate Research Programme (WCRP)
- Pusan National University
- APEC Climate Center (APCC)

2. Project summary

Weather and climate extremes have enormous impacts on society, and are increasing in both severity as well as frequency with increasing global termperature. The project here was to advance the rapidly emerging science of employing subseasonal, seasonal, annual to decadal, and long-term prediction ensembles to improve the prediction and understanding of weather and climate extreme events by hosting the WCRP Workshop on Extremes in Climate Prediction Ensembles (ExCPEns) and early-career scientist (ECS) networking and training program. During the workshop, 68 presentations were made over six sessions, with approximately 300 participants from all over the world in attendance. The ECS event followed the ExCPEns workshop, and consisted of a discussion and networking forum from APN member developing countries, followed by a series of ECS training lecture and discussion sessions open to all 58 ECS registrants. Through the workshop and stakeholder discussions, important scientific results on prediction and future changes of climate extremes were identified. Additionally, new research topics across different time scales were identified and prioritized. Workshop outcomes and related findings will be submitted to a peer-reviewed scientific journal for publication.

Please indicate the project's current status:

☑ Complete

☐ Proceeding according to work plan and logical framework matrix

☐ Ahead of schedule

☐ Behind schedule

☐ Proceeding with some modifications (Please specify):

2.1 Identifying key scientific issues on prediction and future changes of climate extremes

The WCRP Workshop on Extremes in Climate Prediction Ensembles was held online from October 25 to 27, 2021, and sponsored by the Asia-Pacific Network for Global Change Research (APN), WCRP, Pusan National University, and the APEC Climate Center. The workshop focues on emplying subseasonal, seasonal, annual to decadal, and longer-term prediction ensembles to improve the prediction and understanding of extreme weather and climate events. In total, 42 oral talks and 31 poster presentations were completed across the six sessions. Through this workshop, important scientific issues regarding predictions and future changes in climate extremes were identified and a summary of workshop results will be submitted to a peer-reviewed journal for publication.

2.2 Activating the Early-Career Scientist (ECS) network in APN countries

The ECS event that immediately followed the ExCPEns workshop consisted of a discussion and networking forum for ECSs from APN member developing countries. Accordingly, a series of ECS training lectures and discussion sessions were conducte with all 58 ECS registrants. The six lectures focused on the detection, attribution, and prediction of weather and climate extremes, as well as the use and implications of the recently published Working Group I contribution to the IPCC Sixth Assessment Report. The networking forum centered on breakout sessions matching smaller ECS groups with experienced scientists. Two questions that were discussed by all groups were: (1) What are the most important scientific challenges to predicting weather and climate extremes, and how can we tackle them? (2) What are the difficulties faced by ECSs in your country, and what are some possible solutions? Overall, organizers and participants felt that it was a successful event, despite the limitations and challenges posed by remote participation across various time zones; however the ECS event in particular could have been benefited from in-person participation. The important results from the ECS events have been summarized, and a meeting summary will be submitted to the APN Science Bulletin.

3. Project activities

Reporting period: April 2021 – March 2022

3.1 WCRP Workshop on Extremes in Climate Prediction Ensembles (ExCPEns)

The WCRP Workshop on Extremes in Climate Prediction Ensembles (ExCPEns) was held online from October 25 to 27, 2021, and co-hosted by the World Climate Research Programme (WCRP), Pusan National University, and the APEC Climate Center. The workshop focused on employing subseasonal, seasonal, annual to decadal, and longer-term prediction ensembles to improve the prediction and understanding of extreme weather and climate events. The 3-day workshop consisted of six sessions including 42 oral presentations and 26 poster talks. The workshop was announced through various target groups and communities to promote better participation by related stakeholders, such as the WMO (World Meteorological Organization) S2S group, Young Earth System Scientists (YESS) community, WMO Southeast Asia, APCC networks, APN networks, and WCRP networks.

3.1.1 Activities

(1) Abstract submission

- Timeline: April 26 – June 30, 2021 (Extended deadline)
- Applications: 89 applications from 24 countries

(2) Presentation allocation

- The Science Organizing Committee (SOC) categorized the presenters into oral and poster sessions based on the relevance of session topics and the quality of abstracts. Althougth 89 applications were submitted, various applicant personal issues reduced this to a final number of 68 presentations (42 oral and 26 poster).

(3) Presentation during the workshop

- Oral presentation: 15-min presentation
- Poster presentation: Poster presenters were given three ways of presentations: (i) an optional 5-min pre-recorded poster presentation to be uploaded on the open web platform Trello prior to the workshop; (ii) 2-min summary presentations during the sessions; and (iii) 30-min full poster presentations and discussions during the breakout sessions.

(4) Workshop proceedings

- The core writing team, composed of workshop session presenters and session chairs jointly listed the key research outcomes and highlights following the workshop. A draft of the workshop proceedings was subsequentlyl prepared, and has been shared among the writing team for further editing and feedback.

(5) Materials

- All major materials, including programs, presentation files, and pre-recorded poster presentations were uploaded to Trello. The link was shared with all presenters and registered participants before and during the workshop. After the workshop, all materials were uploaded to the APCC website, and video clips were uploaded to the APCC YouTube account (https://youtube.com/playlist?list=PLGUa1D7J0MXbFLqO3O4OMOGcDoAko9iY2).

3.1.2 Sessions

(1) Identification of extremes in observations and climate prediction ensembles

- ***Background***: The identification of extremes in observational data and climate prediction ensembles is an important aspect for assessing the correlated impacts in a societal context, as well as the predictive capacity. Accordingly, Session 1 covered: (i) a review of the definition and characterization of climate extremes, in addition to methodologies for identifying extremes in observational data; (ii) the limitations of different observational datasets for the characterization of extremes, and their influence on prediction validation; (iii) the validation of extremes in climate prediction ensembles against observational estimates; and (iv) the quantification of biases in extremes of climate prediction ensembles, implications for prediction, and possible sources of bias during simulations of extremes.
- ***Presentations***: Samuel Mogen (University of Colorado Boulder) looked at extreme events and their biogeochemical signatures in North Pacific SST anomalies. Of particular interest were SST blob events associated with long-lasting warm SST anomalies. The analysis developed composites for dissolved inorganic carbon (DIC) and dissolved oxygen (DO), revealing that for blob events, DIC concentrations increased (less acidic), while DO decreased. The analysis further analyzed budgets of the respective quantities to assess which processes were most responsible for the biogeochemical signatures. The analysis provided an interesting example of quantifying the influence of extreme events on nonphysical variables. Beyond the assessment of predictive skill for decadal-scale mean quantities, Markus Donat (Barcelona Supercomputing Center) analyzed the prediction of extremes using a perfect predictability approach. Their results indicated that the prediction of temperature extremes was better than that of average temperature; whereas predictive capacity of precipitation was lower due to the inherently noisier time series. The analyses also explored whether modeled climate change projections for the next 20 years could be constrained based on the assessment of decadal predictions, and their results were encouraging. Alternatively, Chloe Prodhomme (University of Toulouse, Meteo-France) explored the predictive skill of heat waves over Europe using seasonal hindcasts from ECMWF SYS5. The results were promising, in that seasonal forecasts skillfully predicted several local heatwave indices, especially over eastern and southern Europe; moreover, model-based forecasts outperformed statistical prediction systems. These results indicate that predicting statistical extremes on a seasonal timescale may be feasible, and could become an important forecast product.
- ***Poster presentations*:** The first presentation involved compound soil moisture–precipitation events by examining the preconditions for flooding events. This statistical study used observation-based data and advanced event coincidence analysis method. The second presentation focuses on CO_2 and aerosol contributions to global warming by applying the fingerprint method to temperature extremes.
- ***Summary:*** The characterization of extremes in observations and climate prediction ensembles examined their spatiotemporal footprints, catalogued particular classes of

