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INVITED REVIEW ARTICLE

The Asian Monsoon and its Future Change in Climate Models: A Review

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Abstract

This study provides an overview of the Asian monsoon and its change as simulated by atmosphere–ocean coupled general circulation models and high-resolution atmospheric general circulation models, focusing on the seasonal mean circulation and precipitation climatology. After reviewing the drivers of and the elements that affect the monsoon, the ability of those climate models to reproduce the Asian monsoon is assessed. The Asian monsoon is better reproduced in the Coupled Modeling Intercomparison Project phase 5 (CMIP5) models than in the CMIP3 models, although biases remain. Projected future changes in the Asian monsoon at the end of the 21st century are then reviewed. Overall projections are similar for both CMIP3 and CMIP5 models with increases in precipitation, albeit with weakened circulation in the South Asian summer, enhanced circulation and increased precipitation in the East Asian summer, and latitude-dependent changes in the winter monsoon circulation in East Asia. However, differences exist in the projected local changes, leading to uncertainty in projections.

Keywords Asian monsoon; GCM; climate simulation; climate change; precipitation

1. Introduction

Classically, the monsoon is a seasonal reversal of surface winds (Ramage 1971); however, now, simply seasonal rainfall is used to characterize regional monsoons because billions of people within the tropics rely on monsoon-related rainfall. Research on monsoons started at local and regional scales, but nowadays the concept of the global monsoon has emerged that considers seasonal changes in tropical divergent circulations and associated precipitation as a whole (Trenberth et al. 2000; Wang and Ding 2006). The monsoon is an ocean–land–atmosphere system with temporal variations ranging over diurnal, synoptic, intraseasonal, seasonal, interannual, and decadal time scales. The monsoon has also varied with glacial–interglacial cycles and on geological time scales, and now future changes in the monsoon system under anthropogenic influences are of great concern. Accumulated observational and paleo-proxy data, field experiments and numerical studies have revealed various aspects of the monsoon and its variability (Webster et al. 1998; Wang 2006; Chang et al. 2011; Ding et al. 2015). This article focuses on the seasonal mean monsoon and its future changes as simulated and projected by climate models.

Numerical modeling of the Asian monsoon commenced with the introduction of atmospheric general circulation models (AGCMs; Manabe et al. 1974; Gilchrist 1977). For example, the effects of mountains (Hahn and Manabe 1975) and snow cover over the Tibetan Plateau (Yasunari et al. 1991) on the Asian monsoon have been investigated. With the development of climate models, the advent of atmosphere–ocean coupled general circulation models (AOGCMs) has enabled us to investigate the effects

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of increasing carbon dioxide (CO_2) and aerosols on the Asian monsoon (Meehl and Washington 1993; Lal et al. 1995; Mitchell et al. 1995; Meehl et al. 1996; Kitoh et al. 1997). In recent decades, AGCMs, AOGCMs and regional climate models (RCMs) have been used to understand the mechanisms of monsoons, forecast the timing of monsoon onset and the seasonal rainfall amount in a coming season, and project future changes in monsoons under global warming (e.g., Webster et al. 1998; Kitoh 2006, 2011; Wang 2006; Chang et al. 2011; Endo and Kitoh 2016).

Climatemodels have been developed and improved over time (Reichler and Kim 2008; Watterson et al. 2014). The Coupled Modeling Intercomparison Project phase 3 (CMIP3; Meehl et al. 2007) and phase 5 (CMIP5; Taylor et al. 2012) has been coordinated by the World ClimateResearch Programme (WCRP). Data from historical simulations and future projections under several scenarios from the CMIP3 and CMIP5 models have formed the basis of the climate projections in the Intergovernmental Panel on ClimateChange (IPCC) Fourth Assessment Report (AR4; IPCC 2007) and Fifth Assessment Report (AR5; IPCC 2013), respectively. Although the models have been improved, they perform less well for precipitation than for surface air temperature (Flato et al. 2013). The multi-model statistics of monsoon simulations have improved from CMIP3 to CMIP5 (Flato et al. 2013; Sperber et al. 2013).

