BAMS Article

AsiaPEX

Challenges and Prospects in Asian Precipitation Research

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ABSTRACT: The Asian Precipitation Experiment (AsiaPEX) was initiated in 2019 to understand terrestrial precipitation over diverse hydroclimatological conditions for improved predictions, disaster reduction, and sustainable development across Asia under the framework of the Global Hydroclimatology Panel (GHP)/Global Energy and Water Exchanges (GEWEX). AsiaPEX is the successor to GEWEX Asian Monsoon Experiment (GAME; 1995–2005) and Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI; 2006–16). While retaining the key objectives of the aforementioned projects, the scientific targets of AsiaPEX focus on land–atmosphere coupling and improvements to the predictability of the Asian hydroclimatological system. AsiaPEX was designed for both fine-scale hydroclimatological processes occurring at the land surface and the integrated Asian hydroclimatological system characterized by multiscale interactions. We adopt six approaches including observation, process studies, scale interactions, high-resolution hydrological modeling, field campaigns, and climate projection, which bridge gaps in research activities conducted in different regions. Collaboration with mesoscale and global modeling researchers is one of the core methods in AsiaPEX. We review these strategies based on the literature and our initial outcomes. These include the estimation and validation of high-resolution satellite precipitation, investigations of extreme rainfall mechanisms, field campaigns over the Maritime Continent and Tibetan Plateau, areas of significant impact on the entire AsiaPEX region, process studies on diurnal- to interdecadal-scale interactions, and evaluation of the predictabilities of climate models for long-term variabilities. We will conduct integrated observational and modeling initiative, the Asian Monsoon Year (AMY)-II around 2025–28, whose strategies are the subregional observation platforms and integrated global analysis.

KEYWORDS: Asia; Precipitation; Atmosphere-land interaction; Field experiments

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Asian terrestrial precipitation, a prominent component of the global water and energy cycles, is an important driver of general atmospheric circulation (Chang et al. 2017, 2018) and supports more than 4 billion people who have developed diverse lives and cultures. Under the tropical and monsoon Asian climate, Asian precipitation is characterized by considerably diversified spatiotemporal patterns from arid to the wettest weather. It ranges across a wide spectrum of climates, including perpetually hot and humid tropics, monsoon climate with seasonal contrasts, and the cold and harsh climates of high mountains with even glaciers. Such diversity creates many challenges for understanding Asian precipitation. Climate modeling, which reflects an integral understanding of the science of climate, has difficulty reproducing the Asian climate (Sperber et al. 2017).

Global warming threatens Asian society, which is known to inhabit one of the regions most vulnerable to climate change worldwide. Recently, from the perspective of the global monsoon, the difference in response of the Asian monsoon to climate change from that of other regional monsoons has been clarified (Endo and Kitoh 2014). The increasing intensity and frequency of heavy rainfall events, heatwaves, and severe droughts resulting from climate change, have caused significant disasters and economic losses (Min et al. 2011; Qiu 2013). Efforts to improve our understanding of monsoon onset and withdrawal, rainfall extremes, and changes in circulation intensity, are currently of critical importance (Wang et al. 2021).

A new Asian hydroclimatological project focusing on terrestrial precipitation, the Asian Precipitation Experiment (AsiaPEX) was launched in 2019. Its science plan has been submitted to the Global Hydroclimatology Panel (GHP) under the Global Energy and Water Exchanges (GEWEX)/World Climate Research Programme (WCRP) framework. Now the science plan is under review, and it is officially listed as a prospective Regional Hydrological Project (RHP), which is expected to be a full RHP after review process of the science plan.

AsiaPEX is the successor of two GEWEX ex-RHPs, namely, the GEWEX Asian Monsoon Experiment (GAME; 1995–2005; Yasunari 2001) and the Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI; 2006–16; Matsumoto 2018), which have been at the forefront of international Asian monsoon hydroclimatological research since the 1990s. In this paper, we describe the project design, initial findings and their impacts on Asian hydroclimatological research, and prospective implementation strategies, including coordinated observational and modeling initiatives.

The GAME project focused on examining the impacts that land surfaces have on Asian monsoon variability over the Eurasian continent. This epoch-making project elucidated land–atmosphere coupling in the Asian monsoon system, thereby facilitating new international collaborations and observational platforms. A coordinated observation initiative was conducted in 1998 to generate data on the roles of land surfaces over subseasonal to seasonal time scales. GAME was conducted region-oriented research strategy.

Based on the achievements of GAME, the MAHASRI project targeted the predictability of the Asian monsoon system. The MAHASRI project elucidated the impact of winter monsoons in South and Southeast Asia (Yokoi and Matsumoto 2008; Chen et al. 2012). This project also advanced our understanding of the climatological and interannual variations in monsoon onset in Southeast Asia (Akasaka 2010; Nguyen-Le et al. 2014; Akasaka et al. 2018), suggesting an enhanced impact from ENSO. Diverse regional precipitation seasonality was also extensively described for South Asia (Fukushima et al. 2019). After considerable flood damage in 2011 in Thailand, real-time monitoring and flood prediction systems were implemented in the Chao Phraya River basin (Hanasaki et al. 2014). Continuous collaborations with Asian operational agencies and various scientific communities since the GAME period have strongly stimulated research activities in Asian countries. We can develop our activities on international alignments through collaboration with empowered research community in these countries. The MAHASRI project was the central component of the Asian Monsoon Years (AMY) program (Matsumoto et al. 2017), the intensive observing period (IOP) of which was from 2008 to 2010.

The primary scientific targets of GAME and MAHASRI were land–atmosphere coupling and improvements of the predictability. They are the fundamental aspects of the Asian hydroclimatological system, which is a coupled ocean–land–atmosphere system (Peng et al. 2018; Turner et al. 2020), occurring at multiple temporal scales of intraseasonal–seasonal–interannual–interdecadal time scales (Turner and Wang 2017). Embedded in this multiscale system, diurnal cycles of precipitation and circulation play essential roles (Chen 2020; Fujinami et al. 2017, 2021; Terao et al. 2006; Ohsawa et al. 2001). Among them, land–atmosphere coupling is a key in climate predictions at subseasonal to seasonal time scales (S2S; Mariotti et al. 2018). We will target these issues, which still remain at the center of many research initiatives because these issues are intrinsic to the understanding of the Asian hydroclimatological system.

Currently, research circumstances and objectives are changing rapidly. Global warming has and will have a strong impact on Asian precipitation under Asian monsoon system (Kamae et al. 2014; Roxy et al. 2015). Therefore, developing detections and future projections of change in precipitation across the Asian continent is an urgent task (Maharana et al. 2021). In contrast, a rapidly increasing amount of data and research methods are available, which facilitate the development of research activities using global observational datasets with global and regional modeling. These datasets must be validated by clear observational evidence.

Based on the current research status, we discuss the most significant feature of AsiaPEX. We pursue a "bottom-up" research design to understand multiscale hydroclimatological systems, characterized by interactions within fine-scale hydroclimatological land–atmosphere coupling processes occurring at the ground surface, the “bottom.” These scales cannot be solely examined using remote sensing datasets and models. As will be discussed in the following sections, we engaged in algorithm development and validation in remote sensing analysis (Shige et al. 2013; Hirose and Okada 2018). We constructed model applications at finer spatiotemporal resolutions to obtain the actual physics of hydroclimatological processes (Sugimoto and Takahashi 2017; Sugimoto et al. 2021). For scale interactions, we focused on diurnal variation that occurs at the base of the land–atmosphere coupling (Fujinami et al. 2021, 2022). Hydrological modeling incorporated anthropogenic impacts, which must be evaluated at the finest scales (Hanasaki et al. 2014). The design of the in situ observation campaign is a central function of AsiaPEX, which was implemented in field campaigns and modeling initiatives to obtain the actual land–atmosphere coupling physics occurring at the “bottom.” AsiaPEX is characterized by collaboration between these “bottom-up” designs and “top-down” designs such as climate projections, S2S predictability studies, and studies on ENSO–monsoon system.

Distinct role of studies in hydrological processes

The unique approach of AsiaPEX is its design as a complement to climate modeling, focusing on understanding the multiscale processes in the Asian hydroclimatological system, in which hydrological processes interact with the atmosphere at the ground surface.

Land surface hydrology and water resource systems in this region have distinct characteristics. Based on Musiake (2003), the key characteristics are as follows. The first group of characteristics is geomorphology or geology. River basins in this region tend to have upstream mountainous areas often characterized by steep slopes, high sediment yield, and the cryosphere in high mountains. Abundant and intense precipitation exacerbates slope failure, landslides, and debris flows. Many of the alluvial plains formed via sediment deposition. Water systems in vast low-lying alluvial plains are vulnerable to ongoing sea level rise and potentially increasing storm surges (e.g., Ikeuchi et al. 2017). These characteristics have shaped the survival patterns of the humans living in these regions, which include paddy fields for rice farming and large/extended levees such that they can endure regular periods of flooding.

