

Supporting regional and international cooperation in research on extremes in climate prediction and projection ensembles: Workshop summary

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ABSTRACT

Weather and climate extremes have enormous impacts on society, and are becoming more severe and frequent as the world warms. Most developing countries in the Asia–Pacific region are highly vulnerable to risks associated with heatwaves and cold spells, droughts and floods, tropical cyclones, wildfires, and other extremes. To support regional and international cooperation for research on weather and climate extremes in the Asia–Pacific region, the World Climate Research Programme (WCRP) hosted an online workshop on Extremes in Climate Prediction Ensembles (ExCPens) from 25 to 28 October 2021 with the support of Asia–Pacific Network for Global Change Research (APN). The workshop aimed to advance the rapidly emerging science of exploiting subseasonal, seasonal, annual to decadal and long-term prediction ensembles to improve the prediction and understanding of weather and climate extreme events. An Early Career Scientist (ECS) event followed the ExCPens workshop and consisted of a discussion and networking forum for ECS from APN member developing countries, along with a series of ECS training lectures and discussion sessions. Through the workshop and discussions among stakeholders, important scientific results on prediction and future changes in weather and climate extremes were communicated. Moreover, new research topics spanning these different time scales were identified and prioritized.

KEYWORDS

Weather and climate extremes, subseasonal to decadal prediction, climate change, early career scientists, APN member developing countries



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HIGHLIGHTS

- There is an urgent need for capacity building to better explain and predict extremes.
- Regional and international cooperation should be enhanced in the Asia-Pacific region.
- The workshop helped to guide ECS in their research and future career.

1. INTRODUCTION

As weather and climate extremes become more severe under climate change, the availability of early warnings for such events is becoming increasingly important. Weather forecasts can provide warnings for specific extreme events but have limited accuracy more than two weeks ahead (e.g., Judt, 2018). Nonetheless, longer-term predictions of climate are possible, and much progress has been made in predicting future climate from weeks to a decade or more ahead. This has been enabled largely by applying comprehensive climate models that represent Earth system components and processes responsible for predictability on these time scales (Merryfield et al., 2020). Fundamentally, ensembles of many predictions from similar observation-based initial conditions are needed to represent the uncertainties inherent in these longer ranges. In addition, climate predictions must be aggregated in time, considering mean conditions (or events within) a particular week, month, season or year, rather than aiming to predict what will occur on a particular day, which is inherently unpredictable at long range (Shukla, 1998).

Such climate prediction ensembles (CPEs) are increasingly being used to predict future climate on subseasonal, seasonal and decadal time scales (Meehl et al., 2021). These predictions often consist of probabilities that mean conditions during the forecast period fall within particular ranges, typically the lower, middle and upper third of the climatological probability distribution (Figure 1A). Although high probabilities for the lower or upper

categories suggest elevated chances of weather or climate extremes, this standard framing does not directly quantify those probabilities or the likely magnitudes of any extremes. However, this lack of predictive information specific to extremes is not due to any fundamental limitation. CPEs can, in principle, predict the entire probability distribution—including the tails—and should be able to quantify the likelihood that shorter-term extremes, such as heatwaves or exceptionally rainy spells, will occur within the predicted period. For such predictions to be useful they must have demonstrable skill, which poses a challenge given the limited number of past cases (at most a few dozen) on which to base an assessment. Moreover, a necessary condition for skill is that natural predictability exists for the predicted phenomenon.

Despite these challenges there has been some initial progress. For example, skill in predicting probabilities for exceeding outer percentiles (5–15%, 85–95%) of the seasonal climatological probability distribution has been demonstrated for single-model and multi-model CPEs (Becker, van den Dool, & Peña, 2013; Becker & Van Den Dool, 2018). Similarly, skill has been demonstrated for predicting the chances that extreme daily events will occur on seasonal (Hamilton et al., 2012) and decadal (Eade, Hamilton, Smith, Graham, & Scaife, 2012) time scales. Significant challenges nonetheless remain. First, the availability of such predictions from operational systems has lagged, partly due to persistent barriers in migrating research outcomes to operations, although some

centres are beginning to provide probabilities for outcomes more extreme than the standard tercile categories (Figure 1B). Second, further research is needed to quantify the capabilities of CPEs to predict extremes across different variables, regions, time scales, etc. Third, co-designing sector-specific climate extreme information relevant to impacts, vulnerability and adaptation is needed. Finally, advancements in basic science relating to definitions and identification of extremes, physical mechanisms that must be accurately modelled, etc. are required for CPEs to realize their potential for predicting weather and climate extremes.

An additional scientific application of CPEs starting to be explored is for ensemble members to serve as many independent realizations of present-day climate evolution in order to better quantify the likelihood of extreme weather and climate events, including unprecedented extremes, in the current epoch (Thompson et al., 2017, 2019).