Figure 1 shows the present-day climatology from observations and simulated data of precipitation and 850 hPa wind fields during boreal summer (June–September; JJAS) and boreal winter (December–March; DJFM). The simulations are based on the CMIP5 multi-model ensemble (MME) mean. The seasonal migration of precipitation is evident with centers over South Asia, East Asia, Southeast Asia and the western North Pacific Ocean in boreal summer as well as over Indonesia and the equatorial oceans in boreal winter. Wind reversal between the southwesterly winds in boreal summer and the northeasterly winds in boreal winter over South and Southeast Asia is also observed. Over East Asia, northwesterly winds in winter replace southerly winds in summer. Models generally reproduce these monsoonal wind and precipitation characteristics, but systematic biases exist (Flato et al. 2013).

Future climate projections by CMIP3 and CMIP5

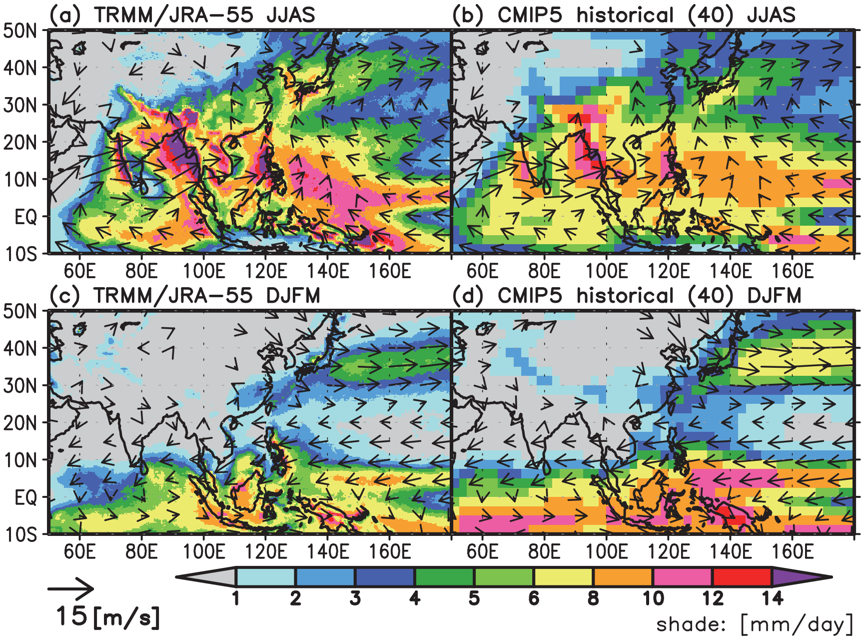


Fig. 1. (a, c) Observed and (b, d) CMIP5 MME, (a, b) June–September, and (c, d) December–March mean precipitation and 850 hPa wind fields. The observations are from TRMM 3B43 (Huffman et al. 2007; 1998–2013) for precipitation (0.25°) and JRA-55 (Kobayashi et al. 2015; 1986–2005) for 850 hPa wind fields (1.25°). The CMIP5 MME is obtained from 40 simulations of the historical period (1986–2005) on a common 2.5° by 2.5° grid.

models show that global precipitation will increase with increasing global mean surface temperatures. The spatial pattern of future surface temperature change will not be uniform, with greater warming over land than over the oceans. An increasing land–sea temperature contrast at the surface may contribute to enhanced monsoon circulation, but a stabilization of the tropical atmosphere may lead to a weakening of tropical circulation. There will be substantial spatial variations in precipitation changes, and there is a likelihood of an increased contrast of annual mean precipitation between dry and wet regions as well as between wet and dry seasons (Collins et al. 2013). It is also projected that extreme precipitation events are likely to be more intense and more frequent in a warmer world (Collins et al. 2013).

This review article provides an overview of the Asian monsoon precipitation and its change in the 21st century, as simulated by climate models, focusing on the seasonal mean circulation and precipitation climatology. Items that are not covered in this review article include meso-scale weather phenomena, changes in seasonality, intraseasonal oscillations, the ENSO–monsoon relationship, tropospheric biennial oscillations, the influence of the stratosphere, and the paleo-monsoon, among others. These should be addressed in further review articles.