simulated and observed extremes as well as their characterization in climate projection ensembles, combined information from decadal and multi-decadal projections, and verified forecasts of local heatwave indices.

(2) Physical mechanisms of extremes in observations and climate prediction ensembles

- ***Background:*** Understanding the physical mechanisms and large-scale drivers of extremes is a prerequisite for improving predictive capacity. To this end, Session 2 constituted: (i) a review of the observational mechanisms of extremes, (ii) the identification of large-scale drivers and important feedback processes of extremes, and (iii) the correlated mechanisms captured by climate prediction ensembles linking predictability to their initial state dependency.
- ***Presentations:*** The increase in frequency and strength of global weather and climatic extremes is creating significant economic damages. Globally, the increase in fatalities due to heatwaves and floods is experiencing statistically significant increasing trends. European heat waves result from large-scale, stationary waves, and can create major impacts on the economy and mortality. Using a nonlinear stationary wave model (NSWM), the role of anomalous stationary waves and their forces during heatwaves was examined. It was shown that the dynamics of heat waves are nonlinear, and European heat waves are created locally by transient momentum fluxes, and remotely by heat-driven SSTs in the tropical Indian Ocean and western Pacific regions. Accordingly, it was suggested that European heat waves can be predicted by considering the nonlinear effects of anomalous stationary waves and heating sources in both proximate and remote tropical regions. In addition, the possibility of drought prediction using machine-learning with large-scale modes of climate variability was proposed. A further study focused on a conditional probabilistic model using the generalized extreme value (GEV) distribution to predict extreme heat waves over France. This method offers a common way to estimate climatic risk and characterize the extreme behavior of rare events by employing three covariates as potential independent predictors of a given statistical trial. It was shown that these forcings, as dynamic and thermodynamic factors, can play important roles as physical drivers of heat wave intensity. The likelihood of extreme heat events over France was then estimated from the regularized GEV using the ridge regression approach. Further, the importance of soil moisture–temperature interactions was discussed due to the recent increasing frequency of hot summer weather events and heat waves over the Mediterranean region.
- ***Poster presentations*:** The first poster presentation focused on the speed of soil moisture recovery from drought conditions using a novel modelling approach, reminiscent of large deviation algorithms. The proposed method started with an ensemble and used those members that evolved in a certain direction (e.g., towards a heat wave), letting them continue and create new ensemble members in this direction; thus, increasing the number of extremes that one can simulate. The underlying theories here also allow for the computation of the occurrence probabilities for extreme events. Such an approach can be useful for better understanding other types of extremes as well. The second presentation focused on the dynamics of East Asian heat waves using an NSWM. This study found evidence of a sudden temperature shift in East Asia, and the proposed approach can also be used to identify forcing terms and regions. The analysis also revealed changes in atmospheric circulation between the first and second halves of the reanalysis data record. The third presentation explored wave breaking over a supercell in the USA; whereas the fourth presentation focused on the compound effects of SST anomalies in the monsoon season and heat waves via AMIP-style experiments and wave dynamics.

- ***Summary:*** Physical mechanisms of extremes in observations and climate prediction ensembles considered the origins and impacts of phenomena such as rare Antarctic sudden stratospheric warming, as well as local and remote drivers of heat, drought, and rainfall extremes.

(3) Regional climate extreme information relavant to impacts, vulnerability and adaptaion

- ***Background:*** Regional and accurate climate information is important for early warning and risk management systems to properly adapt to more frequent and severe climatic extremes. To this end, Session 3 covered: (i) regional climate extreme information currently being used, and that which is further required to enhance early warning systems capable of informing robust decision making, and maximizing socioeconomic benefits while minimizing costs (particularly for highly vulnerable regions/countries); and (ii) the effective delivery medium and shape of climate information to promote regional understanding and communication.
- ***Presentations:*** Future scenario projections can provide valuable information helping regional communities prepare for impending risks associated with high-impact climatic extremes; however, there is massive uncertainty surrounding regional predicted climates due to the inability of dynamical model systems to resolve local climates, as well as the large spread among models. Syed Ahsan Bokhari (Pakistan Meteorological Department) presented demonstrated the possibility of realistically simulating historical precipitation extremes across Pakistan via new, high-resolution, daily downscaled datasets derived from NASA's 21 CMIP5 model simulations known as the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). From this dataset, more reliable projections of future changes in Pakistani precipitation extremes could be obtained at higher spatial resolutions (e.g., regional- or local-scale), resulting in significantly decreased uncertainties compared to other GCMs. Accordingly, this implies that global and multi-institutional project-based efforts for increasing bias correction and resolution or future projections can enhance the collective understanding of regional- and national-level future changes in climatic extremes under warming global temperatures. There have also been significant efforts to link tailored climate information to sectoral usage. Debbie Hudson (Bureau of Meteorology, Australia) introduced a Forearmed project by the Australian Government Department of Agriculture, Water, and the Environment to develop novel sub-seasonal/seasonal forecast products of extremes to equip farmers with appropriate information for adequate forewarning and preparation. The project aimed to incorporate the needs and feedbacks from industry reference groups, including dairy, red meat, grain, sugar, and wine sectors in product development. Nevertheless, the engagement of end users in understanding the complexity of forecasts and terminology (e.g., probability and uncertainty) remains a fundamental challenge.

- ***Poster presentation*****s:** The first presentation examined the high-resolution modeling of extreme precipitation in a warmer world using two different GCMs (resolutions of ~50 and 60 km) both with low number of ensembles. Indices of extremes (ETCCDI), and different types of uncertainty (internal, SST patterns, and total) were employed in this assessment. The second presentation explored the oceanic forcing of spring precipitation over East Asia; whereas the third looked at the impact of global warming on the tropical Pacific Islands in CMIP6.
- ***Summary:*** Regional extreme climate information relevant to the socioeconomic impact, vulnerability, and adaptation of society, including co-developed communication of probabilistic forecasts of extremes for sectoral applications, were proposed here using large-scale observations of climatic variability. Future flood-related economic risk, and the

identification of impactful future changes in rainfall extremes were explored within the climate projection ensembles.