To accelerate progress in meeting these challenges and advancing the science of CPEs given the disproportionate human and economic costs of these extremes that are borne by developing countries (Field, Barros, Stocker, & Dahe, 2012), the World Climate Research Programme (WCRP) organized a scientific workshop on “Extremes in Climate Prediction Ensembles (ExCPEns)” in conjunction with a training and networking event primarily for early-career scientists (ECS) from developing countries of Asia-Pacific Network for Global Change Research (APN). These meetings were conceived to be closely connected. The workshop aimed to consolidate recent scientific progress and stimulate further progress in using CPEs to predict and quantify the likelihoods of weather and climate extremes, inviting participation and perspectives of the ECS; the training and networking event enabled ECS to learn from and network with experienced scientists and each other, to assist in overcoming challenges that ECS from the developing world face in their research efforts and career paths.

2. METHODOLOGY

The WCRP ExCPEns Workshop and associated ECS programme were originally scheduled to be held in-person in Busan, Republic of Korea, in October 2020. The events were postponed for approximately one year as a result of the COVID-19 global pandemic and eventually held primarily virtually via Webex. The ExCPEns workshop took place from 25 to 27 October 2021, and the ECS programme immediately afterwards on 27 to 28 October. APN provided sponsorship under its Scientific Capacity Development programme (CAPaBLE). Initially intended for ECS travel, this funding was mainly applied to operating the online workshop and editing workshop recordings. Additional sponsorship and organizational support were provided by the APEC Climate Center (APCC), which facilitated the associated webspace, registration, and online functioning, as well as WCRP and Pusan National University (PNU).

The ExCPEns workshop featured 42 oral and 26 poster presentations, organized in the six themed sessions described in Section 3.1. These presentations were scheduled in five programmes, starting in the morning, afternoon and early evening of Korean Standard Time (GMT+9) to accommodate global participation. The programmes allowed 15 minutes for each oral presentation, with 2 minutes to summarize each poster before dedicated breakout sessions for poster presentations. Information about the presenters, including gender, career stage, and countries represented by their institutions, is summarized in Table 1. Links to the presentation files and recordings, as well as the programme and abstract book, are provided on the ExCPEns web page, https://www.apcc21.org/act/workView.do?lang=en&bbsId=BBSMSTR_00000000024&nttId=7395.

The ECS Networking and Discussion Forum, reserved for ECS from APN developing countries, was held in the early evening hours (Korean time) of 27 October, following the final session of the ExCPEns workshop. An initial plenary introduction highlighted WCRP’s commitment to a geographi-

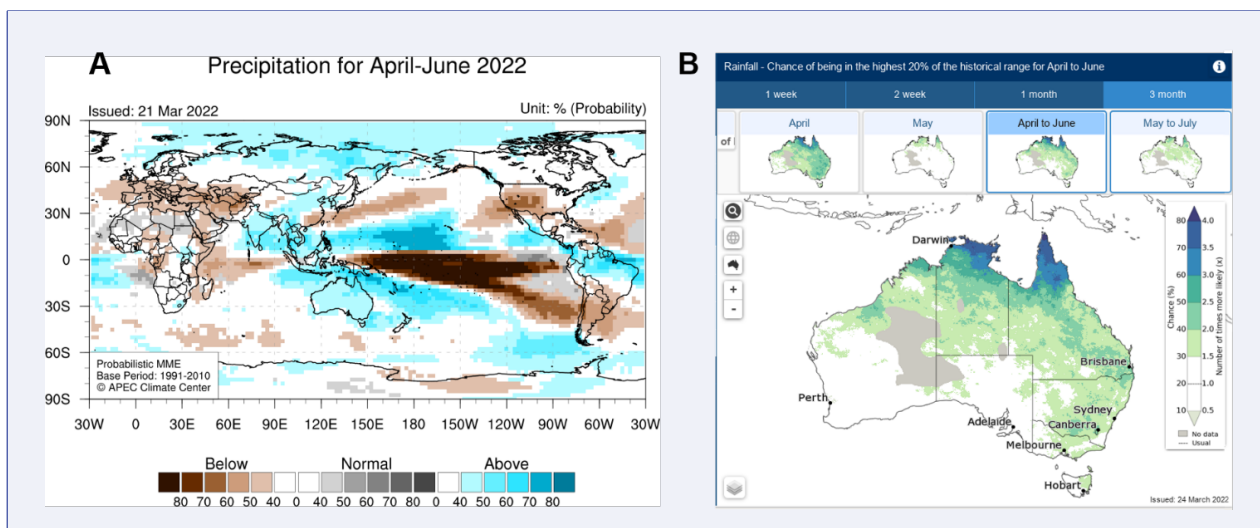


FIGURE 1. Panel (A). Seasonal forecast from the APEC Climate Centre, showing probabilities that precipitation in April–June 2022 falls in the lower (below normal), middle (near normal), or upper (above normal) thirds of the climatological distribution for 1991–2010. Colours indicate probabilities for the most probable category, and white where no category is more probable than 40%. Panel (B). Forecast for the same period from the Australian Bureau of Meteorology shows probabilities for extremely high seasonal precipitation, defined as in the upper fifth (20%) of the historical range. This more specifically describes chances for an extremely wet season than the information in Panel (A) and indicates to the right of the colour bar factors by which occurrence of such an extreme is more (or less) likely than usual.

