Science Bulletin 64 (2019) 1557–1561

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

Science and prediction of monsoon heavy rainfall

Yali Luo [a,*], Liye Li [b], Richard H. Johnson [c], Chih-Pei Chang [d], Lianshou Chen [a], Wai-Kin Wong [e], Jing Chen [f], Kalli Furtado [g], John L. McBride [h], Ajit Tyagi [i], Nanette Lomarda [j], Thierry Lefort [k], Esperanza O. Cayanan [l]

[a] State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China
[b] HIWeather International Coordination Office, Chinese Academy of Meteorological Sciences, Beijing 100081, China
[c] Colorado State University, Fort Collins, CO 80523, USA
[d] Naval Postgraduate School, Monterey, CA 93943, USA
[e] Hong Kong Observatory, Hong Kong 999077, China
[f] Numerical Prediction Center, China Meteorological Administration, Beijing 100081, China
[g] Met Office, Exeter, Devon EX1 3PB, UK
[h] Bureau of Meteorology, Melbourne, Victoria 3001, Australia
[i] India Meteorological Department, Noida 201303, India
[j] World Weather Research Division, World Meteorological Organization, Geneva 1211, Switzerland
[k] Meteo-France, Toulouse 31000, France
[l] Philippine Atmospheric Geophysical and Astronomical Services Administration, Quezon City 1100, Philippines

With the increasing incidence of heavy rainfall events, particularly over the monsoon regions, the highly dense populations are more vulnerable [1]. Research initiatives on observation, modeling, and prediction of monsoon heavy rainfall have been promoted actively by World Weather Research Programme's (WWRP) Working Group on Tropical Meteorology Research (WGTMR) of the World Meteorological Organization (WMO) since 2010. Series of monsoon-heavy-rainfall workshops were held in Beijing (2011), Petaling Jaya (2012), and New Delhi (2015) to benefit scientists worldwide and forecasters from the National Meteorological and Hydrological Services. An international Research and Development Project, namely, the Southern China Monsoon Rainfall Experiment (SCMREX) [2] was established in 2013 to coordinate field campaign experiments and to conduct scientific research on presummer (April-June) heavy rainfall processes in southern China.

The Fourth WMO Monsoon Heavy Rainfall Workshop (MHR-4) was held in Shenzhen in April 2019 to discuss recent advances in analysis, numerical weather prediction (NWP) studies, and development of techniques for observing/forecasting monsoon heavy rainfall, and to review the progress of SCMREX. It was organized by the WWRP WGTMR and hosted by the State Key Laboratory of Severe Weather at Chinese Academy of Meteorological Sciences, China Meteorological Administration (CAMS/CMA), in cooperation with the Meteorological Bureau of Shenzhen Municipality and the Chinese Meteorological Society. The workshop consisted of three days of scientific presentations. The opening keynote lectures highlighted the effect of Madden-Julian Oscillation on East Asia Monsoon revealed by singular value decomposition analysis, field campaigns in South China Sea area focusing on the study of East Asia monsoon circulations and rainfall in the last four decades, and extreme rainfall produced by land-falling tropical cyclones. A total of 91 oral and poster papers were presented. In addition, two short training courses on ensemble forecast were provided. The abstracts volume is available online (http://www.wmo.int/pages/prog/arep/wwrp/tmr/documents/WMOMHR-4AbstractCollection.pdf).

Innovated by the discussions in the MHR-4 Workshop, this paper highlights recent progress on monsoon heavy rainfall research, including topics such as rainfall characteristics and physical mechanisms, field experiment, numerical simulations and model development, forecast methods, and tropical cyclone (TC)-related heavy rainfall. Future research directions and some specific research topics are also proposed.