The remainder of this paper is organized as follows. First, drivers of the monsoon and important elements that affect the monsoon are described in Section 2. Section 3 deals with the Asian monsoon in the historical period and considers how well it is simulated by models. Although the focus is on the Asian monsoon, a sub-section on global monsoon precipitation is included because the Asian monsoon and some of its characteristics may be better understood within the framework of the global monsoon concept. Future projections of the Asian monsoon are reviewed in Section 4. The Asian monsoon is divided into the South Asian, East Asian, Southeast Asian, and western North Pacific monsoons, although some overlap is inevitable. Finally, concluding remarks are given in Section 5.

2. Elements that affect the monsoon

This section describes drivers of the monsoon and important agents that affect the monsoon. Solar insolation, Earth's orbit and rotation, land–sea distribution, orography and composition of the atmosphere regulate the Earth's climate and thereby also the monsoon. Changes in land–sea distribution, orography, orbital forcing, greenhouse gases (GHGs), and aerosols affect the monsoon system on geological time scales. Anthropogenic factors such as GHGs, aerosols, and land use and land cover changes (LULCCs) have influenced and will influence the monsoon system in future.

2.1 Land–sea distribution

The monsoon is driven by the heat contrast between continents and adjacent oceans. Therefore, the warming and cooling of the land and the oceans during the annual cycle influence the intensity and temporal characteristics of the monsoon. The land–sea distribution is the dominant driver of the monsoon.

During geological history, the land–sea distribution on Earth has drastically changed and has affected climate (Crowley and Burke 1998; Ruddiman 2001). There existed a single large continent named Pangaea about 200 million years ago (Ma). Then, the Atlantic Ocean opened and the Pacific Ocean narrowed, and India and Australia separated from Antarctica and moved northward (Ruddiman 2001). The opening of the Drake Passage at ca. 25–20 Ma separated Antarctica from the continent. The closure of the Panama Isthmus at ca. 3 Ma resulted in the present land–sea distribution. Later, the glacial–interglacial cycle modified coastal areas under the influence of sea-level changes.

2.2 Orography

In addition to the land–sea contrast, large-scale mountains such as the Tibetan Plateau and the Rockies have significant effects on climate, including the thermodynamic effect by which the heat contrast is enhanced by the high altitude of mountains and the dynamical barrier effect. Modeling studies have revealed these orographic effects on global and regional climate and monsoons (Manabe and Terpstra 1974; Hahn and Manabe 1975; Tokioka and Noda 1986; Kutzbach et al. 1989, 1993; Ruddiman et al. 1989; Broccoli and Manabe 1992; Kitoh 1997, 2002, 2004; Abe et al. 2003, 2004, 2013). The Tibetan Plateau enhances thermal heating in summer and cooling in winter, thereby leading to intensified Asian summer and winter monsoons. The westerly jet is modified by the height of the Tibetan Plateau, affecting the Meiyu–Baiu rain band in East Asian summer (Abe et al. 2003; Kitoh 2004). The Meiyu–Baiu rain band may not have existed in its current position with its present intensity when the height of the Tibetan Plateau was lower (Kitoh 2004). Wu et al. (2012) demonstrated that diabatic heating in the middle troposphere along the foothills and slopes of the Tibetan Plateau is essential for the Indian summer monsoon. Tang et al. (2013) investigated the effects on the monsoon of smaller-scale mountains such as the Zagros Mountains with a regional climate model. They found that the presence of the Zagros Mountains intensifies the Somali jet and increases summer rainfall in northwestern India. The importance of the East African Highlands has also been discussed (Chakraborty et al. 2009; Johnson et al. 2016).