Category	Oral presenters	Poster presenters	Total
Overall	42	26	68
Female	19	10	29
Male	23	16	39
Student/Postdoc	11	13	24
Faculty/Research Professional	19	9	28
Senior Faculty/Research Professional	12	4	16
APN Member Developing Countries	4	5	9
Other APN Member or Approved Countries	21	12	33
Non-APN Countries	17	9	26

TABLE 1. Summary information for ExCPens workshop presenter genders, career stages, and countries of home institutions.

cally, culturally, and socially diverse global research community and promoted Young Earth System Scientists (YESS), a global community resource for ECS. Following a round of introductions, 43 qualifying EC were divided into six breakout discussion groups, each led by an experienced scientist. Each group focused on three discussion questions, two of which were common across the groups, whereas each of the group leaders formulated the third question. One ECS in each group served as rapporteur and reported on their group’s discussions during a concluding plenary gathering.

The ECS programme continued with a series of six Training Lectures that were held in separate afternoon and evening sessions on 28 October. Each lecture was allocated 30 minutes and was

followed by 15 minutes for questions and discussion. The lecturers were subject matter experts in the US, Canada, UK, Switzerland, and China, and 59 ECS from 21 countries participated. The topics covered, and the outcomes of the ECS networking discussions are reported in Section 3.2. [Figure 2](#) contains a partial group portrait taken during the workshop’s opening session, and [Figure 3](#) indicates countries represented by workshop and ECS session registrants, showing the status of those countries concerning APN.

3. RESULTS AND DISCUSSION

3.1. Workshop outcomes

The workshop was built around six research themes on weather and climate extremes chosen



FIGURE 2. Group portrait of ExCPEns Workshop and Early Career Scientist Training Sessions participants.

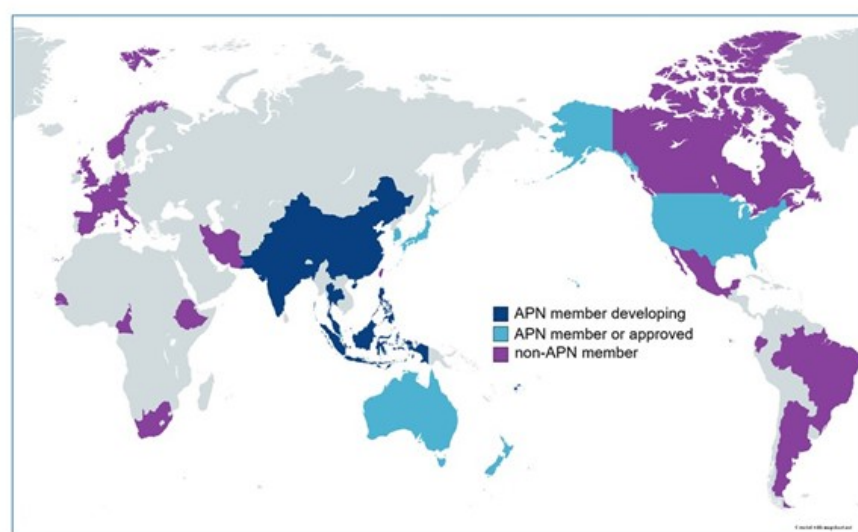


FIGURE 3. Countries represented by Workshop and Early Career Scientist Training Session registrants. (Dark blue: APN member developing countries. Light blue: other APN members or approved countries. Purple: non-APN member countries). Figure created using mapchart.net.

as high-priority research areas. These themes are described in the subsections below, each of which summarizes key aspects from the presentations, areas of consensus and, in some cases, caveats that were raised about certain methods and results, and further research priorities.

3.1.1. Identification of extremes in observation and climate prediction ensemble

The first important step for assessing the impact of extremes in the societal context and the

potential for their prediction is the identification of extremes. Presentations in this theme focused on aspects of extremes such as their spatiotemporal footprints, cataloguing of classes of simulated and observed extremes, their characterization in climate projection ensembles, combining information from decadal predictions and multi-decadal projections, and verification of forecasts of local heatwave indices. A common element was that algorithms for detecting extremes need to be formulated carefully to avoid missing or falsely identifying

events of interest and that these methods should take into consideration the impacts of particular types of extremes in terms of their severity, duration and regional extent (Prodhomme et al., 2021). In addition, model simulations were viewed as valid data sources either to multiply sets of infrequent events used for risk assessments (e.g. Lockwood et al., 2022), or to “fill in” unobserved features of an event using simulations constrained by available observations (e.g. Mogen et al., 2022), provided the simulations are carefully validated and bias corrected. Research priorities in this theme that were identified include (i) assessment of definitions and characterizations of climate extremes, and methodologies for identification of extremes in observational data, (ii) identification of limitations in different observational datasets for the characterization of extremes and their influences, (iii) validation of extremes in climate prediction ensembles against observational estimates, and (iv) quantification of biases in extremes in climate prediction ensembles, associated implications for prediction, and possible model deficiencies responsible for biases in simulation of extremes.

