THE MULTISCALE GLOBAL MONSOON SYSTEM

Research and Prediction Challenges in Weather and Climate

Chih-Pei Chang, Richard H. Johnson, Kyung-Ja Ha, Daehyun Kim, Gabriel Ngar-Cheung Lau, Bin Wang, Michael M. Bell, and Yali Luo

The monsoon is probably the most important atmospheric circulation system in terms of the impact on human lives. It covers more than one-half the globe and affects three-quarters of the world's population. The International Workshop on Monsoons (IWM) series is a part of the World Meteorological Organization (WMO)'s major quadrennial symposia and workshops series under the World Weather Research Programme (WWRP). The IWM series has served scientists a unique venue in that it covers a wide range of scales, both spatial and temporal, recognizing that a monsoon system is inherently a multiscale complex and that it brings theoreticians, field observation specialists, modelers, and forecasters together to make real progress in monsoon science and forecast applications. Since the third IWM (IWM-III) in 2004, the majority of invited review papers of each workshop have gone through a peer review process and been published in the *Global Monsoon System: Research and Forecast* book series (Chang et al. 2005, 2011, 2017).

IWM-VI was organized by the Monsoon Panel of the WWRP Working Group on Tropical Meteorology Research, in cooperation with the Climate and Ocean: Variability, Predictability and Change (CLIVAR)/Global Energy and Water Cycle Experiment (GEWEX) Monsoon Panel, the Madden–Julian Oscillation (MJO) Task Force, the Subseasonal to Seasonal (S2S) Steering Group, the Years of the Maritime Continent (YMC) Scientific Steering Committee, Meteorological Service Singapore, the Chinese University of Hong Kong, the Asia–Pacific Economic Cooperation (APEC) Climate Center, and the World Scientific Publishing Company. The workshop

THE SIXTH WMO INTERNATIONAL WORKSHOP ON MONSOONS (IWM-VI)

WHAT: More than 180 researchers and forecasters met to review and discuss recent research and forecast issues ranging from mesoscale weather to climate change in various monsoon regions of the globe.
WHEN: 13–17 November 2017
WHERE: Singapore

AFFILIATIONS: Chang—Naval Postgraduate School, Monterey, California, and National Taiwan University, Taipei, Taiwan; Johnson and Bell—Colorado State University, Fort Collins, Colorado; Ha—Pusan National University, Busan, South Korea; Kim—University of Washington, Seattle, Washington; Lau—Chinese University, Hong Kong, China; Wang—University of Hawai'i at Mānoa, Honolulu, Hawaii; Luo—Chinese Academy of Meteorological Sciences, Beijing, China
CORRESPONDING AUTHOR: Chih-Pei Chang, cpchang@nps.edu

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opened with a special lecture in memory of Dr. D. R. Sikka, former director of the Indian Institute of Tropical Meteorology, and closed at the completion of the WMO monsoon training workshop for national meteorological and hydrological service staff and the panel discussion of the Global Monsoons Model Intercomparison Project (GMMIP) contribution to phase six of the Coupled Model Intercomparison Project (CMIP6). A total of 169 oral and poster papers were presented, including 38 invited reviews that will be published as the fourth volume of the book series entitled *The Multi-Scale Global Monsoon System*. The highlights of various scientific presentations and programmatic activities at IMW-VI are summarized in the following sections. The abstracts volume is available online (www.wmo.int/pages/prog/arep/wwrp/new/documents/IWM6AbstractsVolume.pdf).

GLOBAL AND REGIONAL MONSOON. Several reviews focused on land–atmosphere–ocean interactions in the South Asian monsoon. Recent research continues to better define the role of land–sea contrast in monsoon variability. One study argues that the overall Asian monsoon domain is characterized by an eastward propagation of anomalies from one summer to the next with a strong biennial tendency—anomalies that are dominated by two anticyclones over the south Indian Ocean and the western North Pacific. The effect of remote El Niño/La Niña forcing on the Asian monsoon variability is well known, but the local monsoon–ocean interaction is also important. Four predictable influences on Asian summer precipitation have been identified: the central Pacific ENSO, the Indo-Pacific monsoon–ocean feedback, the Indian Ocean dipole, and global warming. Extratropical Pacific and Atlantic sea surface temperatures (SSTs) also exhibit a significant influence on the South Asian monsoon rainfall when ENSO is weak or in a transition state.