(1) Physical mechanisms of monsoon heavy rainfall. Heavy rainfall over the monsoon regions is associated with physical processes covering the intraseasonal, synoptic, and mesoscale processes, such as anomalous sea surface temperature over tropical oceans, synoptic features of the monsoon circulation, sea breezes and thunderstorm outflows associated with mesoscale cold pools. Extreme rainfall (>100 mm h^{-1}, >500 mm d^{-1}, even > 1000 mm d^{-1}) over the monsoon regions is often a result of complex interactions among these processes. While few relations between equatorial Pacific sea surface temperature and intensity/frequency of extreme rainfall events over northern Indian have been found, evidences are provided for great influences of sea surface temperature over the tropical Pacific and Indian Ocean on interannual variations of presummer rainfall over South China [3]. Heavy rainfall over Korea during Changma (July–September) is closely associated with continental lows approaching Korea from northwest, confluent system between weakened continental low and North Pacific high, northeastward moving cyclones, disturbances on the edge of the North Pacific high, and high pressure over Northern China. Analysis of rainstorms over northern Taiwan

* Corresponding author.
E-mail address: ylluo@cma.gov.cn (Y. Luo).

https://doi.org/10.1016/j.scib.2019.09.005

island during warm season suggested that the downdraft outflows could change the track of the rainstorm and the location of the heavy rain-affected region, making NWP more challenging. In addition, local surface features (e.g., mountainous topography in northern India and Philippines, urban heat islands over the Pearl River Delta in South China, coastlines and coastal terrains in India and East Asia) play important roles in producing extremely heavy rainfall under favorable environmental conditions provided by the monsoon systems.

(2) Field experiments. Numerous field campaigns have been carried out over the South China Sea to study the East Asian monsoon circulations and rainfall (Fig. 1) during the past four decades. New insights are yielded by these campaigns in a wide range of phenomena and processes associated with East Asian monsoon: winter cold surges, the Borneo vortex, orographic effects, the Meiyu front, mesoscale convective systems, mesoscale convective vortices, the diurnal cycle, and sea surface temperature gradients (Table 1). Progress of the most recent experiment, SCMREX [2], includes physical mechanism studies from large-scale background to rainstorm interior, convection-permitting NWP, and algorithm development and data analysis for remote sensing. Coupling of double low-level jets in the boundary layer and lower-to-middle troposphere [4], synoptic-scale cyclonic and deep-trough anomalies associated with midlatitude Rossby wave train passing by the Tibetan Plateau [5], mesoscale rainband training and bow-echo splitting and re-establishment [6], and urban heat islands [7] are shown to play significant roles in producing the pre-summer heavy rainfall over South China. Positive impacts of assimilating the observational data from the wind profiler network, operational weather radar, lightning detector are demonstrated on predicting convection evolution over inland South China and northern South China Sea [8]. Rain evaporation represented by microphysics schemes is critical for simulating the formation, movement, and morphology of a linear-shaped MCS passing over the SCMREX field campaign [9]. An experimental convection-permitting ensemble prediction system based on the Global/Regional Assimilation and Prediction System is developed for quantitative precipitation forecast (QPF) over southern China. Based on ensemble forecasts using this system, multi-scale characteristics of different-source perturbations and their interactions are investigated [10]. The nonlinear impacts of adding model physics perturbations to initial condition perturbations have the most significant effects on meso-β-scale precipitation perturbations and can effectively improve precipitation prediction.

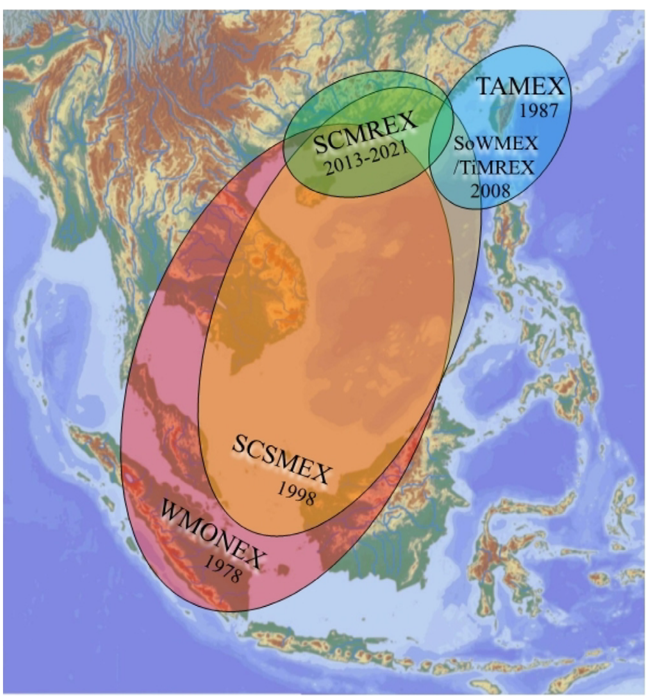

Fig. 1. (Color online) Schematic diagram roughly showing the areas and years of field campaigns over South China Sea aiming at monsoon circulation and rainfall study from 1978 to 2018 (from the opening keynote lecture presented by Richard H. Johnson at MHR-4).