(4) Prediction and predictability of large-scale climate variability relevant to extreme events

- ***Background:*** Patterns of large-scale climatic variability, including the Madden-Julian oscillation (MJO), El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Northern and Southern Annular Modes, can increase the likelihood of extreme climates over particular regions and seasons. Accordingly, Session 4 explored: (i) using climate prediction ensembles to evaluate the predictability of large-scale climate variability patterns, as well as associated climate/Earth system extremes; and (ii) the nature and impacts of large-scale climate events (e.g., El Niño, etc.) that are more extreme than those observed within smaller-scale, individual climate prediction ensembles.
- ***Presentations:*** Takeshi Doi (Japan Agency for Marine-Earth Science and Technology) highlighted that extremely warm conditions experienced throughout much of East Asia during the winter of 2019-20 followed on of the strongest IOD events on record during the preceding autumn. He showed that skill for East Asia winter temperatures from the preceding October is low in 1983-2015 hindcasts of the climate seasonal prediction system. However, the forecast from October 2019 showed an unusually high signal-to-noise ratio suggestive of a robust prediction around Japan and Korea, and was successful in predicting a warm winter in East Asia. He suggests a mechanism where by enhanced convection in the western Indian Ocean excites stationary Rossby waves that weaken the southward penetration of cold air masses to East Asia resulting in warmer than usual winters. Pang-Chi Hsu (Nanjing Universtiy of Information Science and Technology) showed that S2S ensemble predictions can be applied to probe sources of predictability and skill for extreme events on shorter time scales of a few weeks. In the case of predicting Yangtze River heatwaves, S2S models have skill only in the first 2-3 weeks. Skill in predicting the very strong 2003 heatwave was associated with relatively skillful prediction of circulation anomalies associated with the BSISO and resulting low precipitation and soil drying before the heatwave, whereas biases in predicting the component of circulation on MJO time scales of 30-90 days degraded heatwave prediction skill at lead times longer than 15-20 days. Yukiko Imada (Japan Meteorological Agency) argues that sources of predictability can also be studied in ensembles of climate simulations in which SST and sea ice are set to values observed during some historical period. The 100-member ensemble simulation has particularly high resolution of 60 km globally and 20 km over East Asia over the period 1951-2017. She highlighted that potential predictability (defined as the correlation of one ensemble member with the ensemble mean of all the others) of heavy rainfall frequency in this ensemble was found to be relatively high over southern Japan from July to September, particularly in orographically-influenced coastal regions at 20km resolution, and a similar result was seen for western Taiwan in October.
- ***Poster presentations*:** Statistical analyses have been developed to improve the predictability of extremes while incorporating regional characteristics. For example, Erin Towler (National Center for Atmospheric Research) discussed how flooding and droughts in the US are sometimes spatiotemporally connected, and maintain critical societal impacts. To understand the characteristics of connected extremes and their predictability, Ripley’s K clustering and probability of weather types were applied (Prein et al. 2016). Takahito Kataoka (Japan Agency for Marine-Earth Science and Technology) investigated the roles of prediction and predictability of large-scale climate variability on extreme events including evaluation of the performance of seasonal-to-decadal prediction using a state-of-the art climate model in Japan. Compared to earlier version, the latest version has unprecended high vertical levels with increased ensemble numbers, and updated initial condition and assimilation method and shows improved performance in seasonal hindcasts of ENSO,

QBO, Northern Hemisphere sea ice and North Atlantic Oscillation (NAO). Matthew Widlansky (University of Hawaii at Manoa) assessed seasonal prediction of sea-level anomalies using 10 model ensembles. Prediction of sea-level anomaly is especially important for coastal aareas as those areas are exposed to risks from global sea level rise. He found a skillful seasonal forecast in the tropical and subtropical oceans whereas the skill is lower in the higher latitudes. He also highlighted that more accurate initializations of sea level and higher ocean resolution are key in improving forecast skill.

- ***Summary:*** Prediction and predictability of large-scale climate variability relevant to extreme events has focused on using climate prediction ensembles for examining how phenomena (e.g., tropical cyclones and the Indian summer monsoon) are influenced by climatic variability patterns and warming trends on sub-seasonal to multi-decadal time scales. Further, enhancing the accuracy of predicting large-scale patterns can enable stronger predictions of local extremes as well.

(5) Prediction and predictability of specific extreme events (> 10days)

- ***Background:*** Accurate forecasts of extreme weather (>10 days) can benefit society by helping develop early warning systems for enhanced preparedness; however, systematic model errors make it challenging for to adequately capture these events. In light of this, Session 5 covered the predictability of: (i) the onset, evolution, and decay of large-scale, long-lasting extreme events (e.g., heat or cold waves, droughts); and (ii) changes in the probability of extreme event occurrence (e.g., tropical cyclones, tornadoes, and heavy rain episodes) over large spatiotemporal scales, in which individual rates are commonly deemed unpredictable beyond 10 days.
- ***Presentations:*** Hera Kim (Seoul National University) examined the sub-seasonal predictability of extreme events through case studies of global extremes using ECMWF reforecasts. The 51-member forecasts provide probabilistic predictions with corresponding density distributions. Predictions were largely dependent upon event type: heat waves are predictable over 3–4 weeks of timescales, whereas heavy precipitation is predictable over ~2 week timescales. Notably, absolute predictability is still case-dependent, even within same type of extreme event. In their discussion, the extent to which the warming trends contributed to the skill of sub-seasonal predictions was discussed. Tzu-Ting Lo (Central Weather Bureau) introduced the TC (Tropical Cyclone) tracker tool for the CWB (Central Weather Bureau). Application of this tool to the ECEPS and GEFS *v.*12 hindcasts enhanced the forecasting skills in the western North Pacific during MJO Phases 5–7 or active summer monsoons. Statistical post-processing and spatiotemporal track-clustering techniques were also demonstrated to improve forecast reliability. Daehyun Kim (University of Washington) presented on their development of a dynamic forecast-machine learning (ML) hybrid system for lightning prediction based on a constructed relationship between the dynamical forecast ability of large-scale variables. Compared to conventional parameterization, ML-based parameterization improved forecast ability by ~2 days over frequent-lightning regions. Their discussion emphasized the importance of understanding the physical processes behind improved predictions via ML techniques. Elisabeth Vogel (Australian Bureau of Meteorology) introduced a seasonal hydrological ensemble forecasting system for Australia developed by the Bureau of Meteorology. The system is part of the new Australian Water Outlook service, and offers hydrological forecasts at continental- and regional-scales. The system consists of a seasonal climate forecasting system, ACCESS-S, and landscape water balance model, AWRA-L. Forecasts demonstrated the potential for predicting hydrological extremes, such as extremely dry periods, and the corresponding discussion focused on the comparison of predictive skills between the ACCESS-S and AWRA-L outputs (e.g., soil moisture and precipitation/runoff). The importance of understanding the sources of uncertainty between the climate inputs and hydrological model were also

discussed. Wayne Yuan-Huai Tsai (National Taiwan University) analyzed the forecasts of the S2S (subseasonal to seasonal) models, and examined the predictability of the northern Queensland floods in February 2019. The research revealed two large-scale factors that were directly linked to the event: MJO and equatorial Rossby waves (ER). Although MJO proved helpful for extended-range rainfall forecasts, models failed to capture the ER waves, whose negative impacts can overwhelm system predictability.