The East Asian summer monsoon (EASM) displays strong multifaceted characteristics and coupling from intraseasonal to interannual time scales. The western North Pacific subtropical high (WNPSH) is a key system of the ENSO–EASM teleconnection. Its formation during El Niño peak winter is mainly caused by local atmosphere–ocean interaction augmented by moist enthalpy advection and Rossby wave modulation. During the El Niño decaying summer, it is maintained by local SST cooling and Indian Ocean warming. The weakening of the East Asian winter monsoon (EAWM) that started in the late 1980s has been attributed to global warming. However, a strengthening is observed after the early 2000s in spite of the continuing rise of global temperature. Enhanced Ural blocking and diminished September Arctic sea ice concentration have been suggested as possible causes.

The Maritime Continent is a region that is most strongly influenced by ENSO, but during boreal winter the prediction skills over western Indonesia and the Malay Peninsula are low. This is apparently due to two large effects of wind–terrain interaction that offset each other during the ENSO mature phases. The name weak interacting monsoon precipitation (WIMP) was proposed for this difficult-to-predict region, both for a geographical description and for conveying its special nature of weak interacting monsoon rainfall with ENSO. An overview of the YMC field campaign was introduced with its five science themes: atmospheric convection, upper-ocean processes and air–sea interaction, stratosphere–troposphere interaction, aerosols, and prediction improvement. The send-off ceremony for the Research Vessel (R/V) *Mirai* for the first intensive observation period of YMC was held at the end of IWM-VI at the port of Singapore.

A review of Australian monsoon variability on intraseasonal to interannual time scales reported the simulation and prediction of the Australian monsoon in the current climate models, and the outlook of rainfall changes under the representative concentration pathway (RCP) 8.5 scenario. A comprehensive review on the study of both the South and North American monsoons was given. The topics include the annual cycle, variability on various time scales, and modeling and prediction. Several papers reviewed the observational studies and climate modeling of both the West African and central African monsoons. The amplified drought and drying trend over the equatorial African region was mainly explained by SST variations over the Indo-Pacific region, and the enhanced and westward-extended tropical Walker circulation.

MONSOON MESOSCALE PHENOMENA AND HIGH-IMPACT WEATHER. In the East Asian monsoon, intense mesoscale convective systems (MCSs) during the presummer rainy season are often associated with monsoon onset and the meiyu front. Several of these systems were studied during the Southern China Monsoon Rainfall Experiment (SCMREX) in May–June 2013–17 that deployed an extensive array of meteorological instrumentation, including dual-polarimetric radars and vertically pointing cloud-and-precipitation radars. The results

revealed the important role played by the complex terrain in the continuous convective initiation and the weak cold outflows that favor slow movement of the storm leading to extreme rainfall production.

While some papers concentrated on extreme-rain-producing MCSs, other studies addressed processes involved with other types of high-impact and mesoscale weather phenomena. The diurnal cycles are important for extreme rainfall in many monsoon regions. In the EASM the diurnal cycle of the low-level jet strongly influences the precipitation along the mei-yu front. In the Australian monsoon, some of the most intense convection and thunderstorms occur as a result of strong diurnal forcing during the build-up and break periods instead of the active period of the monsoon. Reviews of regional processes contributing to localized flooding include the diurnally driven circulations and topographic effects in a flash-flood thunderstorm over the Taipei basin, the regional- and synoptic-scale conditions associated with heavy precipitation systems over the Amazon and southern South America, and an extreme event in Burkina Faso in 2009.

Much of the heaviest rain accumulation from a tropical cyclone (TC) in the monsoon regions occurs in the primary or outer rainbands well away from the center, and these outer rainbands can also produce tornado outbreaks during landfall. In the absence of TCs and active rainfall, the monsoon circulation can lead to prolonged dry spells and high-impact weather in the form of heat waves. Recent studies have used satellites to map out global patterns of extreme rainfall (Fig. 1). These investigations have indicated increasing trends in the frequency and intensity of extreme rainfall and heat waves in different monsoon regions. An example showed that there has been an increasing frequency of heat waves in Indochina in recent decades as a result of weakening of the circulations associated with the EAWM and the South Asian summer monsoon. A report on African monsoon showed that there have been more extreme rainfall events over the Sahel in recent decades, potentially linked to global warming.