The observing ability over coastal South China has been greatly enhanced by the synthetic observation network. The newly developed instruments include automatic observation stations in different-height buildings over the Guangzhou megalopolis, X-band phased array radars, dual-polarimetric radars, 2DVideo disdrometers, and a Cloud Physics and Heavy Rainfall Field Experiment Base with various-wavelength, vertically pointing cloud-and-precipitation radars. Data quality-control methods and retrieval algorithms are under development to estimate storm-internal dynamic and microphysical properties from observations obtained using these newly deployed sensors [11]. Statistical analysis and case studies (e.g., a super-cell and a linear-shaped MCS) demonstrate promising results.

Field campaigns with high density radiosonde observations in Korea have been led by National Institute of Meteorological Sciences, Korea Meteorological Administration since 2002, targeted on intensive rainfall events during Changma and heavy snowfalls during the cold season. Heavily instrumented aircrafts were utilized by Korea Meteorological Administration from 2008 and by CMA from 2017, aiming at observing the physical properties of aerosols and clouds, as well as atmospheric conditions using dropsondes. These experiences will help more efficient deployment of instrumented aircrafts in future monsoon-rainfall field campaigns, which will provide a valuable data basis for studying aerosol-precipitation-convection interaction and for validating ground-based remote-sensing measurements and products.

(3) Numerical simulations and model development. Convection-permitting simulations with horizontal grid spacings of 1–4 km have been widely used in studies and prediction of monsoon

Table 1
Field campaigns over South China Sea in the study of heavy rainfall from 1978 to 2021.

Field campaigns	Year	Scientific objectives or new insight
The Winter Monsoon Experiment (WMONEX)	1978	Winter cold surges, inter-hemispheric exchanges, near-equatorial convection and its diurnal cycle
The Taiwan Area Mesoscale Experiment (TAMEX)	1987	Meiyu front, mesoscale convective systems (MCSs), orographic effects, local circulations
South China Sea Monsoon Experiment (SCSMEX)	1998	Key processes associated with onset and evolution of southeast Asia summer monsoon
Southwest Monsoon Experiment/Terrain-Influenced Monsoon Rainfall Experiment (SoWMEX/TiMREX)	2008	Terrain effect on the flow and MCSs; MCS dynamics, microphysics, and predictability; mesoscale data assimilation/QPF; convective initiation/diurnal cycle/boundary layer processes
South China Monsoon Rainfall Experiment (SCMREX)	2013–2021	Multi-scale processes governing heavy-rain-producing storms, cloud microphysics, convection-permitting modeling and prediction

heavy rainfall. Numerous studies have demonstrated strong sensitivity of model performance to uncertainties in the initial state and model physical parameterizations in simulations of heavy-rainfall-producing mesoscale convective systems. Efforts are being made to improve numerical model simulation via data assimilation, dynamical core development, and improving physics schemes. Positive impacts of assimilating weather-radar radial velocity and wind profilers' observation over South China [8] have been demonstrated on convection-permitting prediction of convection evolution in monsoon heavy-rainfall events. A new data assimilation method that combines the ARPS Data Assimilation System cloud analysis and Gridpoint Statistic Interpolation assimilation has been developed to construct a rapid refresh assimilation/modeling system over South China. This new data assimilation scheme effectively improves the evolution of pre-typhoon squall lines during the 4-h forecasts. Assimilating lightning observations can also benefit the simulation of storm structure and the associated surface cold pool.

A global nonhydrostatic dynamical modeling system on an unstructured mesh is under development at CAMS [12]. The unstructured mesh enables the possibility of a smooth transition from global to regional modeling in the context of a global model, offering an effective alternative to conventional nested limited-area modeling, which suffers from the problematic treatment of lateral boundaries. A layer-averaged approximation of 3D flow is used as a basis for vertical Eulerian discretization such that the model simulates each layer in a similar manner to the treatment of 2D shallow water flow while permits vertical miscibility. Model evaluation has demonstrated reasonably good performance in dry dynamics associated with multiscale atmospheric wave-like phenomena from planetary waves to mountain gravity waves. The next step is to develop a coherent moist model combining the components of dry dynamics, tracer transport and model physics.