- ***Poster presentations*****:** To better understand seasonal prediction, it is also important to evaluate predictive accuracy, and the physical mechanisms associated with low seasonal predictability. For example, Eun-Pa Lim (Bureau of Meteorlogy, Australia) discussed how the winter and spring seasons of 2020 in Australia were expected to be wet due to La Niña and a negative IOD (Indian Ocean Dipole); however, no excessive amounts of rainfall were observed in the spring, and even a shortage of rainfall was documented over Queensland. It is also shown that a moderate local SST response and early decay of negative IOD induced the failure of seasonal predictions, implying that both large-scale climate variability and regional SST responses play an important role in determining local extremes. Marcelino Villafuerte (Philippine Atmospheric, Geophysical and Astronomical Services Administration) evaluated seasonal and sub-seasonal predictability of tropical cyclones (TCs) over the Philippines using the NCEP 16-day global ensemble forecast system (NCEP-GEFS). The resulting predicted TCs were more intense, longer, and developed further from the eastern boundary of the Philippines. Additionally, TC predictability was influenced by the MJO phase, obtaining better Week 1 performances with MJO phase1, and Week 2 performances with MJO phase5 (Villafuerte et al. 2021). Hui-Ling Chang (Central Weather Bureau) further demonstrated how the pattern of predictable precipitation is dominated by the interaction of complex terrain and the surrounding large-scale circulation over Taiwan. Accordingly, the predictability of extended-range (10–30 days) extreme precipitation events was investigated using analog post-processing (Hamill et al. 2015), revealing that when compared to raw ensemble forecasts, AP-based probabilistic forecasts showed greater capacity to represent the frequency distribution of rain rates with reduced biases.
- ***Summary:*** The discussion on predictability of specific extreme events (>10 days) featured presentations on the prediction of heat waves, hydrological and hydrometeorological extremes, tropical cyclones, monsoon low-pressure systems, and lightning strikes by means of S2S and other sub-seasonal ensemble prediction systems, including the application of machine learning post-processing techniques to enhance ability.

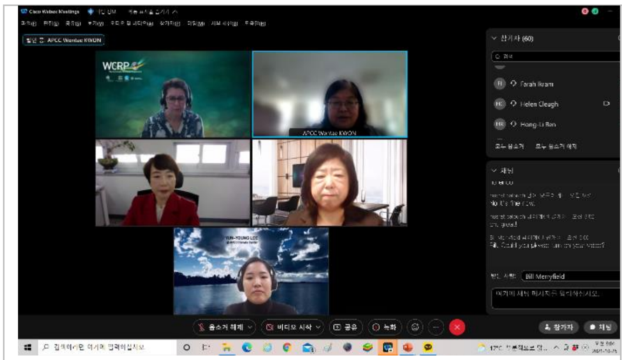
(6) Quantifying current and future risks of climate extrems

- ***Background:*** Direct observations provide just one of many potential manifestations regarding the chaotic evolution of climate systems, and may not adequately represent current conditions under a rapidly changing climate. Realistic climate prediction ensembles can overcome these limitations by providing additional measurements of potential extreme events. Accordingly, Session 6 explored the quantification of such changes in current climatic extremes, including unprecedented events, and how these may evolve in the future.
- ***Presentations:*** Francesco Rgone (Royal Meteorological Institute of Belgium) first discussed the application of their developed method to study rare systemic events of climatic extremes. The concept was to run an ensemble simulation using a numerical model of the system, and check whether the state of the system was close to the desired state (e.g., heatwaves) at fixed intervals. Gillian Kay (UK Met Office) then focused on quantifying the risk of unprecedented, extreme, and dry conditions over Northern Brazil during El Niño events. The likelihood of an unprecedented dry event was quantified as a function of the Nino 3.4 values within the UNSEEN (Unprecedented Simulation of Extrems with Ensembles) ensemble hindcast dataset. It was shown that the probability increased from ~16% when the DJF Nino 3.4 index was 0.5, to ~57% when DJF Nino 3.4 index was

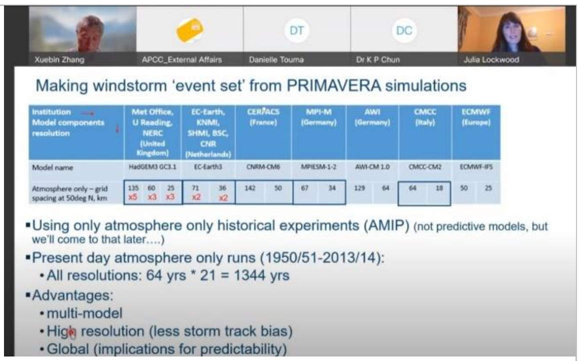
increased to 2. In the third presentation, Jonghun Kam (Pohang University of Science and Technology) quantified the impact of greenhouse gas-induced warming on the probability of longer-term drought events in South Africa, as the area had recently experienced a severe multi-year drought (2015–2019). The fourth presentation by William Merryfield (Environment and Climate Change Canada) assessed the probability of El Niño and La Niña events with unprecedented levels of strength, using a large multi-model hindcast dataset (C3S, Copernicus Climate Change Service). Regarding observations of annual maxima for daily and five-day consecutive precipitation events since 1951, Seungmok Paik (Yonsei university) demonstrated that the influence of anthropogenic greenhouse emissions was robustly detected throughout the globe and in most sub-regions as well, as indicated predominantly by the increase in atmospheric moisture associated with increasing temperatures. Ryo Mizuta (Meteorological Research Institute, Japan) then discussed the results of the Japanese Meteorological Research Institute 60-km AGCM historical, no-warming, 2 K, and 4 K warming simulations, showing that under a global mean temperature increase of 4 K, extreme precipitation events are projected to increase over most parts of the world, particularly for very rare extreme events (e.g., 100-year precipitation events, compared to 1- or 10-year events). Two further session presentations utilized an ultra-high-resolution (~25 km in the atmosphere), fully coupled CESM1.2.2 simulation, one of which by Arjun Nellikkattil (IBS Center for Climate Science) investigated changes in atmospheric rivers, and associated precipitation patterns under different CO_2 emissions scenarios. The presentation highlighted the model's capacity to reproduce the observed global distribution of atmospheric river events and associated precipitation. Jung-Eun Chu (IBS Center for Climate Physics) explored tropical cyclone projections in the presence of mesoscale air–sea interactions across a ~100 year analyses period of current and predicted climates with doubled and quadrupled CO_2 concentrations. Asmerom F. Beraki (CSIR) discussed hydrological changes over Africa according to the CRU dataset, revealing a decreasing meteorological drought index over southeastern Africa, and an increasing index trend over eastern Africa since 1980. Lastly, Laura Baker (University of Reading) explored the 1976 summer heat wave that struck England and Wales, as it correlated with the preceding dry winter–spring, and concurrent dry summer. A comparison of this event to the 2010s using CMIP5 and HadGEM3-A atmosphere-only simulations showed significant increases in the frequency of modern summer heat extremes compared to the 1970s, in addition to a moderate increase in the frequency of summer rainfall deficiencies.