Geological evidence indicates three successive stages of uplift of the Himalayas and the Tibetan Plateau at (1) 40–35 Ma (southern and central Tibetan Plateau), (2) 25–20 Ma (northern Tibetan Plateau), and (3) 15–10 Ma (northeastern to eastern Tibetan Plateau) (Tada et al. 2016). Recent modeling studies have demonstrated the different roles of the Himalayas and various regions of Tibetan Plateau uplift on Asian monsoons (Zhang et al. 2012). For a review of modeling studies of the Tibetan Plateau uplift and monsoon, refer to Liu and Dong (2013). Modeling studies suggest that the first uplift corresponded to an intensification of the Indian summer monsoon, and the second and the third caused intensification of the East Asian summer and winter monsoons. There is good evidence for a link between the second uplift and monsoon behavior: the East Asian summer and winter monsoon intensified and inland desertification started at 25–20 Ma, associated with uplift of the northern Tibetan Plateau (Tada et al. 2016). Therefore, the Himalayas (or the southern Tibetan Plateau) intensify the Indian summer monsoon while the northern Tibetan Plateau intensifies the East Asian summer monsoon as well as the East Asian winter monsoon. The Paratethys Sea existed over the region from Central Europe to Central Asia at 30 Ma. The subsequent retreat of this sea played as important a role in driving the Asian monsoon as the uplift of the Tibetan Plateau (Ramstein et al. 2007). Numerical experiments show that as the Paratethys shrank, the amplitude of the seasonal cycle increased, thereby enhancing the monsoon precipitation.

2.3 *Orbital forcing*

Seasonal variations in incoming solar radiation (insolation) drive seasonal heating and cooling of the continent and ocean. Quasi-periodic changes in the parameters of the Earth's orbit around the sun modify the seasonal and latitudinal distribution of insolation. The obliquity (tilt) of Earth's axis has varied between 22.05° and 24.50° with a 41 thousand-year (kyr) cycle over the past 800 kyr. The eccentricity of the Earth's orbit around the Sun varies between 0.002 and 0.050, with 400 and 100 kyr cycles. Precession of the equinoxes and the longitude of perihelion modulate the seasonal cycle of insolation with 19 and 23 kyr cycles. In particular, changes in precession regulate the intensity of the Northern Hemisphere (NH) land warming in summer, and thus the monsoon. Increased solar radiation in the NH summer, at ca. 9 kyr ago, produced a stronger Asian summer monsoon. The Paleoclimate Modeling Intercomparison Project (PMIP) multi-model mean simulates the stronger rainfall of the African and Asian summer monsoons and its northward shift during the mid-Holocene (Braconnot et al. 2007).

2.4 *Greenhouse gases*

The amount of GHGs regulates the temperature and moisture content of the atmosphere (greenhouse effect), thus affecting monsoons. The atmospheric concentration of carbon dioxide has increased by 40 % from 280 to 400 ppm since the pre-Industrial era. It is projected to increase further under all representative concentration pathway (RCP) scenarios used in IPCC AR5, up to more than three times the pre-Industrial level (IPCC 2013). Atmospheric moisture content is enhanced by GHG warming, which leads to a more intense water cycle throughout the atmosphere. Climatemodel projections show an increase in total monsoon rainfall through the 21st century, largely owing to increasing atmospheric moisture content. Extreme precipitation events over monsoon regions tend to become more intense and more frequent in the future.

2.5 *Aerosols*

Aerosols have a net cooling effect on the global climate system but play various roles in regional climate change because the loading of atmospheric aerosols varies regionally (Ramanathan et al. 2001; Lau et al. 2008). The direct effect of the aerosol increase is the reflection of solar radiation reaching the ground, resulting in cooler surface temperatures. Land–sea thermal contrast will decrease than without the direct aerosol effect, and the summer monsoon circulation will weaken. The "elevated heat pump" effect caused by black carbon would favor an earlier onset of the South Asian summer monsoon (Lau et al. 2006). Model simulations show that the direct effect of aerosols reduces the magnitude of Asian monsoon precipitation change compared with the case in which only GHGs increase (Bollasina et al. 2011; Polson et al. 2014; Song et al. 2014; Sanap et al. 2015). Large uncertainty exists on the indirect influence of aerosols on climate by modifying clouds.