A cloud-aerosol-interacting microphysics scheme is incorporated into the UK Met-Office Unified Model and applied to simulating monsoon heavy rainfall during SCMREX. It is shown that different cloud-droplet numbers in different parts of the domain can be represented by including the processing of aerosol material inside cloud hydrometeors in the Unified Model simulations. Capturing these dependencies is crucial for simulating the organized convections, and affects both the hydrological and radiative impacts of such systems, in a manner consistent with – but not fully replicable by one-way coupled simulations with tuned aerosol concentrations. Another study demonstrates that, in convection-permitting simulations of monsoon heavy rainfall, cloud-fraction diagnosis and microphysical properties of hydrometeor particles have more significant impacts than increasing the number of prognostic variables from single- to double-moment microphysics schemes [13].

The fine-scale sub-daily rainfall characteristics are essential metrics to assess the performance of convection-permitting NWP forecasts within 24 h. By applying metrics such as hourly frequency-intensity structure and diurnal variation, it is found that the European Centre for Medium-range Weather Forecast (ECMWF) model ($\sim$12.5 km) shows a systematic bias in reproducing hourly frequency distributed with intensities, and the heavy rainfall tends to peak too early in the day over south China. The GRAPES_GZ ($\sim$3 km) produces more realistic hourly rainfall characteristics, but some distinct deficiencies are still evident over regions with complex topography. The WRF model (3 km) simulations over eastern China for 10 warm seasons reasonably reproduce the major rainfall characteristics, including seasonal meridional migration, diurnal variation, and climatological characteristics of rain storms (consistent with the findings using the Unified Model [14]). The major deficiency is an overestimation of rainfall intensity and occurrence frequency, especially in the afternoon, which could be partially alleviated by including shallow convective clouds and aerosol effects in the simulations. Moreover, both WRF and Unified Model simulations over Korea suggest an overestimation of ice water content and cloud top height, and a severe underestimation of warm-type heavy rainfall.

(4) Adcances in regional prediction. Productive attempts have been made to improve forecast methods at national and regional operational centers such as the National Meteorological Center (NMC) of CMA, Hong Kong Observatory (HKO), Meteorological Bureau of Shenzhen Municipality, and Meteo-France. The performance of a newly proposed potential forecasting method for short-duration heavy rainfall was demonstrated at the MHR-4 Workshop, by statistical evaluation in rainy season, to be even higher (in terms of verification scores) than the operational short-duration heavy rainfall forecast method at NMC/CMA. HKO has developed deep learning algorithms that improve radar-based rainfall nowcasts, as compared to the existing approach based on tracking radar echoes using optical flow. An enhanced neutral network model has also been developed to retrieve equivalent reflectivity using imagery data from the Himawari-8 satellite. A community version of HKO's nowcasting system has been made available to various National Meteorological and Hydrological Services to support capacity building process and operational rainfall nowcasting services in Asian countries through HKO's Regional Specialized Meteorological Centre (https://rsmc.hko.gov.hk). New post-processing methods to calibrate forecasts from the Ensemble Prediction System (EPS) of ECMWF and its derived products such as Extreme Forecast Index are under active development in the HKO. An ingredients-based approach is employed to all 51 ensemble members of ECMWF EPS to derive probabilistic guidance on potential of thunderstorm and mesoscale diagnostic products that consider favorable factors from conceptual models and forecasters' experiences with respects to dynamics, moisture and atmospheric instability.

In Shenzhen, high spatial-temporal density rainfall observation data are collected in real-time from about 200 automatic weather stations. Based on this dataset the detailed precipitation distribution, various practical service products, and rapid disaster responses become possible. Moreover, equatorial wave theory is promoted to be directly used in operational forecasting, because it reveals the propagating behavior of weather systems in monsoonal/tropical areas and is therefore valuable for early warnings and extended outlooks that are required by stakeholders. It is also recommended that the monitoring of mesoscale outflow boundaries and cold pools should be an important part of the work of forecasters for nowcasting and very short-range forecasting of severe convection.