- ***Poster presentations*:** Sridihara Nayak (Kyoto University) quantified a heavy rainfall event over western Japan in July 2020 by performing high-resolution (1 km) simulations with WRF under present-day and d4PDF (database for Policy Decision making for Future climate change) 4 K warming conditions. The simulation accurately reproduced the duration and peak rainfall intensity of the 2020 heavy rainfall event. Accordingly, it was predicted that under d4PDF 4 K, heavy rainfall events are expected to increase in strength, but decrease in duration. Future rainfall intensification appears to be associated with moisture content and atmospheric instability. Rasmus Benestad (The Norwegian Meteorological Institute) introduced a framework for predicting the probability of 24-h heavy rainfall, as well as a parametric method for predicting intensity-duration-frequency (IDF) curves of rainfall return levels. A major benefit of this framework was its capacity to estimate the IDF without sub-daily rain gauge data, or short observational records. This framework can be applied to downscaled projections based on large ensembles (> 100) of global climate model simulations, thereby providing robust estimates of both probabilities and return levels, while facilitating adaptability to climate change-related heavy rainfall events. Birgit Manning (Deutscher Wetterdienst—DWD) introduced the user-oriented, climate prediction DWD website, aiming at a seamless forecast information archive to cover all possible predictive time ranges. Currently, seasonal and decadal forecast information is available for regional verification, and downscaled information exists for Germany. Construction of sub-seasonal forecast information and user-oriented products for extreme events (e.g., drought) are in progress, and will be added to the website in the near future. On the website, prediction information is divided into basic and expert layers according to the level of informational complexity and difficulty.

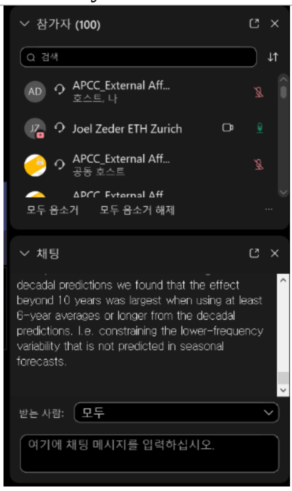
- ***Summary***: Quantifying current and future risks of climatic extremes mandates the extraction of information related to correlated probabilities of weather and climate extremes (including unprecedented extremes) from climate prediction and projection ensembles, as well as high-resolution simulations. Innovative methods applied include the UNSEEN approach, whereby large seasonal and decadal prediction ensembles are used as a "multiplier" of a single observed record of climate variability, while rare event algorithms enhance sample sizes in the tails of distributions.



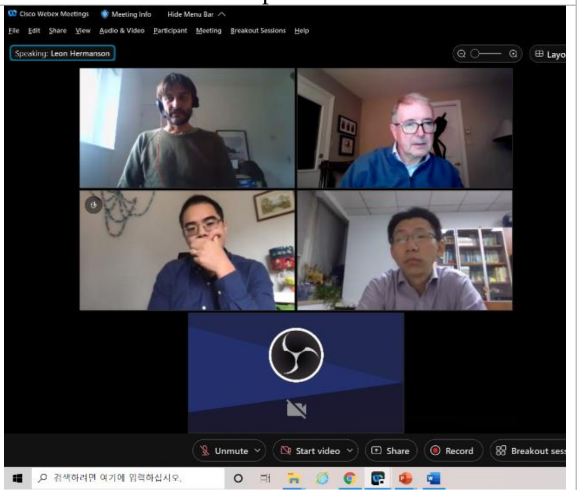
Opening remarks by Dr. Won-Tae Kwon, APCC



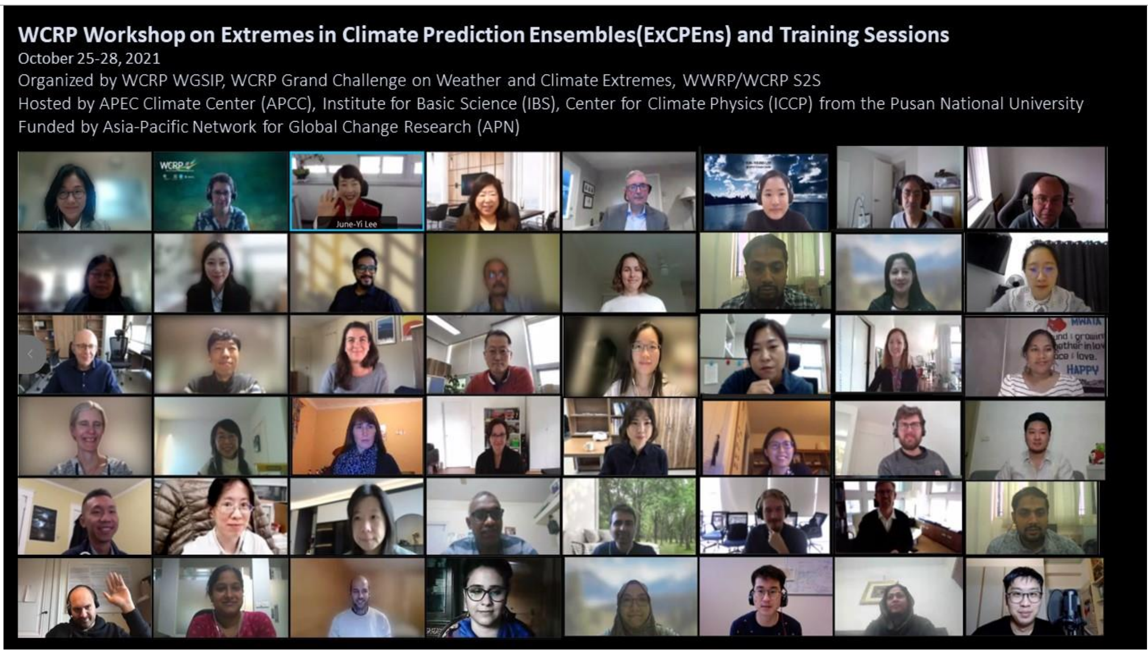
Session presentation



Screenshot of workshop chatting



Q&A during the session presentation



Group photo of workshop participants

Figure 1. Screenshots of the virtual WCRP Workshop on ExCPEns, October 25–28, 2021.