The second group is related to the dense population and vibrant human activity in Asia. As the global hydrological cycle is largely affected by human intervention in the Anthropocene (Oki and Kanae 2006), hydrological processes in this region should be analyzed from a human–water system perspective, which has recently been termed sociohydrology.

The third group is the “climate,” which can first be characterized by abundant and intense rainfall during the wet season. However, dry areas also occur adjacent to wet areas. Flood mitigation and water security must be simultaneously managed in the Asian monsoon region (e.g., Mateo et al. 2014) because the wet season and crop growth season coincide (Endo et al. 2018). This contrasts with goal six of the United Nations Sustainable Development Goals on water, in which flooding is not explicitly included.

In AsiaPEX, land surface processes studies and their application studies are carried out by taking into account the above characteristics of the Asia; for example, land surface modeling will be upgraded in a manner to comprehensively represent the above characteristics.

General objectives and approaches

Based on the discussion above, the general objective of AsiaPEX is to enhance our understanding of terrestrial precipitation over diverse hydroclimatological conditions for improved predictions, disaster reduction, and sustainable development. We primarily adopt an approach-oriented research strategy, which bridges the gaps in the region-oriented research strategy used in GAME. This is because research communities in Asian countries are

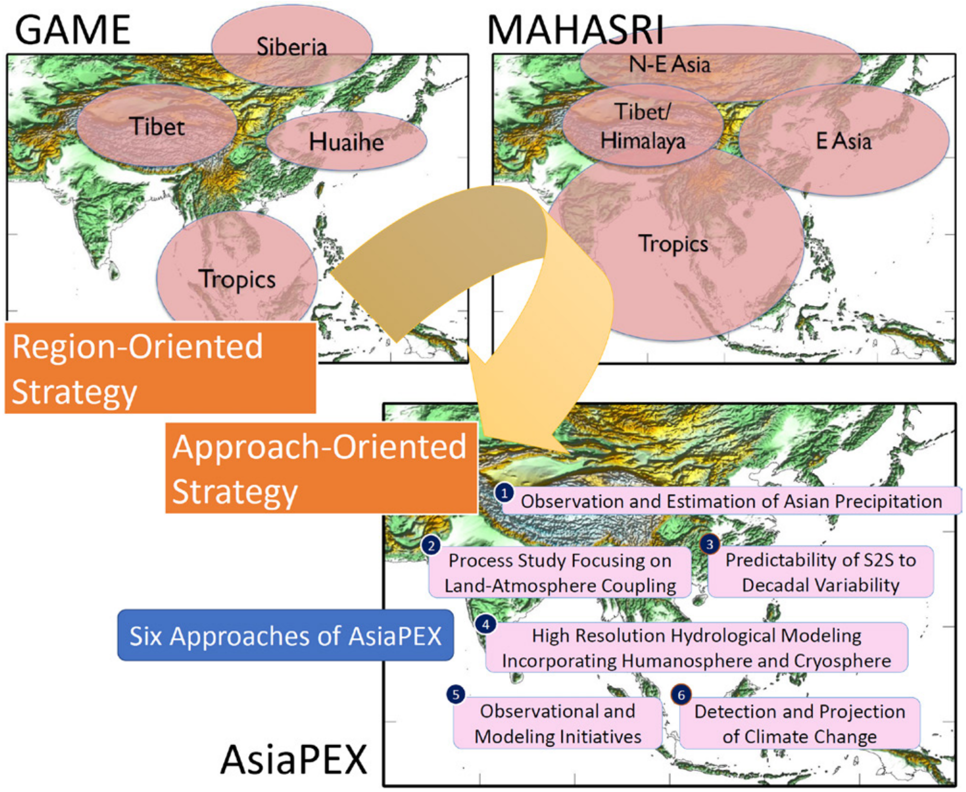

Fig. 1. Research developed through the succeeding Regional Hydrological Projects (RHPs) from GEWEX Asian Monsoon Experiment (GAME) to the Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI). In GAME period, a region-oriented research strategy was utilized. MAHASRI project further cultivated and empowered research communities in these countries. The AsiaPEX adopts an approach-oriented strategy with six scientific approaches confirmed in the Kick-off Conference in August 2019.

empowered, and scientists now tend to conduct research at the hemispheric scale, i.e., not limited to a specific region (Fig. 1).

At the 2019 AsiaPEX conference (Terao et al. 2020), we discussed and finalized six scientific approaches: 1) the observation and estimation of the variation and extremes in Asian land precipitation; 2) process studies of Asian land precipitation with respect to diverse land–atmosphere coupling; 3) understanding and predicting variability in the Asian monsoon from subseasonal to interdecadal time scales; 4) high-resolution land surface hydrological modeling and monitoring, which incorporates the impacts of water withdrawal, agriculture, vegetation, and cryosphere; 5) field campaigns for coordinated observations and modeling initiatives; and 6) the detection and projection of climate change impacts on the regional precipitation across Asia. In the following four sections, we will describe our research strategies.

AsiaPEX observational studies

Multilateral projects attempt to fill observational gaps in Asian regions and reduce any deficiencies associated with precipitation datasets from multiple perspectives, e.g., in situ measurements and remote sensing observations. International collaborations through AsiaPEX will promote collection of more precipitation data, validate the data from the multiple instruments, and bring comprehensive understanding of the precipitation processes over the Asian monsoon regions.

Although daily precipitation datasets using national observation networks of rain gauges have been produced for nearly the entire AsiaPEX region (e.g., APHRODITE-2; Yatagai et al. 2019) or specific countries (e.g., VnGP; Nguyen-Xuan et al. 2016), ground-based measurements using rain gauges and weather radars have been updated to fill the observational gaps. The Himalaya Precipitation Study (HiPRECS) observes precipitation behaviors with rain gauges and automatic weather stations (AWSs), and examines the mechanism causing complex diurnal variations in precipitation over the southern slope of the Himalayan Range (Figs. 2a–c) (Fujinami et al. 2021). Over the past 15 years, 45 rain gauge sites in Bangladesh and northeastern India have been constructed to observe torrential precipitation conditions during multiple field campaigns (Murata et al. 2011; Terao et al. 2017). In Vietnam, AWS and weather radar networks covering the entire country were updated by the Vietnam Meteorological and Hydrological Administration (VNHMA) and the Japan International Cooperation Agency (JICA) (Tonouchi et al. 2020). The Borderless Radar Information Networking over South and Southeast Asia (BRAIN) project is ongoing for quantitative rainfall estimation over large areas of mainly seven countries in the AsiaPEX region (Kamimera 2020). These ground-based measurements or estimates can provide better perspectives on Asian monsoon precipitation.

International data rescue before 1950 is a key project (Allan et al. 2011). The past 200 years of climate data in the AsiaPEX region are currently being reconstructed to aid in understanding climate variability and extreme events based on historical analog data records archived (e.g., data rescue; Kubota et al. 2021; the Twentieth Century Reanalysis (20CR); Slivinski et al. 2019).

Satellite-derived datasets are essential to catch the geographical anomalies of precipitation. The data obtained from the Tropical Rainfall Measuring Mission Precipitation Radar (TRMM PR) and Global Precipitation Measurement *Core Observatory* Dual-frequency Precipitation Radar (GPM DPR) can be used to extract geographically induced precipitation characteristics. Hirose and Okada (2018) constructed a global TRMM PR precipitation climatology dataset with a 0.01° spatial resolution (Fig. 2d). Yamaji et al. (2020) developed the global climatological drop size distribution estimation using GPM DPR, thus facilitating studies on precipitation mechanisms and validations of remote sensing data. Discrepancies have been particularly found among products for orographic precipitation and extreme events (Hirose et al. 2021; Masunaga et al. 2019; Nodzu et al. 2019), such as sensor sensitivity and surface clutter interference. Terao et al. (2017) pointed out prominent underestimations in the TRMM PR in northeastern India (Fig. 2e), characterized by the highest overland precipitation amounts (Kiguchi and Oki 2010). To reveal the cause of this underestimation, Murata et al. (2020) examined the rainfall characteristics over this region near Cherrapunjee using disdrometers. Focusing on near-ground process and the spatial and temporal characteristics of precipitation, satellite-based data should be validated over complex topography especially in highlands (Figs. 2f–h).

Satellite-borne radar observation projects (TRMM and GPM) have facilitated further understanding of Asian terrestrial precipitation. Shige et al. (2004) developed a new method to evaluate the vertical thermodynamic effect of convective clouds based on research on the heating profiles of different types and stages of precipitating clouds in the tropics (Mapes and Houze 1995). Vertical structures of precipitating clouds have been investigated using the TRMM radar echo profiles (Hamada et al. 2014; Shige and Kummerow 2016). These TRMM observations have also enabled the analysis of distribution of different cloud types in Asian regions (Romatschke and Houze 2011).