2.6 *Land use and land cover changes*

Land use and land cover change affects the energy and water balance at the Earth's surface through changes in surface albedo, evapotranspiration, and roughness, thereby playing a crucial role in monsoon winds and precipitation (Yasunari 2011). Alteration in LULCC occurred over Asia and Europe owing to human settlement and the development of agriculture (Pielke et al. 2011). In India and China, between 1700 and 1850, forested areas decreased from 40–50 % of the total land area to 5–10 % as areas under cultivation increased. These extended LULCCs are believed to have resulted in a decrease in monsoon rainfall and a delay in the monsoon onset over the Indian subcontinent and southeastern China (Takata et al. 2009). LULCC from forest to cropland causes the surface roughness to decrease, resulting in an increase in surface wind speed and a reduction in moisture convergence and precipitation. The reduction in precipitation reduces the soil moisture and thus the local evaporation and moist convection, creating a positive feedback and further reductions in precipitation.

Yasunari et al. (2006) and Saito et al. (2006) investigated the relative influences of orography (the Tibetan Plateau) and vegetation on Asian monsoon precipitation and found nearly equally contributions. Enhanced vegetation results in an increase in available radiation, through the albedo effect, which increases both evaporation and atmospheric moisture convergence, and consequently increases precipitation. The effect of LULCC in Asia has also been discussed (e.g., Kanae et al. 2001; Zhang and Gao 2009; Dallmeyer and Claussen 2011; Krishnan et al. 2016).

2.7 *Air–sea interaction*

Air–sea interaction is a major driver of the internal variability of the climate system. The seasonal cycle of the Asian climate is controlled by air–sea interaction. Interannual and interdecadal variability such as El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Pacific Decadal Oscillation (PDO) and the Arctic Oscillation (AO), strongly modulates the Asian monsoon.

Observational and AOGCM results show that the local simultaneous correlation between the June–July–August (JJA) mean SST and precipitation anomalies is positive in the tropical eastern–central Pacific but negative in the western North Pacific. The negative correlation between SST and rainfall anomalies means that the atmosphere affects SST. In contrast, AGCM simulations yield a positive correlation even over the western North Pacific region. Wang et al. (2005) showed the importance of air–sea coupling in predicting Asian–Pacific summer monsoon rainfall. Air–sea interaction is essential for East Asian summer monsoon simulations because the atmosphere affects the ocean by wind–evaporation feedback and cloud–radiation feedback.

The inclusion of air–sea coupling can improve simulations of the East Asian summer monsoon. Song and Zhou (2014b) compared the East Asian summer monsoon climatology and interannual variability of 17 CMIP5 AOGCMs with the corresponding AGCMs. The simulated northwestern subtropical high shifts northeastward and the Meiyu–Baiu rainfall is weaker than observed in both AOGCMs and AGCMs. A cold SST bias exists in AOGCMs, which decreases the surface evaporation and enhances the monsoon circulation, thereby reducing biases in circulation and rainfall.

3. The monsoon in the historical period

3.1 *Global monsoon*

a. *Observations*

The characteristics of the monsoon vary significantly from region to region. The traditional monsoon region extends over all the tropical continents and over the tropical oceans of the western and eastern North Pacific, and the southern Indian Ocean. Over the Americas, a clear seasonal reversal of surface winds is not seen, but there are large differences in precipitation, humidity, and atmospheric circulation between summer and winter (Vera et al. 2006; Marengo et al. 2012). From a global perspective, the characteristics of precipitation over South Asia, East Asia, Australia, Africa, and the Americas can be viewed as an integrated global monsoon system, associated with a global-scale persistent atmospheric overturning circulation (Trenberth et al. 2000). Therefore, definitions of the monsoon in terms of precipitation characteristics rather than wind reversal are increasingly used (Wang and LinHo 2002; Wang and Ding 2006).

Wang and Ding (2006) defined the global monsoon area (GMA) as regions where the local summer-minus-winter (annual range) precipitation exceeds 180 mm and the summer-to-annual rainfall ratio is > 35 %. They defined summer as JJA in the Northern Hemisphere (NH) and December–January–February (DJF) in the Southern Hemisphere (SH). Other authors