(5) TC-related heavy precipitation. TC rainfall amount is closely related to TC's inner circulation features (such as small-scale vortex and shear line), environmental influences (interact with monsoon surge and mid-latitude trough, binary TC interaction), and terrain effect particularly coastal topography and mountain range. A global climatology of distributions and extremes of TC rainfall is analyzed based on TRMM (Tropical Rainfall Measuring Mission) satellite data from 1998 to 2014. It is found that the extreme accumulated rainfall events are predominantly in the North Atlantic and West Pacific. Simple linear correlations between accumulated rainfall and TC lifetime for each basin explain 60%–70% of the variance with correlation coefficients greater than 0.8. Climatologically, TC rainfall accounts for approximately 20%–40% of the total rainfall over southeast China during boreal summer. The dominant mode of TC rainfall reveals a dipole pattern over southern southeast China and eastern southeast China. Variations in TC rainfall intensity at interdecadal scale seem to be unrelated to the TC's own intensity change. Interestingly, decreasing total lightning density (based on precipitation radar and passive microwave observa-

tions from TRMM satellite) in the inner core seems to be a signal for TC rapid intensification with a 6–12 h leading time [15]. This finding appears contradictory to the traditional concept that deep eyewall convection promotes TC intensification. One possible reason is that the symmetric inner core in rapidly intensifying TCs may cause a higher degree of glaciation due to more evenly distributed ice particles in the mixed-phase region, leading to less active riming and lightning production. Another reason could be that the more tilted inner convective tower in rapidly intensifying TCs may induce longer discharge distances and thus reduce the probability of lightning production.

Despite the considerable efforts, NWP models still have very limited ability to forecast TC rainfall, especially for the extremely heavy rainfall and rainfall produced around TC landfalling. Efforts are being made to improve the NWP performance by improving representation of TC structure in the initial state. A dynamical-statistical method that combines NWP predicted TC track (using an objective TC Track Similarity Area Index) and statistical information in historic observations is developed to forecast landfalling-TC precipitation [16]. Its application to predicting accumulative rainfall associated with landfalling TCs influencing South China demonstrates the advantages in predicting intense precipitation at large thresholds (i.e., 100 or 250 mm) compared to dynamical models.

(6) Future research directions. Built upon the important progresses in science and prediction of monsoon heavy rainfall, including heavy rainfall associated with tropical cyclones in the monsoon regions, and high-priority research topics proposed by the international monsoon science community, the following directions are recommended for future monsoon-heavy-rainfall research.

(i) Studies on physical mechanism governing monsoon-heavy-rainfall variation and change across a wide range of scales. More detailed studies are needed on how extreme monsoon rainfall will change as the climate warms, how the global warming, large-scale circulation [17], and local urban effects impact the heavy rainfall changes over the densely populated vulnerable urban areas, how anthropogenic and natural aerosols influence monsoon heavy rainfall under various synoptic conditions, what are the relationships of circulations and associated heavy rainfall among different monsoon regions (e.g., South Asia, East Asia, Australia), what are the roles played by land/sea-air interaction in modulating the monsoon circulation and rainfall.

(ii) Studies on forecast technique to improve the monsoon-heavy-rainfall prediction skill. To further reduce initial errors of NWP, more studies are needed to investigate effectiveness of existing data assimilation methods at convection-permitting resolution and to improve data assimilation techniques to more effectively utilize new observations from the new-generation satellites (Himawari-8, FY-4) and ground-based remote sensors, such as dual-Polarimetric and phased-array radars. Detailed analysis using new, integrated observations is recommended to advance the understanding and reduce uncertainties of model physics schemes, particularly those that represent the boundary layer, cloud-precipitation microphysics, and aerosol-cloud interactions. To better represent the unavoidable uncertainties in monsoon-heavy-rainfall forecast, great efforts need to be made on convection-permitting ensemble forecast, including developing perturbation methods especially model physics perturbations for various monsoon regions, examining the nonlinear impacts of different-source perturbations, developing EPS diagnostics in blending with radar and satellite nowcasts. Also needed is conducting systematic QPF evaluation for convection-permitting simulation/prediction made in the operational centers over the monsoon regions, and carrying out forecasting experiments to test new forecast techniques and conceptual models.