AsiaPEX process studies

This section discusses process studies (Sprintall et al. 2020) focusing on specific crucial physical processes that penetrate Asian hydroclimatological systems. In the first subsection, we discuss scale interactions. They are key concepts for understanding climate systems (Kuettner and Parker 1976). The second subsection focuses on land–atmosphere coupling,

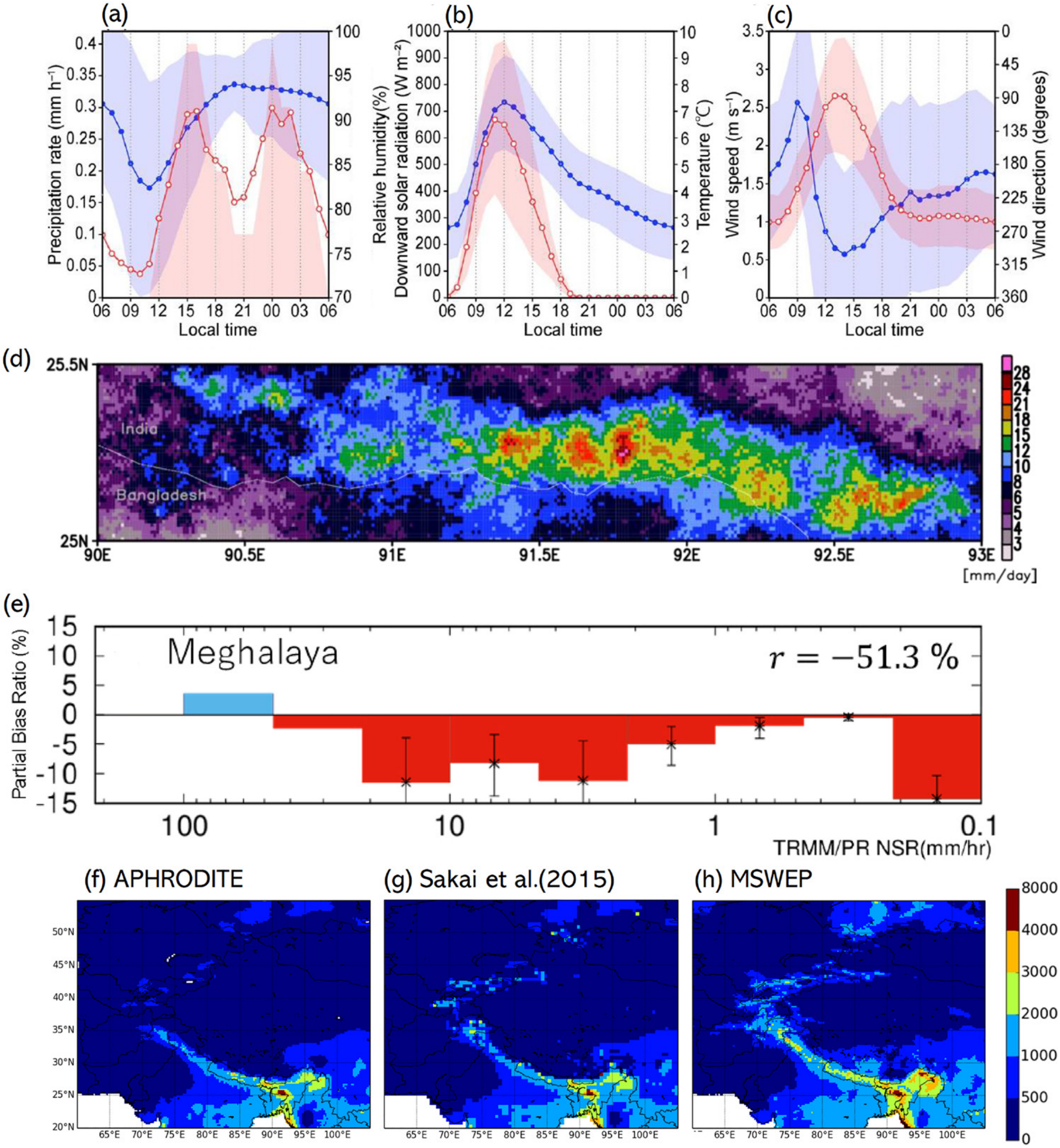

Fig. 2. **(a)–(c) Observations from June to September 2016–18 using AWS (Sunako et al. 2019) installed on the southern slope of the Himalayan Range in the Rolwaling valley of eastern Nepal at 4,806 m above mean sea level near the glacier (27.84°N, 86.49°E; Fujinami et al. 2021). Red (blue) lines indicate unconditional precipitation rate (relative humidity), downward shortwave radiation (surface air temperature), and wind speed (wind direction), respectively. Shading indicates the quartile range for precipitation and ±1 standard deviation for other variables. (d) Climatological precipitation estimates around the southern slope of the Meghalaya Plateau from the TRMM PR data, with a spatial resolution of 0.01° from 1998 to 2013 (Hirose and Okada 2018). (e) Validation of the TRMM PR precipitation by precipitation intensity against six tipping-bucket rain gauges installed on the southern slope of the Meghalaya Plateau in the region of 25.21°–25.31°N, 91.58°–92.12°E, including Cherrapunjee, from 2006 to 2013 (Terao et al. 2017). Error bars indicate the 95% bootstrap confidence interval. The bias ratio of TRMM PR is shown as *r* in the upper-right corner. Comparison of three different mean annual precipitation estimates (Watanabe et al. 2019) from (f) APHRODITE (Yatagai et al. 2012), (g) "Sakai rainfall" (Sakai et al. 2015), and (h) MSWEP (Beck et al. 2017).**

a physical process that drives the Asian hydroclimatological system. Recent research on global energy and water exchange cycle strongly suggests the crucial role of the land surface in global hydroclimatological systems (Mariotti et al. 2018). Extreme events have emerged as urgent physical processes that must be understood and predicted to reduce the disaster risks for Asian residents (IPCC 2012). The last subsection discusses the high mountain cryosphere, which impacts the climate via land–atmosphere coupling, acting as a water tower for a substantial number of continental Asia residents (Immerzeel et al. 2020). Large uncertainties in precipitation estimations remain, especially for high mountainous areas.

Spatiotemporal interactions. Much of the precipitation in the Asian monsoon region occurs as a result of mixed interactions among various atmospheric variabilities with widely ranging spatiotemporal scales. Although the separation of each component is not necessarily unambiguous, each component may be characterized by their own typical time scales: diurnal cycle (~1 day), synoptic-scale disturbances (3–7 days), quasi-biweekly oscillation (QBW; ~10–20 days), boreal summer intraseasonal oscillation (BSISO; 30–90 days), interannual variability (~2–10 years), and multidecadal variability (~>10 years). Thus, for a complete understanding of monsoon precipitation, we must understand not only the dynamics and physics of each component, but also the interaction processes among each component. In this subsection, we briefly review the current understanding of such interaction processes.

Diurnal precipitation can explain a large fraction of the total overland summer rainfall and rainfall on the surrounding oceans in the Asian monsoon domain (Ohsawa et al. 2001; Dai et al. 2007; Kikuchi and Wang 2008), including high rainfall areas such as the southern slopes of the Himalayan range; the Meghalaya Plateau; and coastal regions of western India, western Myanmar, and the Maritime Continent (Hirose et al. 2008; Romatschke et al. 2010; Ogino et al. 2016; Fujinami et al. 2017; Fig. 3a). Synoptic-scale disturbances and intraseasonal oscillations strongly modulate diurnal variation (e.g., BSISO and QBW) (Singh and Nakamura 2010; Sato 2013; Deshpande and Goswami 2014; Fujinami et al. 2017; Fig. 3a).

Synoptic-scale low pressure systems (LPSs) are also essential rain-bearing systems and consequently induce a significant fraction of extreme precipitation events (Houze et al. 2011; Webster et al. 2011; Hurley and Boos 2015; Fujinami et al. 2020; Takahashi et al. 2015; Bohlinger et al. 2017). The development of LPSs, sometimes transforming into a tropical cyclone (TC), often occurs under a favorable large-scale environment (e.g., a humid lower troposphere with weak vertical wind shear; Kikuchi and Wang 2010; Yanase et al. 2012; Ditchek et al. 2016). As the QBW and BSISO highly modulate the environment, these intraseasonal variabilities largely determine the behavior and fate of LPSs (Goswami et al. 2003; Straub and Kiladis 2003; Krishnamurthy and Ajayamohan 2010; Hatsuzuka and Fujinami 2017; Fig. 3b). However, the detailed processes by which the QBW and BSISO affect LPSs remain an open question (Cohen and Boos 2016; Fujinami et al. 2020; Takahashi et al. 2015).