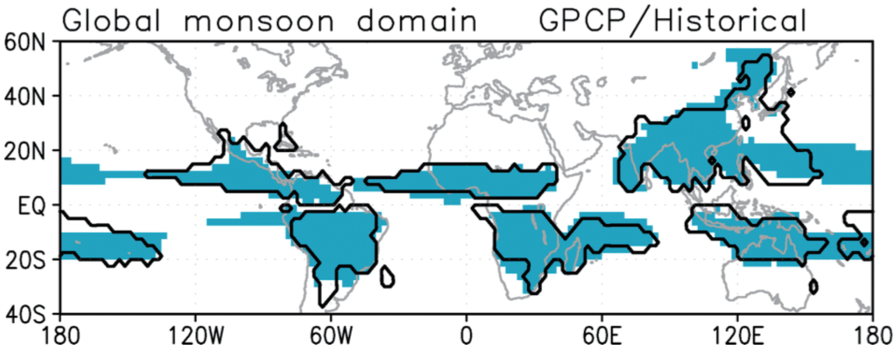


Fig. 2. Observed (thick contours) and simulated (shading) global monsoon domain, defined where the annual range of rainfall (difference between May–September and November–March) is greater than 2.5 mm day^{-1}. The observed domain is from GPCP, and the simulated data are the multi-model mean precipitation data for 1986–2005 from an ensemble of 29 CMIP5 models.

have used different criteria, but the global monsoon is not sensitive to the exact criteria (Hsu 2016). Figure 2 is the global monsoon domain defined as the region where the annual range of rainfall (difference between May–September and November–March) is greater than 2.5 mm day^{-1} (Kitoh et al. 2013) based on Global Precipitation Climatology Project (GPCP) data (Huffman et al. 2009). Global monsoon precipitation (GMP) is defined as the total summer monsoon precipitation within the GMA. A global monsoon intensity (GMI) index is also defined as GMP amount per unit area. The global monsoon is the dominant mode of the annual variation in tropical circulation, characterizing the seasonality of the tropical climate (Wang and Ding 2008).

Historical precipitation records show a decreasing trend in the global land monsoon precipitation over the second half of the 20th century (1948–2003) (Wang and Ding 2006; Zhou et al. 2008b). Changes in both the GMA and GMI contribute to this decreasing tendency (Zhou et al. 2008a). However, during a more recent period (1979–2008) the combined (ocean and land) monsoon precipitation has increased mainly owing to a significant upward trend in NH summer monsoon precipitation (Wang et al. 2012). When the change in the monsoon-affected domain is considered, the fractional increase in monsoon area is greater than that in total precipitation such that the ratio of these two measures (GMI) exhibits a decreasing trend for the most recent 30-year (1979–2008) period (Hsu et al. 2011).

Time series of observed GMP show decadal variability, possibly related to SST variations. Zhang and Zhou (2011) evaluated the changes in global land monsoon precipitation by using multiple rain-gauge precipitation datasets. The multi-decadal features of various regional monsoons for the period 1901–2001 were identified, with an overall increasing trend in GMI from 1901 to 1955, followed by a decreasing trend up to 2001. The warming over the central Pacific and the tropical Indian Ocean may have contributed to the reduction in global land monsoon precipitation during the period 1950–2000, while the negative phase of the PDO during 1998–2012 (global warming hiatus) would have led to increasing GMP, primarily by transporting moisture into the western Pacific region, thus intensifying the Asian monsoon precipitation (Wang et al. 2014). Increasing thermal contrast between the NH and the SH favors a larger GMP because more moisture is transported inter-hemispherically (Wang et al. 2012).

b. Model evaluation

Kim et al. (2008) investigated the reproducibility of the global monsoon climate variability simulated by the CMIP3 models. They found that the CMIP3 MME simulates a reasonably realistic climatology of the global monsoon precipitation and circulation, but models have common biases such as a northeastward shift of the intertropical convergence zone (ITCZ) over the tropical North Pacific. They also indicated that models with higher spatial resolution generally reproduced a better spatial pattern of global monsoon precipitation than did lower-resolution models. Compared with the Atmospheric Model Intercomparison Project (AMIP) models, the 20-km mesh MRI AGCM reproduces the most realistic annual cycle of global monsoon precipitation (Wang et al. 2011).