(iii) Further field campaigns and sharing of data products. Studies would include conducting and coordinating field observations over the monsoon regions, using three-dimensional operational observing networks and portable instruments (instrumented aircrafts and various radars) to obtain integrated datasets. More efforts are needed to make standard data products that would be easily accessed by broad scientists and forecasters.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Key Basic Research and Development Program of China (2018YFC1507400), the National Natural Science Foundation of China (41775050), and the Basic Research & Operation Funding of Chinese Academy of Meteorological Sciences (2017Z006). The contributions by Kalli Furtado to this work were supported by the UK-China Research & Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund.

References

[1] Li W, Jiang ZH, Zhang XB, et al. Additional risk in extreme precipitation in China from 1.5 °C to 2.0 °C global warming levels. Sci Bull 2018;63:228–34.
[2] Luo YL, Zhang RH, Wan QL, et al. The Southern China Monsoon Rainfall Experiment (SCMREX). Bull Am Meteorol Soc 2017;98:999–1013.
[3] Yuan CX, Liu JQ, Luo JJ, et al. Influences of tropical Indian and Pacific oceans on the interannual variations of precipitation in the early and late rainy seasons in South China. J Clim 2019;32:3681–94.
[4] Du Y, Chen GX. Heavy rainfall associated with double low-level jets over Southern China. Part II: convection initiation. Mon Weather Rev 2019;147:543–65.
[5] Huang L, Luo YL, Zhang DL. The relationship between anomalous presummer extreme rainfall over South China and synoptic disturbances. J Geophys Res 2018;123:3395–413.
[6] Liu X, Luo YL, Guan ZY, et al. An extreme rainfall event in coastal South China during SCMREX-2014: formation and roles of rainband and echo trainings. J Geophys Res 2018;123:9256–78.
[7] Wu MW, Luo YL, Chen F, et al. Observed link of extreme hourly precipitation changes to urbanization over coastal South China. J Appl Meteorol Climatol 2019;58:1799–819.
[8] Zhang X, Luo YL, Wan QL, et al. Impact of assimilating wind profiling radar observations on convection-permitting quantitative precipitation forecasts during SCMREX. Weather Forecast 2016;31:1271–92.
[9] Qian QF, Lin YL, Luo YL, et al. Sensitivity of a simulated squall line during SCMREX to parameterization of microphysics. J Geophys Res Atmos 2018;123:4197–220.
[10] Zhang XB. Multi-scale characteristics of different source perturbations and their interactions for convection-permitting ensemble forecasting during SCMREX. Mon Weather Rev 2019;147:291–310.
[11] Liu L, Ruan Z, Zheng JF. Comparing and merging observation data from Ka-band cloud radar, C-band frequency-modulated continuous wave radar and ceilometer systems. Remote Sens 2017;9:1282.
[12] Zhang Y, Li J, Yu RC, et al. A layer-averaged nonhydrostatic dynamical framework on an unstructured mesh for global and regional atmospheric modeling: model description, baseline evaluation and sensitivity exploration. J Adv Model Earth Syst 2019;11:1685–714.
[13] Furtado K, Field PR, Luo YL, et al. Cloud microphysical factors affecting simulations of deep convection during the presummer rainy season in Southern China. J Geophys Res Atmos 2018;123:10477–505.

[14] Li PX, Furtado K, Zhou TJ, et al. The diurnal cycle of East Asian summer monsoon precipitation simulated by the Met Office Unified Model at convection-permitting scales. Clim Dyn 2018. https://doi.org/10.1007/s00382-018-4368-z.
[15] Xu WX, Rutledge SA, Zhang WJ. Relationships between total lightning, deep convection, and tropical cyclone intensity change. J Geophys Res Atmos 2017;122:7047–63.
[16] Ren FM, Qiu WY, Ding CC, et al. An objective index of tropical cyclone track similarity and its preliminary application in the prediction of the precipitation associated with landfalling tropical cyclones. Weather Forecast 2018;33:1725–42.
[17] Hu YY, Han H, Chen Z. Widening and weakening of the Hadley circulation under global warming. Sci Bull 2018;63:640–4.

Yali Luo received her Ph.D. degree at University of Utah, United States in 2003. She is currently the chief scientist of the Southern China Monsoon Rainfall Experiment (SCMREX), the WMO/WWRP Research & Development Project and a senior scientist at the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China. Her research mainly focuses on convective storms and extreme weather.