Longer-time-scale variabilities significantly modulate these subseasonal variabilities. For instance, recent studies have shown that ENSO has substantial control on determining the active region of the BSISO (Dwivedi et al. 2015; Liu et al. 2016; Wu and Cao 2017; Li and Mao 2019). Further, longer time-scale variability, such as the Atlantic multidecadal oscillation (AMO), Pacific decadal oscillation (PDO), and Southern Annular Mode, may also contribute to the interannual variability in Asian monsoon precipitation (Chattopadhyay et al. 2015; Prabhu et al. 2016). Asian land precipitation is significantly dominated by the interdecadal Pacific oscillation (IPO; Ha et al. 2020a). However, previous studies have not revealed how these multidecadal variabilities account for the multidecadal variability observed in the Asian monsoon (Krishnamurthy and Goswami 2000; Goswami et al. 2015).

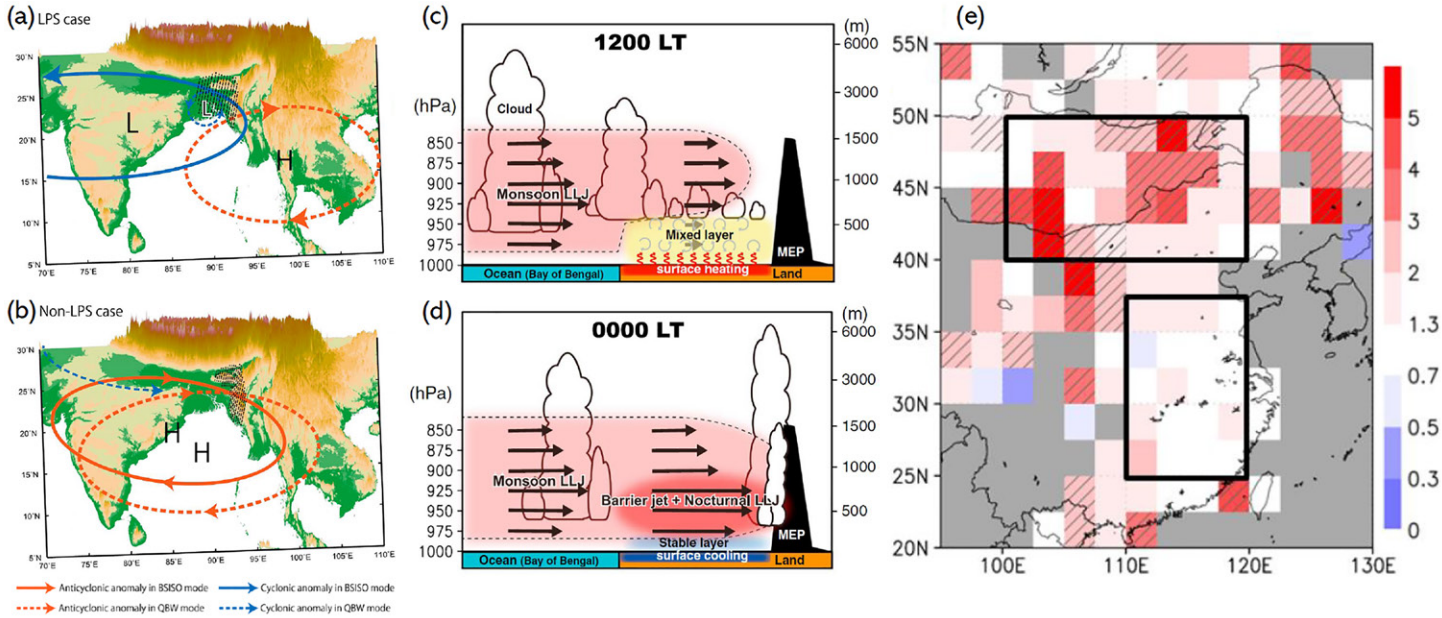

Fig. 3. Recent advances in scale interactions and land surface–convection coupling. Hatsuzuka and Fujinami (2017) analyzed active precipitation phases of the quasi-biweekly oscillation (QBW) mode over Bangladesh to obtain different types of (a) low pressure system (LPS) cases and (b) non-LPS cases. They showed that the differences between these cases could be explained by varying impacts from the westward-propagating anticyclonic QBW mode from the western Pacific and the boreal summer intraseasonal oscillation (BSISO) mode. Fujinami et al. (2017) showed that the large-scale barrier jet, which develops along the Arakan Mountains, is controlled by the change in turbulent frictional forces within the boundary layer, owing to shallow convection diurnal variability. (c) During the day, convection in the mixing layer suppresses the wind speed. (d) At night, wind speeds accelerate, owing to the development of the stable layer. Teramura et al. (2019) analyzed the formation mechanism of mesoscale convective systems (MCSs) over the East Asian landmass. (e) The surface heterogeneity impact (SHI) index measures the impact that land surface heterogeneity has on MCS formations. Hatching indicates the grid where the SHI index shows significant increase associated with the increase of land surface heterogeneity. This shows the relative importance of surface temperature heterogeneity for convective systems.

Land–atmosphere coupling. The influence of land surface temperature and soil moisture heterogeneities on hydroclimatology in Asia has received attention for years, as well as the land-use/land-cover changes. The local-scale heterogeneity of land surface conditions contributes to the formation of mesoscale convective systems over East Asia (Teramura et al. 2019; Fig. 3e), similar to those in the Sahel region, North America, and the Tibetan Plateau. Several studies have discussed how soil moisture affects the diurnal cycles of precipitation over South and Southeast Asia (Ono and Takahashi 2016; Sugimoto and Takahashi 2017). The diurnal cycle of boundary layer heating accelerates low-level monsoon flow, causing a nocturnal precipitation peak around the Meghalaya Plateau (Fujinami et al. 2017; Figs. 3c,d) and the Himalayas (Fujinami et al. 2021). Precipitation variability at a subseasonal to seasonal time scale and regional-scale land surface conditions, characterized by snow cover (Sato and Nakamura 2019) and soil moisture (Erdenebat and Sato 2016), plays a role in maintaining and strengthening the positive feedback between the land and atmosphere, resulting in a severe precipitation deficit and drought events in Northeast Asia. Cloud-resolving model simulations showed the importance of orographic effects that encourage moisture transport and its convergence leading to local-scale precipitation (Lin et al. 2018; Sugimoto et al. 2021).

Surface and subsurface soil moisture also plays a crucial role in Earth's hydrometeorological cycle at the land–atmosphere interface (Senevirante et al. 2010). Very limited high spatiotemporal surface and subsurface in situ soil moisture observations have been continuing, using sensor networks, a telemetric sensor network, and hydrological models over core South Asia (Bogena et al. 2013; Foolad et al. 2017; Srivastava et al. 2015), where soil moisture variability is significantly complex due to strong coupling between soil moisture and surface temperature (Ganeshi et al. 2020, 2023). Monitoring sites of soil temperature and soil moisture were also established over the Tibetan Plateau to quantify uncertainties in satellite products and models (Su et al. 2011). Then, a new land model was developed to calculate the thawing–freezing process of permafrost over the plateau (Yu et al. 2018).

Extreme events. Enhanced uncertainties and unprecedented variability in the evolution of weather and climate patterns, their intensity and duration, augment weather and climate extremes. Climate change will likely lead to more frequent and intense extreme weather events (IPCC 2021). Their prediction at sufficient lead time and accuracy is challenging (Das 2022). The role of scale interactions and land–atmosphere coupling in the evolution of weather and climate extremes, their intensity, frequency, and duration, needs to be explored.

Abnormal weather, such as severe rainfall and heatwaves, has recently had a significant toll on Asia, both in terms of human and economic losses. Temperatures in India and China broke records in 2018 and 2019, reaching 50°C in India in June 2019. In July 2018, a record-breaking heatwave affected large areas of Japan, the Korean Peninsula, and China.

Cloudburst events have increased over the Himalayas. The southern plains of the Himalayas have experienced severe storms, including an increased frequency of dust storms over the semiarid zones of western India (e.g., Sarkar et al. 2019), enduring squall lines over the Indo-Gangetic plains, and tornados over east-northeastern parts of the Indian subcontinent (Department of Hydrology and Meteorology 2019). Rainfall extremes cause flooding over the region (Krishnan et al. 2020; Dimri et al. 2017). In most Asian countries, flooding has been a major concern in recent decades.

Drought conditions can aggravate poverty, inflame regional conflicts, and damage agriculture. The climate model projections also highlight the increase of drought, its area, frequency, and severity (Krishnan et al. 2020). Improved forecasting is required to better prepare for droughts, which can warn people in advance.

Observations from the projects like HiPRECS, BRAIN, TRMM, and GPM (mentioned in the previous section) can be used for the process studies of the extreme weather (their spatiotemporal interactions, land–atmosphere coupling, and development of more accurate warning and prediction system).