The skill of CMIP5 models in simulating observed global monsoon domains has been investigated by Hsu et al. (2013) and Kitoh et al. (2013). Both of these studies show that the ensemble mean precipitation of CMIP5 models reproduces the observed GMA, GMP, and GMI, although the spread of individual models is large. Figure 2 compares the observed and simulated CMIP5 MME mean representation of the global monsoon domain (Kitoh et al. 2013). Regionally, models have difficulty in simulating monsoon rainfall in East Asia and the tropical Pacific. The underestimation of the monsoon domain in East Asia was noted by Kim et al. (2008) for the CMIP3 models and remains the same in the CMIP5 models. Even the best CMIP5 models cannot remedy this deficiency (Lee and Wang 2014). Tung et al. (2014) used a model-dependent precipitation threshold (i.e., a type of bias correction) to define the Asian summer monsoon domain. They found that the CMIP5 models better reproduce the Asian summer monsoon domain than the CMIP3 models both for hit rate and threat score. Tung et al. (2014) also noted that models that use the hybrid convective parameterization, combining bulk mass flux and CAPE closure schemes, are better than models with other convection schemes.

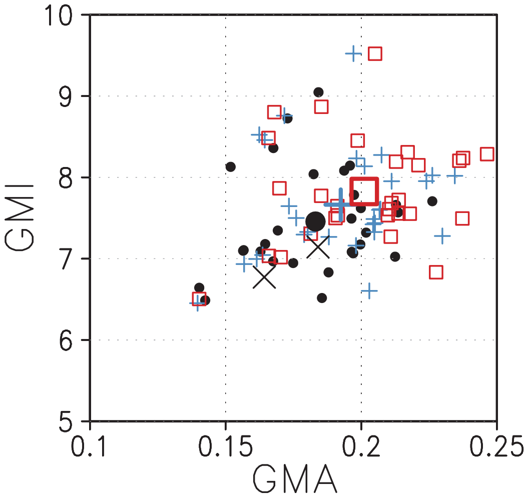


Fig. 3. Scatter diagram of global monsoon area (GMA) against global monsoon intensity (GMI; mm day^{-1}) for observations and simulations. GPCP and CMAP values are shown as crosses. The present-day simulations are displayed as closed circles, with plus signs for RCP4.5 future values and squares for RCP8.5. The large closed circle, large plus sign, and large square denote the CMIP5 multi-model means from a 29-member ensemble. GMA is scaled by global surface area. Adapted from Kitoh et al. (2013).

Hsu et al. (2011) and Kitoh et al. (2013) assessed the GMA and GMI of each model against observations. Figure 3 shows a scatter diagram of GMA against GMI for two observational datasets, GPCP (Huffman et al. 2009) and CMAP (Xie and Arkin 1997), as well as for 29 CMIP5 models. Note that observations (GPCP and CMAP) have approximately 10 % uncertainty in estimating GMA. The multimodel ensemble closely matches the observations although with a slight overestimation. However, there is large inter-model scatter in both GMI and GMA, indicating that each model has difficulty in reproducing the areal distribution of precipitation and its amount.

3.2 Asian monsoon

a. AOGCMs

(1) South Asian monsoon

The skill of CMIP3 models in simulating the South Asian monsoon precipitation was investigated by Kripalani et al. (2007b), who showed that 19 of the 22 models examined reproduced the observed annual cycle well, with peaks of varying magnitude during boreal summer. There is evidence that the CMIP5 models are better than the CMIP3 models at simulating the Asian–Australian monsoon system. Several studies have reported that the CMIP5 MME mean is more skilful than the CMIP3 MME mean (Li et al. 2012; Sperber et al. 2013; Ogata et al. 2014; Wang et al. 2014). However, CMIP5 and CMIP3 have common biases in boreal summer mean precipitation (Sperber et al. 2013; Shashikanth et al. 2014). Both underestimate the seasonal mean precipitation amount over the Asian continent from India to Southeast Asia, and over eastern China, Korea, and southern Japan (and thus weaker Meiyu–Baiu rainfall), while they yield overestimates over the western Indian Ocean and the Maritime Continent. The cold bias in SST over the Arabian Sea in the CMIP5 models may be one reason for a dry bias over India (Levine et al. 2013). The CMIP5 models' simulation of ENSO–monsoon relations is inadequate (the correlation is too weak) (Sperber et al. 2013). Although most models still have deficiencies in simulations of the spatial or intra-seasonal variation in monsoon precipitation, some models show improved skill in the northward propagation of convection (Sperber et al. 2013). The CMIP5 models also simulate the seasonal cycle of precipitation over the Indo–Australian monsoon region better than the CMIP3 models (Jourdain et al. 2013) but have a dry bias in the early rainy season (Seth et al. 2013). Tung et al. (2014) noted a delayed onset of the South Asian summer monsoon by CMIP models compared with observations.