3.1.2. *Physical mechanisms of extremes in observations and climate prediction ensembles*

Understanding physical mechanisms and large-scale drivers for weather and climate extremes is a prerequisite for improving the prediction of extremes. Presentations on this theme emphasized the origins and impacts of phenomena such as rare Antarctic sudden stratospheric warmings (Lim et al., 2021) and local and remote drivers of heat, drought, and rainfall extremes. Examples of local drivers examined include low soil moisture amplifying dry and heat extremes, and variations in atmospheric moisture supply leading to drought onset and termination. In contrast, remote drivers include sea surface temperature variability and the Madden-Julian Oscillation (MJO) and Quasi-Biennial Oscillations. Areas of consensus were that climate extremes are often influenced by confluences of multiple large-scale drivers (e.g. Holgate et al., 2020 ; Jia et al., 2022), and that soil

moisture can be an especially important driver for heat extremes (e.g. Materia et al., 2022). Some caveats were that relationships between large-scale drivers and local extremes might not be stationary in a warming climate, and that very high resolution may be needed to accurately model sea surface temperature and other influences on precipitation extremes (Chen, Hsu, Liang, Chiu, & Tu, 2022). Research priorities in this theme that were identified are (i) a better understanding of mechanisms of extremes in observation, (ii) better identification of large-scale drivers and important feedback processes for extremes, and (iii) verification of mechanisms of extremes captured by CPEs, linking predictability and their initial state dependency.

3.1.3. *Regional climate extreme information relevant to impacts, vulnerability and adaptation*

Accurate and regionally well-tailored climate information has become important for early warning and risk management to adapt to more frequent and severe weather and climate extremes. Presentations on this topic highlighted aspects of particular socioeconomic relevance including co-developed communication of probabilistic forecasts of extremes for sectoral applications, using observed large-scale climate variations as predictors to estimate future flood economic loss risk, and identifying impactful future changes in rainfall extremes in long-term climate projection ensembles. Contrasting approaches included determining statistical connections between climate patterns and economic loss (Hu, Wang, Liu, Gong, & Kantz, 2021) , and interfacing with sectorial users to develop climate extreme forecast information that applies to decision-making in the agricultural sector (Hayman & Hudson, 2021). Two research areas prioritized in this theme were (i) assessment of regional climate extreme information currently used and additionally required to enhance early warning systems for robust decision-making, to maximize the socioeconomic benefits and to minimize the costs of extreme events, particularly for highly vulnerable regions and countries; and (ii)

development of effective delivery and shaping of climate information to promote understanding and communicating with regional society.

3.1.4. Prediction and predictability of large-scale climate variability relevant to extreme events

Patterns of large-scale climate variability, including the MJO, El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Boreal Summer Intraseasonal Oscillation (BSISO) and Northern and Southern Annular Modes, can increase the likelihood of climate extremes in particular regions and seasons. Presentations under this theme focused on using climate prediction ensembles to examine how climate extremes are influenced by large-scale climate variability patterns and warming trends on subseasonal to multi-decadal time scales and to what degree skill in predicting large-scale patterns enables skilful prediction of local extremes. One point of agreement was that for models to realize predictability and skill due to tropical patterns of variability (MJO, ENSO, IOD, BSISO), it is necessary both to accurately predict those patterns and correctly represent the corresponding teleconnections (Doi, Behera, & Yamagata, 2020; Feng, Klingaman, Hodges, & Guo, 2020). Biases in representing large-scale environmental conditions can degrade modelled teleconnections, which points to a reduction of systematic model errors as one way to improve prediction skill (Xie, Yu, Chen, & Hsu, 2020; Imada & Kawase, 2021), although accuracy of the initialization also plays a role (Long et al., 2021). The prioritized research topics in this theme include (i) the use of CPEs to predict and evaluate the predictability of large-scale climate variability patterns and associated climate/Earth system extremes, and (ii) examination of the nature and impacts of large-scale climate events on more severe extremes than any yet observed in individual CPE realizations.

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

There is increasing interest in predictability and prediction of extreme weather beyond ten days, which is sometimes considered a limiting range for useful weather predictions. Skillful forecasts of extreme events beyond ten days would help to develop early warning systems for better preparedness that would benefit society. However, model systematic errors make it challenging for models to adequately represent extreme events. Presentations in this theme highlighted the current state of prediction of heatwaves, hydrological and hydrometeorological extremes, tropical cyclones, low-pressure monsoon systems, and lightning utilizing subseasonal to seasonal (S2S) and other subseasonal ensemble prediction systems, including applications of machine learning for post-processing to enhance the skill. One perspective common to several of the presentations is that predictability of specific extreme events can be conditional; for example, dry Australian hydrological extremes are predicted more skillfully than wet extremes (Vogel et al., 2021), and Indian heat waves are predicted skillfully beyond week two for certain regions and probability ranges (Mandal et al., 2019). Caveats that were raised include that predicted magnitudes of extreme events are often underestimated by the ensemble mean even when other aspects of an event are predicted accurately (Domeisen et al., 2022); some events may not be predicted as well as expected from the accuracy of historical predictions (Tsai, Lu, Sui, & Cho, 2021); and multi-model ensembles do not always outperform the best-performing individual model (Deoras, Hunt, & Turner, 2021). The research topics to be further focused upon include (i) prediction and predictability of the onset, evolution and decay of large-scale, long-lasting extreme events (e.g., heat or cold waves, droughts) at all time scales beyond ten days, and (ii) prediction and predictability of changes in the probability of occurrence over a large region and large period of time of some extreme events,

such as tropical cyclones, tornadoes, and heavy rain episodes, for which individual occurrence is usually not predictable beyond ten days.