High mountain cryosphere. Many studies have shown that the Asian monsoon strongly affected by the Asian cryosphere, including the seasonal snow cover, glaciers, and permafrost. Snowmelt runoff predominantly contributes to the water resources of many river basins within High Mountain Asia (HMA). The total snowmelt contribution to basins at >2,000 m MSL ranges between 65% and 72% for the Syr Darya, Amu Darya, Indus, and Brahmaputra Rivers while it is approximately 43% for the Ganges (Armstrong et al. 2019). Satellite-based studies have reported different trends in the snow-covered area (SCA) over HMA, in which the winter SCA has increased in westerly dominated basins since 2000; it has either decreased or remained stable elsewhere (Immerzeel et al. 2009; Tahir et al. 2016). The snow water equivalent decreases from spring to summer, while it significantly increases in some areas of the Pamir–Tien Shan region in winter (Smith and Bookhagen 2018). Glaciers in the HMA are considered water reservoirs for downstream communities of more than 1 billion people (Immerzeel et al. 2020). The availability of glacial meltwater is essential during the dry season and drought periods. Although the rate of shrinking of HMA glaciers is comparable to that of the global mean (Hugonnet et al. 2021), their spatial distribution is heterogeneous (Brun et al. 2017), which can be attributed to the spatial and temporal variability of the monsoon (Sakai and Fujita 2017), and changes in snow accumulation (Smith and Bookhagen 2018).

Although the role of permafrost in the water cycle and its interaction with the monsoon remain unclear, field studies have observed its decline (Fukui et al. 2007). Based mostly on research from other regions or continents, Gruber et al. (2017) concluded that widespread permafrost thawing will almost certainly occur in the future. This persistent change in subsurface conditions will affect sediment budgets, geohazards, hydrology, water quality, and vegetation. Similar to the shrinking rate of HMA glaciers, permafrost thawing may also be heterogeneous, owing to the spatial and temporal variability of the monsoon, which requires more data.

There are some discrepancies in the changes in the cryospheric elements addressed above, which are mainly due to heterogeneous terrain and dynamic multiatmospheric phenomena, including monsoon variability prevalence in the region. Therefore, there is an urgent need for an interdisciplinary study on the Asian monsoon in relation to the HMA cryosphere.

Modeling studies in AsiaPEX

Modeling the Asian monsoon remains a challenging problem given the complexity of the multiscale interactions and the interactions among climate subsystems, and uncompleted representation of the terrain (Sperber et al. 2017). Recent analyses have shown that certain state-of-the-art climate models can predict Asian summer monsoon rainfall more than 1 year in advance (Takaya et al. 2021), wherein the key aspect is the ability to reproduce the ocean–atmosphere interactions such as ENSO–Indo–western Pacific Ocean capacitor (IPOC) mode (Xie et al. 2009; Terao and Kubota 2005). However, problems related to land–atmosphere interactions and long-term climate predictions remain the major issues in modeling studies. We discuss here challenges and efforts for regional and global modeling, and climate projection.

Regional modeling collaborations. To advance the regional modeling capability, the Coordinated Regional Climate Downscaling Experiments (CORDEX) was developed over regions of Asia under WCRP. Coordination of the intensive observation initiative of AsiaPEX and CORDEX experiment will benefit understanding of the Asian hydroclimatological system. The international partnership promoted CORDEX to produce an ensemble of high-resolution past and future climate projections at the regional scale. The CORDEX East Asia has provided new insights into the impact of the Tibetan Plateau on the Asian hydroclimatological system (Niu et al. 2021; Tang et al. 2017). The CORDEX South Asia program has significantly contributed to evaluations of the past and future climates in complex regions, such as the Hindu Kush Himalaya (HIMAP; Sanjay et al. 2017; Krishnan et al. 2019).

The new CORDEX Flagship pilot study, i.e., the Convection-Permitting Third Pole (CPTP), was launched in 2019, aiming to conduct nonhydrostatic RCMs with high-resolution (<10 km) climate modeling (Zhou et al. 2021). A downscaling project, using a nonhydrostatic regional climate model system (NHRCM; Sasaki et al. 2011; Ishizaki et al. 2012), is also ongoing, which aims to create long-term climate projections. Using the high-resolution modeling strategy, Yu et al. (2018) showed that the presence of Asian orography, including the Tibetan Plateau, strengthens both the Indian and East Asian summer monsoons. Studies have also attempted Asian monsoon modeling with anthropogenic aerosol forcing (Lau et al. 2000; Krishnan et al. 2016; Turner and Wang 2017). Li et al. (2016) report that on a continental scale, aerosols reduce surface insolation and weaken the land–ocean thermal contrast, thus inhibiting monsoon development.

The East Asia Regional Reanalysis (EARR) from 2010 to 2019, with a 12-km horizontal resolution, was developed to provide high-resolution regional reanalysis and reforecast fields over East Asia (Yang et al. 2022).

Global modeling collaborations. The fidelity of global models in simulating the Asian monsoon of a complex of interactive climate subsystems is a cornerstone for providing its reliable climate prediction and projections. Advanced climate modeling capabilities based on Earth system models (ESMs), which incorporate various components of the Earth system, offer an emerging opportunity for the climate prediction and projection of the Asian monsoon (Swapna et al. 2015, 2018).

Meanwhile, the models' representation of Asian precipitation is still not enough due to insufficient models' representation of physical processes along with insufficient coverage and quality of in situ and satellite observations (Annamalai et al. 2021). There is an urgent need to identify sources of model errors and to improve models. For instance, modeling of terrestrial influence on precipitation is a key element for improving precipitation processes over the Asian monsoon region (Koster et al. 2011; Boos and Hurley 2013; Ashfaq et al. 2020). The detailed observations from the planned field campaigns in AsiaPEX are expected to provide better process understanding and modeling. In this sense, process understanding enriched by the AsiaPEX observations and modeling effort are a tandem force that drives scientific research on the Asian hydroclimatological system.

The initialization of climate subsystems is another area that requires further exploration. Observations of ocean subsurface states have significantly increased over previous decades with the enhanced deployment of floating and mooring buoys in the Indian Ocean and adjacent oceans (Hermes et al. 2019). Satellite observations of terrestrial, atmospheric, surface, and subsurface conditions (such as soil moisture) should also contribute to the improvement of the quality of initial conditions from data assimilation systems. Moreover, a diagnosis of the initial error growth in initialized predictions is expected to inform model errors and deficiency of physical processes.

Climate projections and modeling. We must advance our modeling skills to achieve reliable hydroclimatic projections across Asian regions. Modeling studies have shown that the frequency and intensity of extreme rainfall events will increase, in addition to an increasing risk of drought over Asian monsoon regions (Krishnan et al. 2020). Ha et al. (2020b) estimated the precipitation sensitivity of Asian subregional monsoon systems (Fig. 4a), showing that regional precipitation sensitivity will have distinct characteristics over the monsoon domain in the future (Fig. 4b). The most significant change in the mean (extreme) was observed over the Indian (east Asia) monsoon (Figs. 4c,d). Enhanced monsoon precipitation projections in climate models from CMIP3 to CMIP5 and CMIP6 are a result of improved parameterizations and increases in the horizontal resolution (Ha et al. 2020b). Various modeling activities exist as well as large ensemble experiments. Dynamic downscaling simulations, including CORDEX, have also been performed for various regions. These datasets are a useful source for detection and attribution of past events and changes, and future projections for the numerous aspects of AsiaPEX.

Peculiar characteristics of the Asian monsoon include the largest Eurasian continent, warmest Maritime Continent, Indo-Pacific Ocean, and highest and massive area, i.e., the Tibetan Plateau. A large population has resulted in continued land-use and land-cover changes as well as aerosol emissions. For more reliable monsoon precipitation projections, improvements to the various physical processes in climate models are necessary. Anthropogenic aerosols significantly modify subregional precipitation changes (Krishnan et al. 2016). Representations of the precipitation climatology, including the diurnal cycle, remain