MJO, BSISO, AND S2S MONSOON PREDICTION. Several presentations were devoted to the underlying dynamics of the MJO and the boreal summer intraseasonal oscillation (BSISO), the dominant sources of predictability in the intraseasonal time scale around many monsoon regions. A review of the current theories for the MJO showed that moisture dynamics is an essential part of all theories, with one exception. The relative importance of wave dynamics, moisture advection, and cloud–radiation feedbacks differ significantly across the theories, suggesting that further studies need to focus on these processes. Global and regional model simulations showed that air–sea coupling affects the MJO directly

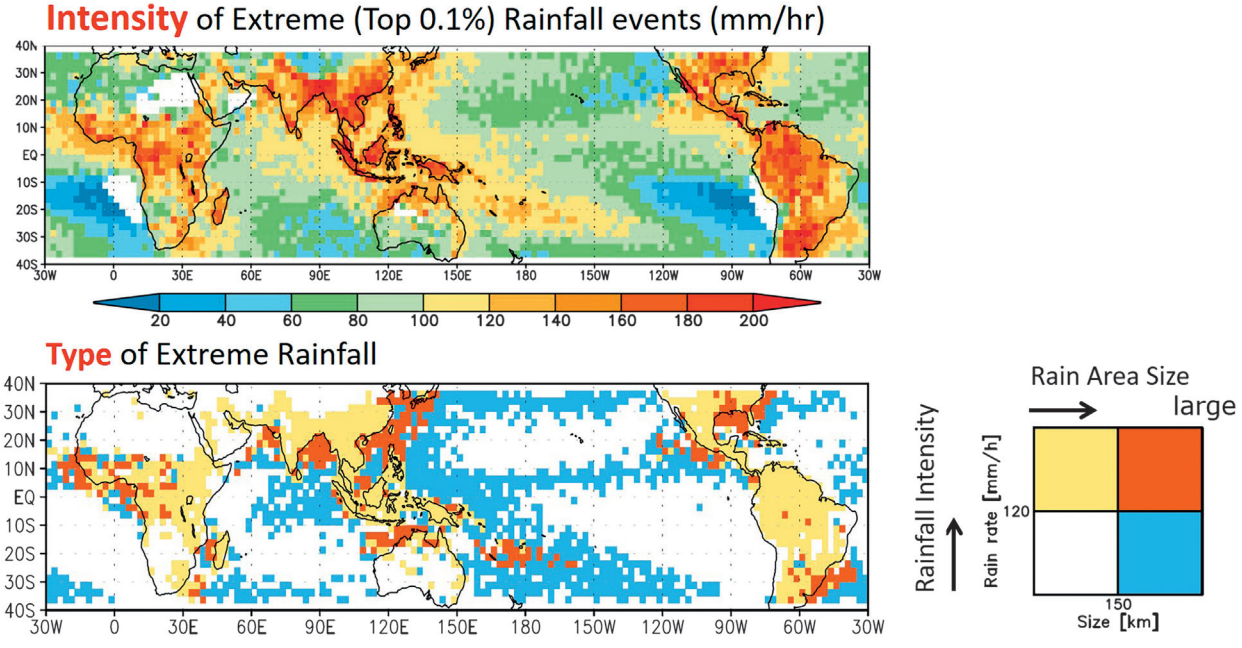

Fig. 1. Characteristics of regional rainfall extremes observed with Tropical Rainfall Measuring Mission (TRMM) data, 1998–2010 [from the invited review presented by Yukari Takayabu at IWM-VI) which was adapted from Hadama et al. (2014)].

through its influence on the MJO-scale moisture anomalies, and also indirectly by modulating the mean state.