3.2 Early Career Scientist (ECS) Networking and Training

In conjunction with the WCRP Workshop on ExCPEns, the ECS Networking and Training Program was held on October 27 and 28, 2021. The program aimed to build capacities to understand, predict, and assess the risks and impacts of weather or climatic extremes. In total, 59 ECSs from 21 countries participated in training sessions on extreme detection, prediction, and projection of future climate extremes, with 36 ECSs from APN developing countries participating in the closed networking program, together with globally established scientists.

3.2.1 Activities

(1) Application submission

- Timeline: April 26 – July 31, 2021 (Extended deadline)
- Applications: 59 applications from 21 countries

(2) Networking and discussion forums from the ECS of APN developing countries

- The 36 ECSs were randomly divided into six groups, with mentors allocated to each group. Mentors initiated communication and networking via email prior to the forum, and provided the list of questions to be discussed during the networking and training event. The common questions for the groups were as follows.
  - ➢ What are the most important scientific challenges for predicting weather and climate extremes, and how can we tackle them?
    - A. Some challenges are posed by modeling limitations, such as limited resolution and imperfect parameterizations, leading to errors with representing teleconnection patterns, and limitations for providing local-scale information.

B. Additional challenges result from the limited length of modern observational records, and the relative rarity of some extreme events, leading to insufficient sampling for forecast calibration and verification.
C. Possible solutions include: the application of machine learning to improve model parameterizations and resolve errors through post-processing, longer hindcast periods to increase the number of rare events, better understanding of climate change impacts on predictability and skill, and downscaling of global model outputs to better represent small-scale processes as well as orographic effects contributing to extremes.

- What are the difficulties faced by ECSs in your country, and what are some possible solutions?
  A. The discussed barriers included: the lack of modern computational facilities, and difficulties with data accessibility in home countries; lack of training opportunities to keep pace with the rapidly changing technology and scientific developments, as well as lack of scientific communication with experts in the field; and above all, limited opportunities for finding relevant employment following graduation.
  B. The WCRP and other international organizations could help by: providing or connecting ECSs to relevant training courses covering scientific developments, basic climate dynamics, and academic writing; and providing fellowships or otherwise facilitating postdoctoral employment for ECSs from developing countries.

Table 1. ECS Networking & Training groups and mentors.

Group	Mentor (affiliation)
Group 1	Dr. William Merryfield (Co-chair of WCRP/Working Group on Subseasonal to Interdecadal Prediction (WGSIP))
Group 2	Dr. Xuebin Zhang (Co-chair of WCRP/Grand Challenge(GC)-Extremes)
Group 3	Dr. Frederic Vitart (Co-chair of WCRP/WWRP/Subseasonal to Seasonal Projection(S2S))
Group 4	Prof. June-Yi Lee (Co-chair of WCRP/WGSIP)
Group 5	Prof. Christian Franzke (IBS Center for Climate Physics)
Group 6	Prof. Erich Fischer (ETH Zurich)

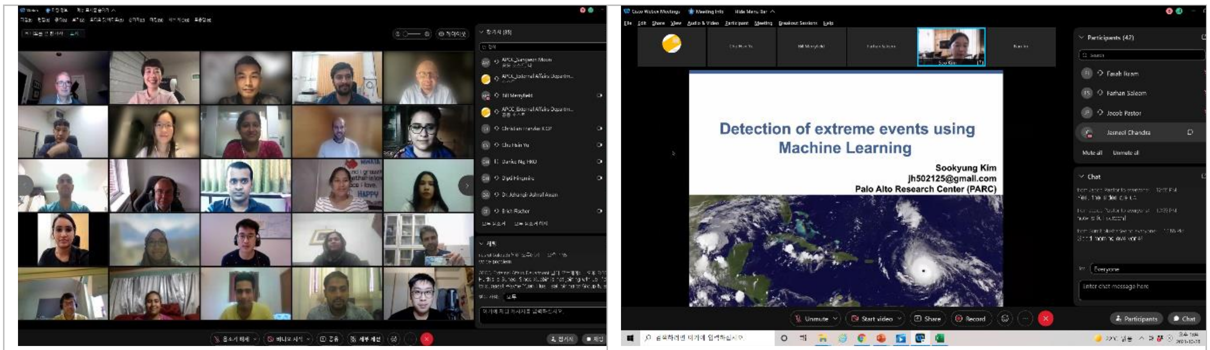
(3) Training programs

- Fifty-nine early-career scientists participated in the training program, which consisted of two sessions on the detection, prediction, and projection of future climatic extremes, containing six lectures in total.
- **Lecture Summary*:*** Sookyung Kim (Palo Alto Research Center) presented a lecture on detection of extreme events using machine learning, including: data challenges in scientific research, detection and localization of extreme climate events, a super-resolution model for downscaling processes, as well as tracking and predicting extreme climate events. Megan Kirchmeier (Environemnt and Climate Change Canada) spoke on the topic of extreme event attribution, including an illustrative introduction, as well as a conceptual focus on simple, popular methods, along with suggested references for additional details. Frederic Vitart (ECMWF) reviewed the predictability of extreme events in sub-seasonal to seasonal (S2S) time scales, highlighting sources such as Madden Julian oscillation, soil moisture, stratospheric initial conditions, Rossby waves, SSTs/sea-ice, and aerosols. Jin-Ho Yoon (Gwangju Institute of Science and Technology) introduced important regional assessment results in AR6, along with how to use the IPCC AR6 Interactive Atlas. They also

highlighted that climate change is globally ubiquitous, affecting every inhabited region worldwide, with correlated anthropogenic influences contributing to many of the observed changes in weather and climatic extremes. Erich Fischer (ETH Zurich) provided lectures on high-warming storylines and rare extremes, which emphasized that: (1) low-likelihood outcomes are often associated with the greatest risks; (2) warming substantially larger than the current best estimate cannot be ruled out; (3) it is necessary to prepare for events of unprecedented intensity; and (4) different independent approaches can help us understand low-likelihood, high-impact events in the near future. The final lecture was delivered by Xuebin Zhang (Environment and Climate Change Canada) on the weather and climatic extremes under climate change, highlighting: observed changes in extremes, their attributtion, and proximate causes; regional-scale projected changes in extremes; and key messages from the AR6 WGI Chapter 11.

Table 2. ECS Networking & Training sessions and lectures.