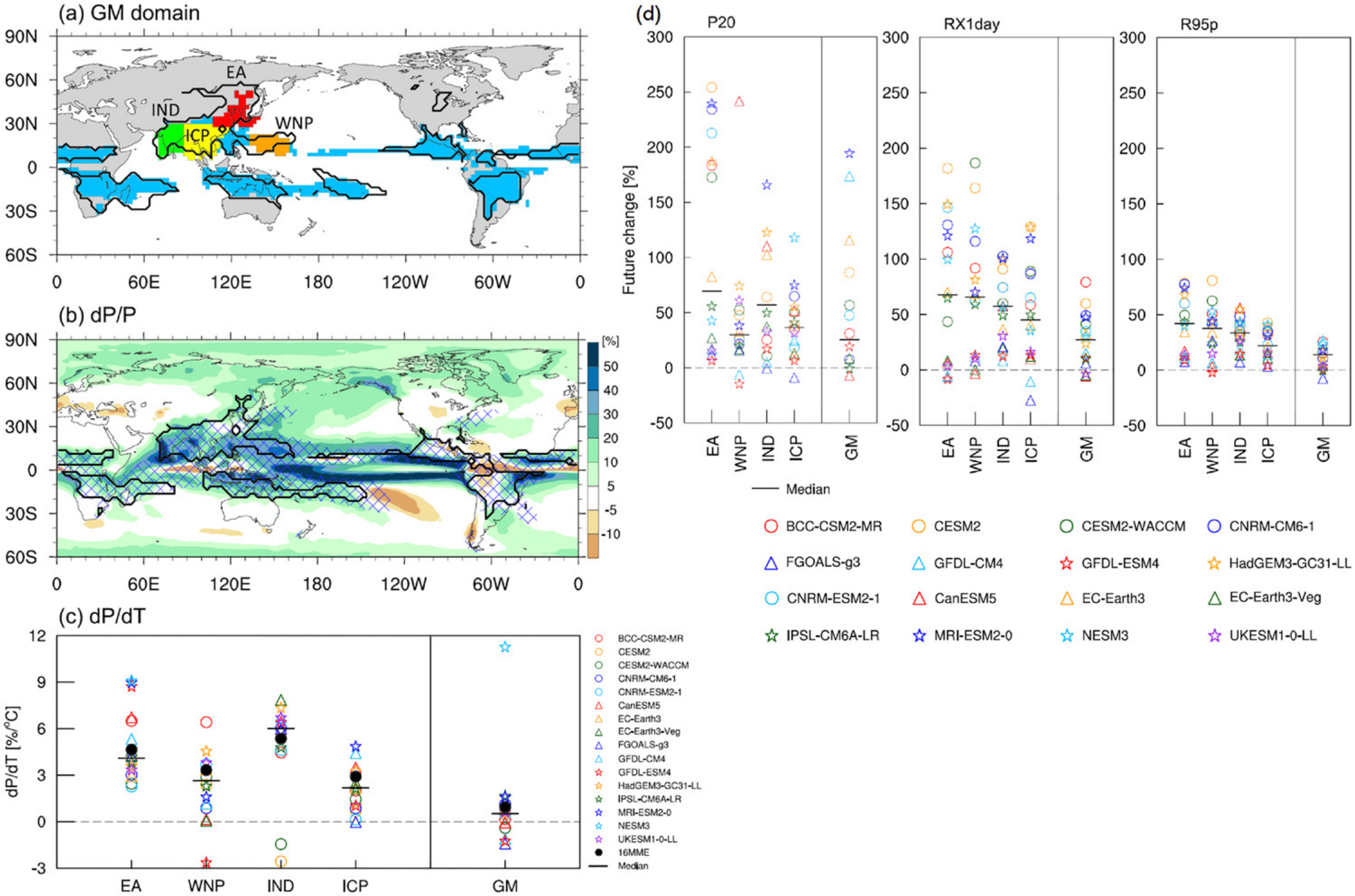

Fig. 4. **Overview of future climate projections in the Asian region based on Ha et al. (2020b). (a) Global monsoon (GM) domain (shaded), as defined by Ha et al. (2020b), based on a harmonic analysis using seasonal precipitation cycles. Four different color shades indicate the regions of East Asia (EA), western North Pacific (WNP), India (IND) and Indo-China Peninsula (ICP) [referred to in (c) and (d)]. (b) Projection of future precipitation shown by the percent change in precipitation, as calculated from the 16-member multimodel ensemble. In the hatched area, precipitation exceeds 4 mm day^{-1}. The black line is the GM domain. (c) Projected precipitation change per 1°C of global warming in CMIP6 SSP2-4.5 scenarios in the summer season from May to September over EA, WNP, IND, and ICP. Changes are plotted for each area defined by the different color shades in (a). (d) Projected percent changes in extreme precipitation for each area for parameters (left) P20 (20-yr return value of precipitation), (center) RX1day (maximum daily precipitation), and (right) R95p (95th percentile of the wet-day precipitation) (Ha et al. 2020b).**

insufficient across Asian monsoon regions, some of which are related to imperfect representations of land–atmosphere coupling (Ashfaq et al. 2017). The incorporation of surface and subsurface soil moisture is relevant for the diurnal cycle, heat exchanges between the land and atmosphere, and precipitation initiation and frequency. The vegetation–land–atmosphere coupling is not still fully understood. From previous studies, it has been realized that climate model predictions show substantial terrestrial drying, but increased runoff, which is a kind of contradiction. This contradiction can be linked to an absence of vegetation responses to an elevated atmospheric CO_2 concentration. Under CO_2 abundant climate, vegetation and soil's respiration, stomatal resistance, and photosynthesis still remain unknown. The water stress and evapotranspiration response through modified vegetation and soil's roles should also be investigated.

Impacts of AsiaPEX field campaigns

AsiaPEX is characterized by a number of collaborative research projects across different fields and interests. This section discusses the synergistic effect of AsiaPEX, owing to collaborations among field campaigns. We discuss two field studies that have significant impacts on the entire

AsiaPEX research. One is a project over the Maritime Continent (MC) and the other is on the Tibetan Plateau. The former focused on various variability in the weather–climate system over the MC. The latter has been the center of our research interests due to its uplifted land surface covering a substantial area (Yao et al. 2019). Based on experiences in these collaborations, we will conduct an integrated observational and modeling initiative, which will be discussed in the third and fourth subsections.

Impact from the MC. The MC is surrounded by the Indo-Pacific warm pool and characterized by complicated configuration of numerous islands with long coastlines. Cumulus convective activity is the strongest in the world, which energizes global atmospheric circulation. Ogino et al. (2016, 2017) have revealed that precipitation amount over coastal waters is generally larger than that over the open ocean and inland especially for islands with horizontal scales larger than 1° (Fig. 9 of Hirose et al. 2017), and suggested that a "three-region" global water cycle concept should supersede a classical "two-region" (ocean and land) concept (Figs. 5a,b). The coastal area is regarded as a "dehydrator" of the tropical atmosphere.

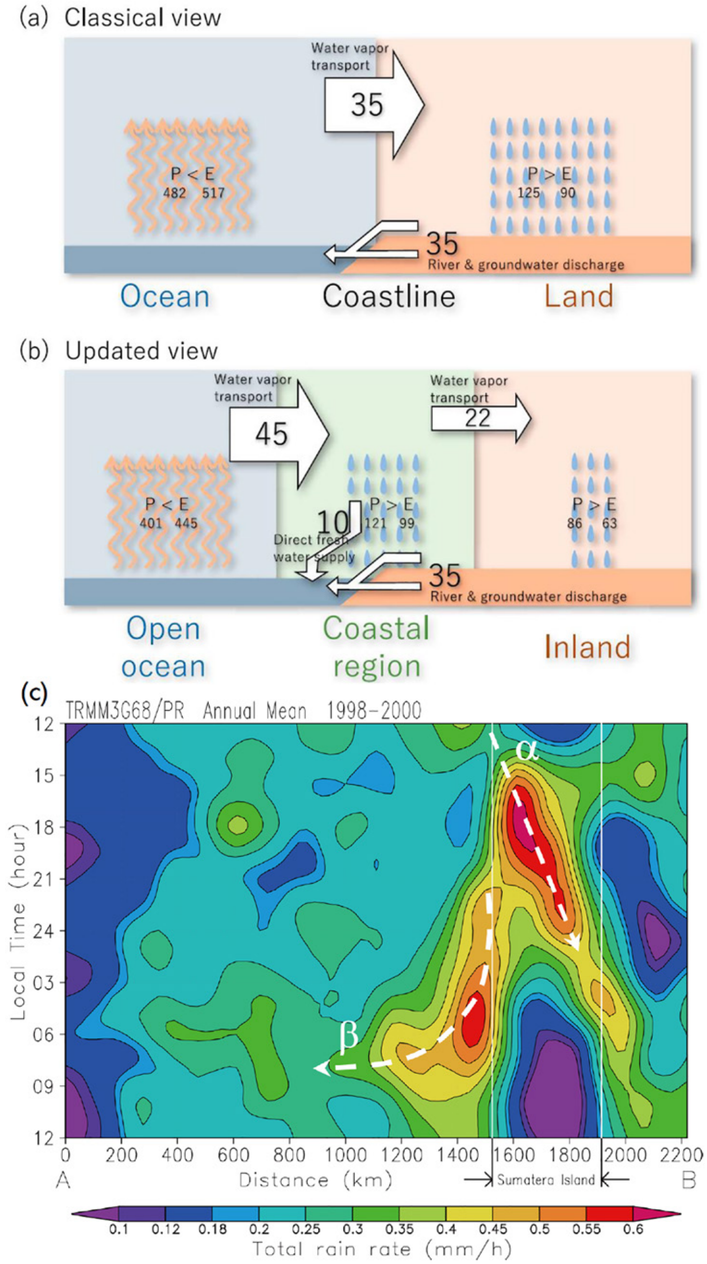

Fig. 5. (a) Classic and (b) updated view of ocean–land–water circulation. Updated view is based on the "three-region" concept, where the coastal region acts as a "dehydrator." Annual water vapor transport from the open ocean to the coastal region is 45 × 10^3 km^3. However, the water vapor transported to the inland region is only 22 × 10^3 km^3, which is less than half, indicating that remarkable dehydration occurred as precipitation within the coastal region. Figure is adopted from Ogino et al. (2017). (c) A view of the diurnal land–sea precipitation peak migration over Sumatra depicted from the TRMM PR 3G68 product (Mori et al. 2004). This section is almost perpendicular to the coastal line in a southwest-to-northeast direction, with land areas indicated on the horizontal axis. Dashed arrows α and β indicate the diurnal migration of precipitation systems.