A robust relationship was reported between models' MJO simulation fidelity or prediction skill and their representations of the mean state. An analysis of the S2S models showed that models with smaller biases in the mean horizontal moisture gradient tend to exhibit a superior MJO prediction skill. An examination of MJO moist static energy budget in the European Centre for Medium-Range Weather Forecasts (ECMWF) hindcasts showed that the weaker-than-observed mean horizontal moisture gradient in the model causes a weakening of horizontal moisture advection associated with the MJO, thereby weakening the MJO's eastward propagation. The apparent relationship between the mean state and the MJO simulation/prediction skill in the multimodel ensemble suggests that a better representation of monsoons in models could lead to improved MJO simulation/prediction.

A comprehensive review of the intraseasonal variability over the Maritime Continent (MC) area included the "interference" hypotheses that underscore the roles of the complex topography and the strong diurnal cycle of convection on the weakening and southward detouring of the MJO, and the "moisture mode view" hypothesis that emphasizes the distribution of the mean low-level moisture and the rectified effects of high-frequency synoptic variability on the MJO-scale circulation. Other reports showed that the wind anomalies associated with the EAWM play a major role in driving the 10–20-day variability of precipitation over the South China Sea and the intraseasonal SST variability via surface latent heat flux anomalies.

The MJO and the BSISO influence monsoon onsets and high-impact weather events, such as precipitation extremes. A report using the S2S hindcast dataset showed models are capable of forecasting the probability of the Australian monsoon active episodes as a function of the MJO phase. Another report demonstrated the potential use of the real-time BSISO forecast in the flood warning system over the Mekong River basin. Reliable MJO and BSISO forecasts, therefore, have great potential to be used in flood and disaster forecasting and agricultural planning.

MODELING. Various modeling aspects of the monsoon systems were presented, covering a broad range of phenomena, such as daily extreme precipitation events, synoptic disturbances, and seasonal and interannual changes, as well as decadal and centennial variability, in the monsoon regions of East Asia, Southeast Asia, the South China Sea, India, and western Africa. Efforts are being made to reproduce the monsoon characteristics in the present-day climate and to project their behavior under climate change in the future. The availability of more computer power has facilitated the increasing use of models with high spatial resolution, as well as experimentation with multimodel, multimember ensembles.

A review showed the success in obtaining realistic simulations of heavy rainstorms and typhoons around Japan, using a cloud-resolving model with a large computational domain (exceeding 1,000 km × 1,000 km) and a very fine grid system (about 1 km × 1 km). Another review reported the projection of future changes of mean and extreme precipitation using a 20- and 60-km mesh global atmospheric general circulation model. In a warmer climate, mean precipitation is projected to increase in most land monsoon regions, especially in East Asia. Extreme precipitation is projected to increase even faster except for some regions around the western tropical Pacific. A significant decrease of tropical cyclones over the western tropical Pacific results in small changes in future maximum 1-day precipitation, but their interannual variability will increase.

A review by the CLIVAR Working Group on Monsoons reported that, despite the considerable efforts, notable errors still exist in the simulation of precipitation climatology of the Asian–Australian monsoon system. Attempts to identify the causes of these model errors and to improve model performance were discussed. Some preliminary GMMIP/CMIP6 model results on the interdecadal Pacific oscillation and the Tibetan Plateau on monsoon climate were showcased.

THE WAY FORWARD. The participants discussed important progress in monsoon research and prediction across all scales with a focus on extremes in monsoon weather and climate. However, changes in the regional monsoons cannot be fully understood unless they are formulated together through the perspective of the global monsoon climate system. Therefore, the speakers recommended that more detailed studies are needed on how the regional monsoons and their variabilities are linked, and how much of the observed increases in extreme events are due to climate change by human action versus natural variability. In addition, further field campaigns and process studies are encouraged to improve model parameterizations and validation. Several issues on causes of monsoon onset and mechanism for genesis and propagation of monsoon disturbances remain

debated. Since most atmospheric general circulation models have great difficulty in correctly simulating the WNPSH and the mei-yu/changma/baiu front system, research efforts on several fronts, including high-resolution modeling and the radiative impacts of clouds, were suggested. Subseasonal prediction has recently become part of the operational forecast suite in many forecasting centers around the world. Further research progress will provide increasing benefits in filling the gap between weather and seasonal predictions.

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