3.1.6. Quantifying current and future risks of climate extremes

Observations provide just one of many potential realizations of the chaotic evolution of the climate system and may not adequately represent the full range of extreme events that can occur in a changing climate. Realistic climate prediction ensembles overcome these limitations by providing many more realizations of potential extreme events. Presentations in this theme focused on extracting information about current and future probabilities of weather and climate extremes, including unprecedented extremes, from climate prediction and projection ensembles and high-resolution simulations. Innovative methods applied include the UNprecedented Simulated Extremes using ENsembles (UNSEE) approach, whereby large seasonal and decadal prediction ensembles are used as a “multiplier” of the single observed record of climate variability (Kay et al., 2022), and rare event algorithms that enhance sample sizes in the tails of distributions (Ragone & Bouchet, 2021). Additional studies focused on estimating how anthropogenic warming has influenced the severity of recent observed droughts (Kam, Min, Wolski, & Kug, 2021) and possible recurrences of a historical drought (Baker, Shaffrey, & Hawkins, 2021), as well as extreme precipitation severity more generally under historical and future warming (Paik et al., 2020; Mizuta & Endo, 2020). Common elements included that model outputs need to be validated carefully against observations and, if necessary, bias corrected, and that finite computational resources need to be allocated based on the problem being addressed. For example, although very high resolution is essential for accurately representing tropical cyclones, century-long simulations are sufficient for examining changes in their global statistics (Chu et al., 2020), in contrast to the thousands of simulated years needed to represent occurrences of the rarest events (e.g. Thompson et

al., 2019). For this theme the research priority is better quantifying the changes of extremes in the current climate, including unprecedented events, and how they will evolve in the future.

3.2. Early career scientist training and networking outcomes

In conjunction with the ExCPEnS workshop, an ECS Training and Networking programme was held from 27 to 28 October 2021. The programme aimed to build global research capacities for understanding, predicting, and assessing risks and impacts of weather and climate extremes.

3.2.1. ECS Training Programme

Table 2 summarizes the ECS Training programme, which took place in two sessions. In Session 1 on Extreme Detection and Prediction, Sookyung Kim of the Palo Alto Research Center lectured on the detection of extreme events using machine learning, including data challenges in scientific research, detection and localization of extreme climate events, super-resolution models for downscaling key processes, and tracking and predicting extreme climate events. Megan Kirchmeier-Young of Environment and Climate Change Canada lectured on extreme event attribution, including an illustrative introduction to event attribution, focusing on simple, popular methods and suggesting references to consult for additional details. Frederic Vitart from the European Centre for Medium-Range Weather Forecasts reviewed the predictability of extreme events on S2S time scales highlighting sources of S2S predictability such as MJO, soil moisture, stratospheric initial conditions, Rossby waves, sea surface temperatures, sea-ice, and aerosols.

Session 2 on Projection of Future Climate Extremes focused on outcomes from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). Jin-Ho Yoon of Gwangju Institute of Science and Technology introduced the important regional assessment results in AR6 (Gutiérrez et al., 2021) and demonstrated how to use the IPCC AR6

Session	Lecture Title	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)

TABLE 2. Summary of ECS training programme including sessions, lecture titles and lecturer information.

Interactive Atlas (<https://interactive-atlas.ipcc.ch/>). He highlighted that climate change is affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes. Erich Fischer of ETH Zurich lectured on high-warming storylines mainly based on Chapter 4 of the Working Group I (WGI) contribution to AR6 (Lee et al., 2021) and very rare extremes. He emphasized that (1) low-likelihood outcomes are often associated with the greatest risks, (2) warming substantially larger than the best estimate cannot be ruled out, (3) we need 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 last lecture was given by Xuebin Zhang of Environment and Climate Change Canada on weather and climate extremes in a changing climate. He highlighted observed changes in extremes and their attribution, projected changes in extremes, projected changes in extremes at the regional scale, and key messages throughout Chapter 11 of the WGI contribution to AR6 (Seneviratne et al., 2021).

3.2.2. Networking and Discussion Forum for ECS from APN Developing Countries

The ECS networking forum centered on breakout sessions matching ECS small groups with experienced scientists. Two questions were discussed by all of the groups. The first was about what the most important scientific challenges are for predicting

weather and climate extremes and how we can tackle them. The outcomes of the discussion were as follows:

- ▶ Some challenges are posed by modelling limitations, such as limited resolution and imperfect parameterizations, leading to errors in representing teleconnection patterns and limitations for providing information at local scales.
- ▶ Additional challenges result from the limited length of the modern observational record, particularly land variables such as soil moisture and the rareness of some extreme events leading to insufficient samples for forecast calibration and verification.
- ▶ Possible solutions include the application of machine learning to improve model parameterizations and correct model errors through post-processing, longer hindcast periods to increase the sample of rare events and better understand climate change impacts on predictability and skill, and downscaling of global model outputs to better represent small-scale processes and orographic effects contributing to extremes.