One of the significant variabilities in coastal precipitation is the diurnal cycle. Generally, land precipitation occurs mostly in the afternoon and early evening, whereas precipitation areas tend to migrate offshore from the coast during the night and early morning. Coastal waters surrounding Sumatra (Mori et al. 2004, Fig. 5c), the Malay Peninsula (Fujita et al. 2010), Borneo/Kalimantan (Ichikawa and Yasunari 2006), Java (Mori et al. 2018), and New Guinea (Zhou and Wang 2006) are among the areas with significant offshore migration features. Though several physical mechanisms for the migration have been proposed, the most essential one is still not identified, or may be case dependent. Detailed observation over coastal land and water should help in deepening our understanding (e.g., Yokoi et al. 2017, 2019), and overcoming our difficulty in simulating diurnal cycle numerically despite recent rapid advancements in model development (e.g., Dipankar et al. 2019).

The Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) is one of the dominant intraseasonal variabilities in the tropical atmosphere and influences weather and climate all over the world. The MC modulates the behavior of the MJO and is sometimes referred to as a "barrier" against MJO propagation. MJO signals tend to weaken (Zhang and Ling 2017) and their propagation characteristics become uneven (Hsu and Lee 2005; Kim et al. 2017). Causes of the barrier effect include steep topography (Hsu and Lee 2005), minimal land heat capacity (Maloney and Sobel 2004), and a vigorous diurnal cycle (Hagos et al. 2016). On the other hand, the MJO modulates the diurnal cycle activity (Peatman et al. 2014), suggesting mutual interaction between diurnal and intraseasonal scales.

To promote research activity to deepen our understanding of such weather–climate system variabilities over the MC, an international project named "Years of the Maritime Continent" (YMC; Yoneyama and Zhang 2020) was conducted in 2017–20. Not only research agencies and universities but also operational agencies of countries in the MC participated in this project, seeking opportunity for research collaboration.

Impact from TPE. The Tibetan Plateau (TP) is considered Earth's "Third Pole." The TP is considered a research priority in the field of global climate change because it plays a crucial role in the surface energy balance and global change feedback (Wu et al. 2007).

The most direct effect of the TP occurs via thermodynamic and dynamic influences on the regional Asian monsoon and at the global scale (Wu et al. 2012). The TP acts as an elevated heat source closely related to the strength of the western North Pacific subtropical high (Wu et al. 2014) and droughts/floods in eastern China (Lai and Gong 2017; Zhu et al. 2010). The thermodynamic effects of the TP play an important role in the Asian monsoon break (Yanai et al. 1992), rising air currents of the TP (Wu et al. 2014), and moisture transportation in the coupled land–atmosphere–ocean system (Chen et al. 2012). The large-scale TP topography forces airflow to rise, creates encircling flow, and reduces its transport to central Asia (Broccoli and Manabe 1992), thus strengthening the Asian monsoon. Lin et al. (2018) found that models with a finer resolution resolve precipitation over the southern slope, significantly reducing the precipitation bias over the TP (Fig. 6a). Both observations and models support the role of the TP in the East Asian subtropical westerly intensification, tropical easterly strengthening, and South Asian high pressure (Liu et al. 2020).

Owing to its extreme elevation, the TP has more snow cover (Li et al. 2018). Snow cover influences weather and climate systems via the heat flux (Jones et al. 2001), thermodynamics (Jordan et al. 1999), and atmospheric vertical motion. Snowmelt directly affects river runoff recharge (Marsh 1999). Previous research indicates that a decrease in snow cover on the TP weakens the Asian monsoon (Yanai et al. 1992) and causes a delay in the seasonal reversal of the East Asian monsoon (Duan and Wu 2008), significantly affecting precipitation anomalies in the Yangtze River basin and southern Japan (Chou 2003). To represent the snow dynamics over the TPE, blowing snow modeling is essential. Xie et al. (2019) recently applied a blowing snow model to the TPE, which significantly improved the climate model description of snow dynamics and land–atmosphere interactions over the TP (Fig. 6b).

The higher elevation of the TP often results in lower precipitation rates due to the rain-shadow effect (Yin et al. 2004). However, the annual precipitation is increasing in most parts of the TP, whereas it is decreasing in the eastern and southeastern areas (Kuang and Jiao 2016; Arakawa and Kitoh 2012). Observation data show that the rate of precipitation at

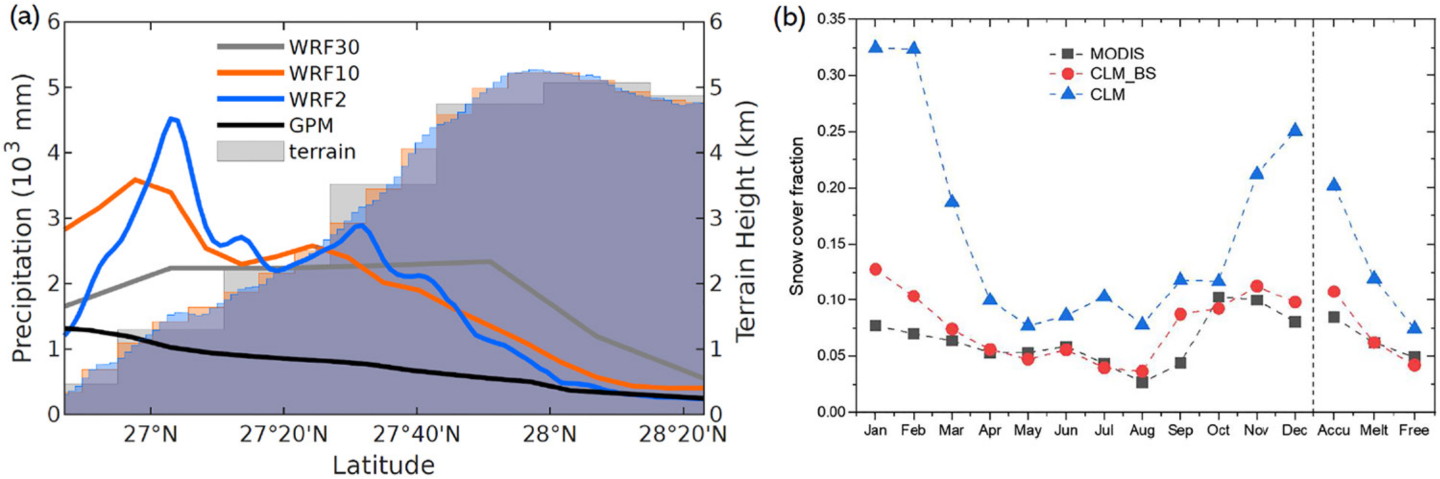

Fig. 6. **(a) Simulated precipitation over the southern slope of the Tibetan Plateau using different spatial resolutions. Results of calculations at resolutions of 30, 10, and 2 km are plotted in different colors (Lin et al. 2018). Estimation from Global Precipitation Measurement (GPM) mission is indicated by a black line, showing underestimation of precipitation over the complex terrain of the southern slope of the Himalayan Range. (b) Snow-cover fractions simulated with and without the blowing snow model are plotted with red and blue lines. Observed snow-cover fraction is shown by the black line (Xie et al. 2019).**

high altitudes is increasing faster than that at low altitudes; this tendency is strongly altitude dependent (Arakawa and Kitoh 2012).

Integrated observation and modeling initiatives. While recent satellite-derived observations and reanalysis data offer an opportunity to investigate the details of the weather–climate system relevant to the Asian monsoon, conducting special observation activities is important for a more comprehensive understanding of the dynamical and physical processes that govern the system. When we consider the detailed plans of observation activities, collaboration with other observation projects is important for maximizing outcomes for human, funding, and instrument resources.

Local meteorological and hydrological agencies have established and continuously operated routine observation networks. Besides their operational purposes, routine observation data are also valuable for research purposes, and thus should contribute to make the special observation more fruitful. For example, Yokoi et al. (2017, 2019) combined shipborne radar data of a research vessel taken during YMC observation campaigns with operational radar data in Indonesia to study precipitation diurnal cycle. Dual-Doppler analysis was also attempted using the two radars. Furthermore, the frequency of operational upper-air observation at a weather station in Indonesia was increased during the campaign periods. Such activities require cooperation between the research community and operational meteorological and hydrological agencies. The YMC project encouraged cooperation between multiple research groups, as well as between research groups and local operational agencies by providing opportunities for exchange of information and opinions such as organizing international workshops.