Session	Lecture	Lecturer
Session 1. Extreme Detection and Prediction	Detection of extreme events using Machine Learning	Dr. Sookyung Kim (Palo-Alto Research Center)
	Extreme event attribution	Dr. Megan Kirchmeier (Environment and Climate Change Canada)
	Predictability of extreme events in S2S time scales	Dr. Frederic Vitart (European Centre for Medium-Range Weather Forecasts)
Session 2. Projection of Future Climate Extremes	How to use the AR6 WGI interactive Atlas for climate change studies	Prof. Jin-Ho Yoon (Gwangju Institute of Science and Technology)
	Low likelihood, high impact events assessed in AR6 WGI Chapter 4	Prof. Erich Fischer (ETH Zurich)
	Change of extremes assessed in AR6 WGI Chapter 11	Dr. Xuebin Zhang (Environment and Climate Change Canada)



ECS Networking and Discussion forum group photo

ECS Training session lecture

Figure 2. Screenshots of the ECS Training and Networking Program.

3.3 Adjustments or changes to the timeline of activities (if any)

Upon submission, the project was proposed to have an offline workshop; however, due to the COVID-19 pandemic, the project team decided to virtually host the workshop and related events. As the workshop and training were hosted online, the scheduled project was changed to promote the participation of global experts, scientists, and stakeholders, especially APN developing countries. In addition, budget items related to hosting offline workshops (e.g., invitation costs for early career scientists from APN developing countries, workshop operation costs, etc.) were removed from the plan, while additional budgets for editing video clips, and honorarium for training lecturers and discussion mentors were added. The changes were approved by the APN secretariat in advance of the planning and execution of the expenditure.

3.3.1 Changes in project work plan

To promote global participation, the deadlines for abstract submission and ECS program applications were extended to June and July, respectively; whereas the timeline for preparing offline workshops was cancelled.

3.3.2 Changes in budgeted items

With the cancellation of an offline conference in favor of hosting an online workshop, the budget for travelling costs, including flights, accommodations, and daily subsistence allowance (DSA) were removed. In its place, a budget for the honorarium of lecturers, mentors, and workshop clip editing was added.

Table 3. Itemized budget changes for the ExCPEns.

Items	Initial contract (USD)	Revised contract (USD)
Budget items	1. Participation support: $33,860 - Flight: $20,000 - Hotel: $9,200 - Per Diem: $4,160 - Airport Transfer: $500 2. ECS networking event: $640 3. Workshop facilities: $2,800 4. Publication costs: $2,700	1. Workshop preparation: $10,400 - Honorarium: $3,000 - Workshop abstract book: $2,200 - Workshop clip editing: $5,200 2. Publication costs: $4,200
Total budget	**$40,000 USD**	**$14,600 USD**

3.4 Challenges or issues

The global COVID-19 pandemic forced the revision of the project from an in-person, offline workshop to an online format. While the offline workshop could have provided the focused and in-depth participation for those gathered in a physical venue, the online workshop had difficulties accruing worldwide participants at the designated time. To maximize participation, the project team organized two online workshops per day by splitting sessions into two different time zones (Table 4).

Table 4. Workshop session allocation.

Items	GMT (KST)	Sessions		
1 – October 25, 2021	0000–0300 (0900–1200)	Session 1 (A)	Session 2 (A)	Session 3
2 – October 25, 2021	1000–1300 (1900–2200)	Session 1 (B)	Session 2 (B)	Poster A
3 – October 26, 2021	0000–0300 (0900-1200)	Session 4 (A)	Session 5 (A)	Poster B
4 – October 26, 2021	1000–1300 (1900–2200)	Session 4 (B)	Session 5 (B)	Poster C
5 – October 27, 2021	0600-0900 (1500–1800)	Session 6		

4. Project outcomes

4.1 Outputs and outcomes

Table 5. Outputs and outcomes.

Outputs	Outcomes
WCRP Workshop on ExCPEns was hosted to discuss subseasonal, seasonal, annual, decadal, and multi-decadal time scales of predictive ensembles	Brought together members of global and regional climate prediction communities to share expertise and recent developments on weather and climate extremes
ECS networking and training program was held to discuss global and regional climate research	Enhanced ECS networking and connectivity to the broader global and regional research communities in the Asia-Pacific region

4.2 Key facts & figures

- Sixty-eight professionals and ECSs made presentations during the WCRP Workshop on ExCPEns (42 oral seminars and 26 poster presentations)
- Approximately 300 participants worldwide attended the workshop
- Fifty-nine early-career scientists were trained during the ECS training program
- Thirty-six early-career scientists enhanced their capacity and built their networks by actively participating in small group discussions and networking events with one of six mentors.

5. List of project deliverables to date

The anticipated outcomes from the WCRP ExCPEns are:

- Formal cooperation across the diverse research communities within the WCRP, including the WCRP Working Group on Subseasonal to Interdecadal Prediction (WGSIP), the WCRP Grand Challenge on Weather and Climate Extremes (GC-Extremes), WWRP/WCRP Sub-seasonal to Seasonal Prediction Project (S2S), and possibly CLIVAR Monsoon and WMO Tropical Cyclone communities, all of which involve scientists from APN member countries.
- A summary of key research results and recommendations for furthering scientific advancements in this area will be submitted to a peer-reviewed scientific journal.
- A priority list of proposed new research topics in the area of subseasonal-to-multidecadal prediction ensembles, with due consideration of end-user requirements in the Asia-Pacific region.
- Enhanced ECS networking and connections to broader global and regional research communities in the Asia-Pacific region.
- Enhanced knowledge and capacity of scientists in APN developing countries for research on weather and climate extremes.

5.1 Formal cooperation across diverse research communities

Formal cooperation within the WCRP, including the WCRP Working Group on Subseasonal to Interdecadal Prediction (WGSIP), the WCRP Grand Challenge on Weather and Climate Extremes (GC-Extremes), and WWRP/WCRP Subseasonal to Seasonal Prediction (S2S), was achieved through the Science Organizing Committee (SOC) of the project. Through in-depth discussions, SOC carefully designed the workshop composition, including session topics, presentation methodologies, and targeted groups for workshop announcement. The SOC also led the workshop session, participated as mentors in small group discussions during ECS networking and discussion programs, in addition to providing lectures during the ECS training program

Table 6. SOC members.