The second question concerned the difficulties faced by ECS in developing countries and what some possible solutions are. The outcomes of the discussion were as follows:

- ▶ Among the barriers discussed were lack of state-of-the-art computational facilities and difficulties with data accessibility in ECS home countries, lack of training opportunities for keeping up with rapidly changing technology and scientific developments and for scientific communication, and above all, limited opportunities for finding relevant employment after graduation.
- ▶ WCRP and other international organizations could help by providing or connecting ECS to training courses covering scientific developments, basic climate dynamics and academic writing, and by providing fellowships or otherwise facilitating postdoctoral employment for ECS from developing countries.
- ▶ Both of these questions bear on the critical need for improving capabilities for extreme event prediction in APN developing countries and the Global South more broadly, as these regions are particularly exposed and vulnerable to associated adverse impacts (IPCC, 2022). Types of weather and climate extremes identified by the ECS as especially threatening to their regions include tropical storms (typhoons, cyclones and hurricanes), extreme rainfalls, heatwaves, and lightning, and especially compound extremes, such as combined heatwaves, and drought. Scientific advances in predicting such events, including on local scales, will be enormously beneficial and should be an international research priority. Strengthening career development opportunities for ECS in these countries will accelerate such advances by providing new capacities for targeted research and associated services tailored to local needs. ExCPEns, through its scientific presentations and lectures, as well as connecting experienced scientists with ECS, sought to contribute to these objectives.

4. CONCLUSION

This project aimed to advance the rapidly emerging science of exploiting 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 Scientists Training and Networking Programme. During the workshop, 68 presentations were made during six sessions. About 300 participants from all over the world attended the workshop. The Early Career Scientist (ECS) event followed the ExCPEns workshop and consisted of a networking and discussion forum for ECS from APN member developing countries, along with a series of ECS training lectures and discussion sessions open to all ECS registrants.

Through the workshop and discussion among stakeholders, the project team identified the following high-priority research topics addressing end-user requirements in the Asia-Pacific region:

- ▶ Improvement of high-frequency and high-resolution observation, especially for land processes such as soil moisture, by integrating information across in situ and satellite observations, reconstructions, and reanalyses;
- ▶ Development of tailored regional forecasts of weather and climate extremes;
- ▶ Advanced dynamical or statistical downscaling of global model ensembles to better represent small-scale processes and orographic effects contributing to extremes;
- ▶ Better understanding of climate change impacts on predictability and prediction skills for large-scale variability relevant to extremes;
- ▶ Production of longer hindcasts to increase the sample size of rare events;
- ▶ Application of machine learning to improve model parameterizations and correct model errors through post-processing.

By bringing together researchers from across regions and career stages, the ExCPens Workshop and ECS Programme helped to consolidate and stimulate research on understanding and predicting weather and climate extremes from subseasonal to climate change time scales. By engaging with ECS primarily from APN developing countries that tend to be most impacted by extremes, these events additionally enabled learning and networking to assist the next generation of scientists in tackling critical research challenges that must be met to increase the resilience of vulnerable regions in a changing climate.