Learning from the YMC and other overarching projects, the AsiaPEX project should become a platform for encouraging such cooperation. Such coordinated observations can effectively enhance the observation network through system experiments (e.g., Hattori et al. 2017). Coordinated observations reinforce the frequency and horizontal density of measurements. Therefore, sensitivity experiments can be more effectively implemented in numerical forecasts through the assimilation of observational data.

AMY-II field campaign. We propose a well-designed integrated observational and modeling initiative, AMY-II, targeting on variability in the Asian hydroclimatological system at the spatial scale of the Asian continent and S2S time scales. Though detailed planning should be left to future discussion, we discuss basic ideas here. We intend to prioritize the land–atmosphere coupling process, which remains an extremely challenging area of study, even with the recent rapid development of climate modeling and satellite remote sensing technologies. We will invite all regional-scale field campaigns and crosscutting research initiatives relevant to the above research objective of AMY-II. In particular, we will organize discussions in the Monsoon Panel in WCRP and will suggest participation in all panels in GEWEX. GAME and MAHASRI have constructed frameworks for international collaboration among Asian countries. We will develop ongoing collaborative efforts among these countries.

To elucidate the strategic targets of AMY-II, we shall review the lessons learned from GAME, MAHASRI, AMY, and YMC and outcomes of recent activities of AsiaPEX that are effective in understanding terrestrial precipitation over diverse hydroclimatological conditions.

Our recent research outcomes show that the subregional process-oriented coordinated observational platforms that reach the "bottom," i.e., interactions within the fine-scale hydroclimatological land–atmosphere coupling processes occurring at the ground surface, will play a key role in AMY-II. The concept "subregion" here does not indicate the substructure of the regions on which GAME and MAHASRI are focused; instead, it indicates a hydroclimatological unit that has hypothesized water and energy exchange processes at the ground surface. Discussions on subregional platforms will encourage collaboration among empowered scientific communities in Asian countries, including local operational institutions. Ogino et al. (2016) discovered that precipitation is confined to coastlines to a width of approximately 300 km. One of the most prominent outcomes of MAHASRI is the hydrological models over the Chao Phraya River basin that simulate the impacts of reservoir operation for mitigating floods (Mateo et al. 2014; Hanasaki et al. 2014), which was developed over a river basin with a spatial scale of several hundred kilometers. Fujinami et al. (2017, 2021), Sugimoto et al. (2021), and Yokoi et al. (2017) suggested the importance of processes that are relevant to different subregions with specific land surface and topological characteristics.

Moreover, recent developments in climate science provide large amounts of data, such as high-resolution reanalysis, climate model outputs, databases containing ensemble forecasts from operational centers, and rapidly increasing data sources from satellites. Through the integration of these datasets, we have developed scientific research activities using global datasets (Ogino et al. 2016; Xie et al. 2019; Sato and Nakamura 2019; Takaya et al. 2021). To improve predictability at the S2S scale, we will conduct reanalysis and impact studies of field campaign using model intercomparison project.

These strategic targets are expected to synergistically solve current issues in understanding of Asian precipitation, improving spatiotemporal resolutions and accuracy of precipitation. Recent progress in estimation of precipitation patterns is remarkable, due to impacts of satellite remote sensing and subregional data collection including data rescue projects. However, coverage of terrestrial precipitation measurement in most of Asian region is not enough especially for detection of extremes and accurate precipitation over vast remote areas over Asia. Satellite measurements still have difficulties over the high-elevation mountainous precipitation regions where ice-phase physics play a dominant role and the topography is complex. We expect innovations from integrated observational networks in subregional platforms with specific method to improve the accuracy of precipitation estimations in different time scales. For example, measurement of the mass balance of glacier can validate the accuracy of precipitation estimations in seasonal and interannual time scales (Khalzan et al. 2022). Ground-based radar systems are a promising method, though we should overcome many issues of different operation policies and qualities associated with national boundaries (Kamimera 2020), Improvement of the quality in ground-based radar observation in different

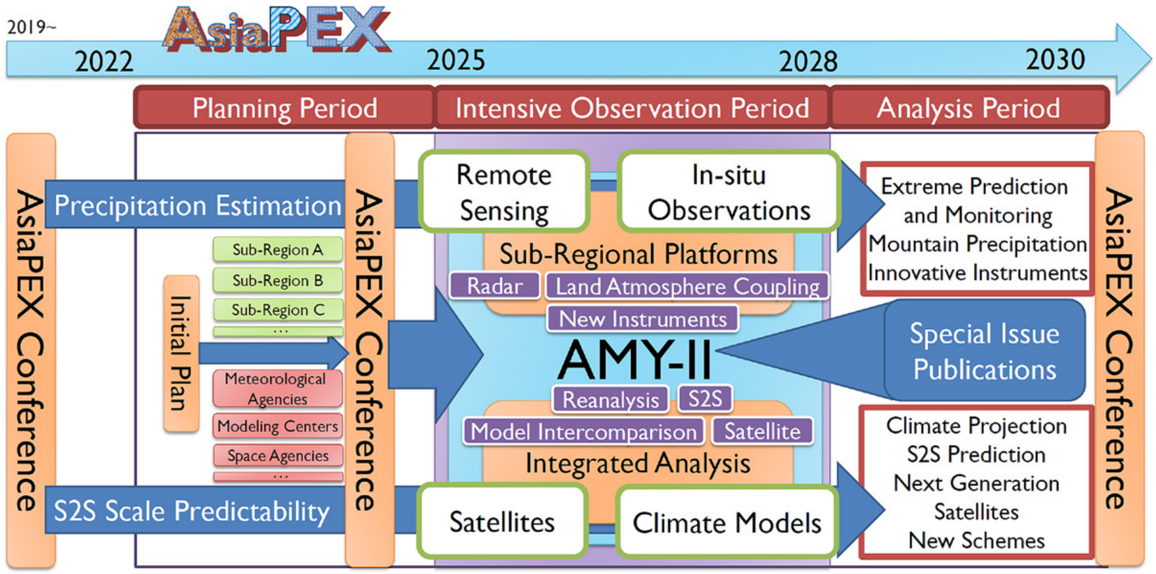

Fig. 7. Conceptual figure for AMY-II. We propose two strategic targets of AMY-II: the subregional platforms for process-oriented observation and integrated analysis using global datasets. They will contribute to two goals: innovation in precipitation estimation and improvement in S2S-scale predictions. Intensive observation periods will be scheduled between 2025 and 2028. The AsiaPEX conference for discussion of the AMY-II will take place in 2024.

countries using in situ precipitation measurements in subregional platforms has a strategic importance in AsiaPEX. Improvement of precipitation measurement in subregional platforms will contribute overall AsiaPEX studies including high-resolution hydrological modeling, and many practical use for climate change adaptation.

The next step in the science of AMY-II will be a combination of 1) the subregional process-oriented coordinated observation platforms at scales of tens to hundreds of kilometers with collaborative observations and 2) integrated analysis using global modeling, reanalysis, and remote sensing dataset that can be underpinned by subregional observation platforms. The expected goals of AMY-II are 3) innovations in precipitation estimation in the Asian region and 4) improvements in S2S-scale predictabilities (Fig. 7). We will seek various subregional platforms aiming to resolve hydroclimatological processes and to validate global datasets over highly diverse land–atmosphere coupling processes, including anthropogenic and glacier impacts.

These coordinated observational and modeling initiatives will be organized from 2025 to 2028, including at least two series of boreal summer/winter monsoon seasons (Fig. 7). The complete results will be evaluated considering the reduction in uncertainty in precipitation distribution and extremes, improvement in predictability, and quality of reproduction of the Asian precipitation by climate models.

Summary

This paper describes recent activities and plans under AsiaPEX and elucidates the characteristics of Asian land precipitation. We have held and will hold conferences, workshops, and sessions to exchange research ideas and extend international collaborations (Terao et al. 2020). As an integrated goal of our activity, we proposed a coordinated observational and modeling initiative, AMY-II, as described in the previous subsection. This project will serve as a benchmark for understanding Asian land precipitation and provide insight into a wide range of hydroclimatological issues, such as land–atmosphere–cumulus convection coupling, extreme rainfall, flood and drought management, mountain precipitation, cryospheric variability, and global water resources. Our activities will benefit Asian countries in disaster impact mitigation, climate change adaptation, and sustainable development. We have achieved various practical applications (Hong and Kim 2015; Kim et al. 2020). In particular, the WCRP Lighthouse Activities provide us a systematic vision to address the needs of the general population (Findell et al. 2023; Polcher et al. 2021).

The world faces an unprecedented risk of rapid global temperature rise. Our research will establish a foundation of convincing climate projections under global warming. It will facilitate mitigations and adaptations to climate change. This is the mission of AsiaPEX under a changing climate.

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