Name	Affiliation
June-Yi Lee	Co-chair of WCRP/WGSIP, Pusan National University, ICCP
William Merryfield	Co-chair of WCRP/WGSIP, Environment and Climate Change Canada
Frédéric Vitart	Co-chair of WCRP/WWRP/S2S, European Centre for Medium-range Weather Forecasts
Xuebin Zhang	Co-chair of WCRP/GC-Extremes, Environment and Climate Change Canada
Doug Smith	WCRP/Explaining and Predicting Earth System Change, UK Met Office
Arun Kumar	WCRP/WWRP/S2S, Climate Prediction Center, National Oceanic and Atmospheric Administration
Hong-Li Ren	WCRP/WGSIP, Beijing Climate Center, China Meteorological Administration
Catherine Michaut	WCRP, Institut Pierre Simon Laplace, University of Versailles Saint-Quentin-en-Yvelines
Yun-Young Lee	APEC Climate Center

5.2 Key research results and recommendations for furthering scientific advancements to be submitted for publication

The key research results within the six areas relevant to climate prediction are summarized as follows: First, **the characterization of extremes in observations and climate prediction ensembles** focused on certain aspects, such as the spatiotemporal footprints, as well as cataloging particular classes of simulated and observed extremes, their characterization in climate projection ensembles, the combination of information from decadal to multi-decadal predictions, and verification of local heatwave index forecasts. Second, **the physical mechanisms of extremes in observations and climate prediction ensembles** considered the origins and impacts of phenomena, such as rare Antarctic sudden stratospheric warming, as well as local and remote drivers of heat, drought, and rainfall extremes. Third, **regional climatic extreme information relevant to impacts, vulnerability, and adaptation** considered aspects of particular socioeconomic relevance, including: co-developed communication of extreme event probabilistic forecasts for sectoral applications; the use of observed, large-scale climatic variations as predictors to estimate the risks of future flooding and associated economic losses; and the identification of impactful future changes in rainfall extremes for climate projection ensembles. Fourth, **the prediction and predictability of large-scale climatic variability relevant to extreme events** focused on using climate prediction ensembles to examine precisely how phenomena (e.g., tropical cyclones and the Indian summer monsoon) are influenced by climate variability patterns and warming trends on sub-seasonal to multi-decadal time scales, in addition to the degree with which accurately predicting large-scale patterns enables the prediction of local extremes. Fifth, **the prediction and predictability of specific extreme events (>10 days)** featured presentations on the prediction of heat waves, hydrological and hydrometeorological extremes, tropical cyclones, monsoon low-pressure systems, and lightning strikes by means of S2S and other sub-seasonal ensemble predictive systems, including applications of machine learning techniques for post-processing to enhance accuracy. Finally, the **current and future risks of climatic extremes** focused on extracting information regarding the correlated probabilities of weather and climatic extremes, including unprecedented events, from climate prediction and projection ensembles, as well as high-resolution simulations. The applied innovative methods included the UNSEEN approach, whereby large seasonal and decadal prediction ensembles are used as a "multiplier" of single observed climate variability records, and rare event algorithms enhance sample sizes in the tails of distributions.

5.3 Priority list of proposed research topics within the area of subseasonal-to-multidecadal prediction ensembles, with due consideration of end-user requirements in the Asia-Pacific region

The most important scientific challenges in predicting weather and climatic extremes in the Asia-Pacific region were first identified. The first challenge is posed by modeling limitations (e.g., limited resolutions, and imperfect parameterizations), leading to errors in the representation of teleconnection patterns, and limitations for providing local-scale information. The second challenge stems from the limited length of modern observational records, along with the rarity of some extreme events, leading to insufficient sampling for adequate forecast calibration and verification. Accordingly, the priority list of proposed new research topics, with due consideration of end-user requirements in the Asia-Pacific region, is as follows:

- Improve high-frequency, high-resolution observations, especially for land processes such as soil moisture, by integrating information across gauges, satellites, reconstructions, and reanalyses.
- Develop tailored models for the regional forecasting of weather and climatic extremes.
- Advance dynamic or statistical downscaling of global model ensembles to better represent small-scale processes and orographic effects contributing to extreme events.
- Increase the understanding of climate change impacts on predictability and predictive skills for large-scale variability relevant to extreme events.
- Produce longer hindcast datasets to increase the sample size of rare events.
- Develop the application of machine learning techniques to improve model parameterizations, and correct model errors through post-processing.

5.4 Enhanced ECS networking and connections to the broader regional and global research communities within the Asia-Pacific

In the ECS networking and discussion forum, a breakout group discussions targeting ECSs from APN developing countries was organized with globally established scientists to understand and share the challenges they have been facing as within the region, and seek possible resolutions. During these small-group discussion, the ECSs were able to broaden their networks with mentors, and other ECSs within the Asia-Pacific region.

5.5 Enhanced knowledge and capacity of scientists in APN developing countries regarding weather and climate extremes

ECSs were provided with opportunities to introduce their research and work as oral or poster presenters during the workshop. In addition, the training sessions specifically targeted ECSs to build capacities for understanding, predicting, and assessing the risks or impacts of weather and climatic extremes, particularly within the Asia-Pacific region.

6. List of pending project deliverables

6.1 Summary of key research results and recommendations for furthering scientific advancements to be submitted to a peer-reviewed scientific journal

A summary of key research results and recommendations is in preparation by a core writing team to be submitted to the special issue on climate extremes of the Asia-Pacific Journal of Atmospheric Sciences, under the Meeting Summaries section. This manuscript contains the current status and challenges to the mechanisms, predictability, and prediction of climatic extremes based on climate projection ensembles. The topics discussed cover the characterization and physical mechanisms of extremes in observations and climate prediction ensembles, regional climate extreme information relevant to impacts, vulnerability and adaptation, prediction and predictability of large-scale climatic variability relevant to extreme events, prediction and predictability of specific extreme events, and the quantification of current as well as future risks of climatic extremes.

7. Future directions

Explaining and predicting global climate change, including climate extremes and hazards from subseasonal to multi-decadal time scales, is one of the thrust areas under the WCRP. ExCPEns and the accompanying ECS training were successful in promoting the importance of utilizing climate prediction ensembles for this thrust area, and it is anticipated that as a result of the project here, there will be more related activities in the field, including workshops, training, and international funding activities within the immediate future.

Acknowledgement

We would like acknowledge the contributions from the WCRP, APEC Climate Center, and Pusan National University for supporting this project.

Appendices

A. WCRP Workshop on ExCPEns Abstract Book
B. Workshop Presentation Files
C. Workshop Poster Presentation Files
D. ECS Lecture Files
E. Video Clips
F. List of Workshop Participants
G. Program survey for ECS (Early-Career Scientists) program

References

Hamill, T. M., Scheuerer, M., & Bates, G. T. (2015) Analog probabilistic precipitation forecasts using GEFS reforecasts and climatology-calibrated precipitation analyses. Monthly Weather Review, 143(8), 3300-3309.

Prein, A. F., Holland, G. J., Rasmussen, R. M., Clark, M. P., & Tye, M. R. (2016) Running dry: The U. S. Southwest’s drift into a drier climate state. 43(3), 1272-1279.

Villafuerte, M. Q., Lambrento, J. C. R., Ison, C. M., Vicente, A. A., de Guzman, R. A., & Juanillo, E. L. (2021) ClimDatPh: an online platform for Philippine climate data acquisition. Philippine Journal of Science, 150, 53-66.