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REFERENCES

- Baker, L., Shaffrey, L., & Hawkins, E. (2021). Has the risk of a 1976 north-west European summer drought and heatwave event increased since the 1970s because of climate change? *Quarterly Journal of the Royal Meteorological Society*, 147(741), 4143–4162. doi:10.1002/qj.4172
- Becker, E. J., & Van Den Dool, H. (2018). Short-term climate extremes: Probabilistic forecasts from a multi-model ensemble. In *42nd NOAA Climate Diagnostics Prediction Workshop* (pp. 46–48). Norman, OK: NOAA.
- Becker, E. J., van den Dool, H., & Peña, M. (2013). Short-Term Climate Extremes: Prediction Skill and Predictability. *Journal of Climate*, 26(2), 512–531. doi:10.1175/jcli-d-12-00177.1
- Chen, C. A., Hsu, H. H., Liang, H. C., Chiu, P. G., & Tu, C. Y. (2022). Future change in extreme precipitation in East Asian spring and Mei-yu seasons in two high-resolution AGCMs. *Weather and Climate Extremes*, 35, 100408. doi:10.1016/j.wace.2022.100408
- Chu, J. E., Lee, S. S., Timmermann, A., Wengel, C., Stuecker, M. F., & Yamaguchi, R. (2020). Reduced tropical cyclone densities and ocean effects due to anthropogenic greenhouse warming. *Science Advances*, 6(51). doi:10.1126/sciadv.abd5109
- Deoras, A., Hunt, K. M. R., & Turner, A. G. (2021). Comparison of the Prediction of Indian Monsoon Low Pressure Systems by Subseasonal-to-Seasonal Prediction Models. *Weather and Forecasting*, 36(3), 859–877. doi:10.1175/waf-d-20-0081.1
- Doi, T., Behera, S. K., & Yamagata, T. (2020). Wintertime Impacts of the 2019 Super IOD on East Asia. *Geophysical Research Letters*, 47(18). doi:10.1029/2020gl089456
- Domeisen, D. I. V., White, C. J., Afargan-Gerstman, H., Ángel G. Muñoz, Janiga, M. A., Vitart, F., ... Tian, D. (2022). Advances in the Subseasonal Prediction of Extreme Events: Relevant Case Studies across the Globe. *Bulletin of the American Meteorological Society*, 103(6), 1473–1501. doi:10.1175/bams-d-20-0221.1
- Eade, R., Hamilton, E., Smith, D. M., Graham, R. J., & Scaife, A. A. (2012). Forecasting the number of extreme daily events out to a decade ahead. *Journal of Geophysical Research: Atmospheres*, 117(D21). doi:10.1029/2012jd018015
- Feng, X., Klingaman, N. P., Hodges, K. I., & Guo, Y. P. (2020). Western North Pacific Tropical Cyclones in the Met Office Global Seasonal Forecast System: Performance and ENSO Teleconnections. *Journal of Climate*, 33(24), 10489–10504. doi:10.1175/jcli-d-20-0255.1
- Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- Gutiérrez, J. M., Jones, R. G., Narisma, G. T., Alves, L. M., Amjad, M., Gorodetskaya, I. V., ... Yoon, J. H. (2021). Atlas. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, ... B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1927–2058). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi:10.1017/9781009157896.021
- Hamilton, E., Eade, R., Graham, R. J., Scaife, A. A., Smith, D. M., Maidens, A., & MacLachlan, C. (2012). Forecasting the number of extreme daily events on seasonal timescales. *Journal of Geophysical Research: Atmospheres*, 117(D3). doi:10.1029/2011jd016541
- Hayman, P., & Hudson, D. (2021). Forewarned is forearmed - Exploring the value of new forecast products from the BOM to enable more informed decisions on profit and risk on grain farms.

- Grains Research and Development Corporation (GRDC) Update Paper, Retrieved from <https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/05/forewarned-is-forearmed-exploring-the-value-of-new-forecast-products-from-the-bom-to-enable-more-informed-decisions-on-profit-and-risk-on-grain-farms>
- Holgate, C. M., Dijk, A. I. J. M. V., Evans, J. P., & Pitman, A. J. (2020). Local and Remote Drivers of Southeast Australian Drought. *Geophysical Research Letters*, 47(18). doi:10.1029/2020gl090238
- Hu, X., Wang, M., Liu, K., Gong, D., & Kantz, H. (2021). Using Climate Factors to Estimate Flood Economic Loss Risk. *International Journal of Disaster Risk Science*, 12(5), 731–744. doi:10.1007/s13753-021-00371-5
- Imada, Y., & Kawase, H. (2021). Potential Seasonal Predictability of the Risk of Local Rainfall Extremes Estimated Using High-Resolution Large Ensemble Simulations. *Geophysical Research Letters*, 48(24). doi:10.1029/2021gl096236
- IPCC. (2022). Summary for Policymakers. In H. O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, K. Mintenbeck, ... B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3–33). Cambridge, UK and New York, NY, USA: Cambridge University Press. doi:10.1017/9781009325844.001
- Jia, L., Delworth, T. L., Kapnick, S., Yang, X., Johnson, N. C., Cooke, W., ... Tseng, K. C. (2022). Skillful Seasonal Prediction of North American Summertime Heat Extremes. *Journal of Climate*, 35(13), 4331–4345. doi:10.1175/jcli-d-21-0364.1
- Judt, F. (2018). Insights into Atmospheric Predictability through Global Convection-Permitting Model Simulations. *Journal of the Atmospheric Sciences*, 75(5), 1477–1497. doi:10.1175/jas-d-17-0343.1
- Kam, J., Min, S. K., Wolski, P., & Kug, J. S. (2021). CMIP6 Model-Based Assessment of Anthropogenic Influence on the Long Sustained Western Cape Drought over 2015–19. *Bulletin of the American Meteorological Society*, 102(1), 45–50. doi:10.1175/bams-d-20-0159.1
- Kay, G., Dunstone, N. J., Smith, D. M., Betts, R. A., Cunningham, C., & Scaife, A. A. (2022). Assessing the chance of unprecedented dry conditions over North Brazil during El Niño events. *Environmental Research Letters*, 17(6), 064016. doi:10.1088/1748-9326/ac6df9
- Lee, J. Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., ... Zhou, T. (2021). Future Global Climate: Scenario-Based Projections and Near-Term Information. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 553–672). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi:10.1017/9781009157896.006
- Lim, E. P., Hendon, H. H., Butler, A. H., Thompson, D. W. J., Lawrence, Z. D., Scaife, A. A., ... Wang, G. (2021). The 2019 Southern Hemisphere Stratospheric Polar Vortex Weakening and Its Impacts. *Bulletin of the American Meteorological Society*, 102(6), 1150–1171. doi:10.1175/bams-d-20-0112.1
- Lockwood, J. F., Guentchev, G. S., Alabaster, A., Brown, S. J., Palin, E. J., Roberts, M. J., & Thornton, H. E. (2022). Using high-resolution global climate models from the PRIMAVERA project to create a European winter windstorm event set. doi:10.5194/nhess-2022-12
- Long, X., Widlansky, M. J., Spillman, C. M., Kumar, A., Balmaseda, M., Thompson, P. R., ... Mitchum, G. (2021). Seasonal Forecasting Skill of Sea-Level Anomalies in a Multi-Model Prediction Framework. *Journal of Geophysical Research: Oceans*, 126(6). doi:10.1029/2020jc017060
- Mandal, R., Joseph, S., Sahai, A. K., Phani, R., Dey, A., Chattopadhyay, R., & Pattanaik, D. R. (2019). Real time extended range prediction of heat waves over India. *Scientific Reports*, 9(1). doi:10.1038/s41598-019-45430-6
- Materia, S., Ardilouze, C., Prodhomme, C., Donat, M. G., Benassi, M., Doblas-Reyes, F. J., ... Gualdi, S. (2022). Summer temperature response to extreme soil water conditions in the Mediterranean transitional climate regime. *Climate Dynamics*, 58(7–8), 1943–1963. doi:10.1007/s00382-021-05815-8
- Meehl, G. A., Richter, J. H., Teng, H., Capotondi, A., Cobb, K., Doblas-Reyes, F., ... Xie, S. P. (2021). Initialized Earth System prediction from subseasonal to decadal timescales. *Nature Reviews Earth & Environment*, 2(5), 340–357. doi:10.1038/s43017-021-00155-x
- Merryfield, W. J., Baehr, J., Batté, L., Becker, E. J., Butler, A. H., Coelho, C. A. S., ... Yeager, S. (2020). Current and Emerging Developments in Subseasonal to Decadal Prediction. *Bulletin of the American Meteorological Society*, 101(6), 869–896. doi:10.1175/bams-d-19-0037.1
- Mizuta, R., & Endo, H. (2020). Projected Changes in Extreme Precipitation in a 60-km AGCM Large

- Ensemble and Their Dependence on Return Periods. *Geophysical Research Letters*, 47(13). doi:10.1029/2019gl086855
- Mogen, S. C., Lovenduski, N. S., Dallmann, A. R., Gregor, L., Sutton, A. J., Bograd, S. J., ... Yeager, S. (2022). Ocean Biogeochemical Signatures of the North Pacific Blob. *Geophysical Research Letters*, 49(9). doi:10.1029/2021gl096938
- Paik, S., Min, S. K., Zhang, X., Donat, M. G., King, A. D., & Sun, Q. (2020). Determining the Anthropogenic Greenhouse Gas Contribution to the Observed Intensification of Extreme Precipitation. *Geophysical Research Letters*, 47(12). doi:10.1029/2019gl086875
- Prodhomme, C., Materia, S., Ardilouze, C., White, R. H., Batté, L., Guemas, V., ... García-Serrano, J. (2021). Seasonal prediction of European summer heatwaves. *Climate Dynamics*, 58(7–8), 2149–2166. doi:10.1007/s00382-021-05828-3
- Ragone, F., & Bouchet, F. (2021). Rare Event Algorithm Study of Extreme Warm Summers and Heatwaves Over Europe. *Geophysical Research Letters*, 48(12). doi:10.1029/2020gl091197
- Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., & Zhou, B. (2021). Weather and climate extreme events in a changing climate. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, ... B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1513–1766). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi:10.1017/9781009157896.013
- Shukla, J. (1998). Predictability in the Midst of Chaos: A Scientific Basis for Climate Forecasting. *Science*, 282(5389), 728–731. doi:10.1126/science.282.5389.728
- Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Hardiman, S. C., Ren, H. L., ... Belcher, S. E. (2019). Risk and dynamics of unprecedented hot months in South East China. *Climate Dynamics*, 52(5–6), 2585–2596. doi:10.1007/s00382-018-4281-5
- Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S., & Belcher, S. E. (2017). High risk of unprecedented UK rainfall in the current climate. *Nature Communications*, 8(1). doi:10.1038/s41467-017-00275-3
- Tsai, W. Y. H., Lu, M. M., Sui, C. H., & Cho, Y. M. (2021). Sub-seasonal Forecasts of the Northern Queensland Floods of February 2019: Causes and Forecast Evaluation. *Atmosphere*, 12(6), 758. doi:10.3390/atmos12060758
- Vogel, E., Lerat, J., Pipunic, R., Frost, A. J., Donnelly, C., Griffiths, M., ... Loh, S. (2021). Seasonal ensemble forecasts for soil moisture, evapotranspiration and runoff across Australia. *Journal of Hydrology*, 601, 126620. doi:10.1016/j.jhydrol.2021.126620
- Xie, J., Yu, J., Chen, H., & Hsu, P. C. (2020). Sources of Subseasonal Prediction Skill for Heatwaves over the Yangtze River Basin Revealed from Three S2S Models. *Advances in Atmospheric Sciences*, 37(12), 1435–1450. doi:10.1007/s00376-020-0144-1