(2) East Asian monsoon

Kripalani et al. (2007a) examined the East Asian monsoon precipitation simulated by CMIP3 models. Of the 22 models examined, 14 reproduced the observed annual cycle for East Asia. Using various metrics, Boo et al. (2011) showed that CMIP3 models can simulate the large-scale circulation of the East Asian monsoon reasonably well but not precipitation, seasonal cycle, and interannual variability. The models' performance in reproducing the monsoon rain band is also poor (Lin et al. 2008). Ninomiya (2012) noted that most CMIP3 models fail to reproduce the Baiu rain band. Most CMIP3 models underestimate the frequency of heavy precipitation in the tropics (Dai 2006) and East Asia (Kusunoki and Arakawa 2012).

For East Asian summer precipitation, CMIP5 models exhibit significant improvement over CMIP3 models in the seasonal mean pattern correlation and spatial standardized deviation ratio (Chen and Sun 2013a; Seo et al. 2013). However, the underestimation of precipitation over China, Korea, and Japan found in CMIP3 models remains in CMIP5 models (Chen and Sun 2013a). Song and Zhou (2014a) compared the simulation skill for the climatology and interannual variability of East Asian summer monsoon between CMIP3 and CMIP5 AGCMs. The early summer Meiyu–Baiu rain band is inadequately simulated. There is a weaker and southward shifted western Pacific anticyclone, which is related to poor reproducibility of the interannual dipole rainfall pattern. This teleconnection is improved from CMIP3 to CMIP5. Wang et al. (2005) noted the importance of air–sea coupling processes for simulations of the East Asian summer monsoon. Song and Zhou (2014b) compared the East Asian summer monsoon simulated by 34 CMIP5 AOGCMs with the corresponding AGCMs. Although AOGCMs have local cold SST biases, these lead to decreases in surface evaporation and enhance the circulation, so the climatological low-level monsoon circulation and Meiyu–Baiu rain band are represented better in AOGCMs than in AGCMs. The interannual variability (the Indian Ocean–western Pacific anticyclone teleconnection pattern) is better simulated in AOGCMs than in AGCMs. Huang et al. (2013) noted the large spread among CMIP5 models in simulating the climatology and interannual variability of summer precipitation over Eastern China. Uncertainties in simulating large-scale circulation features such as the East Asian subtropical jet and western Pacific subtropical high are possible reasons for the large model spread in summer monsoon precipitation.

Kusunoki and Arakawa (2015) showed that both the CMIP5 and CMIP3 models have some difficulty in simulating the seasonal march of the rainy season over China, the Korean Peninsula, and Japan with underestimated precipitation intensity over East Asia. Nevertheless, the CMIP5 models perform better in reproducing the precipitation over East Asia than the CMIP3 models with respect to the geographical distribution of precipitation throughout the year, the seasonal march of the rainy season and extreme precipitation events. Models that simulate annual precipitation more realistically tend to yield more realistic precipitation intensity in both CMIP5 and CMIP3.

For the Asian winter monsoon, the spread between the CMIP5 models is large for the lower-tropospheric meridional wind and precipitation along the coast of East Asia (Gong et al. 2014). Approximately half of the CMIP5 models capture the observed ENSO–East Asian winter monsoon relationship: i.e., a weak East Asian winter monsoon in El Niño years (Gong et al. 2014). Both CMIP5 and CMIP3 models overestimate precipitation over East Asia in the October–April season (Kusunoki and Arakawa 2015).

(3) Southeast Asian and western North Pacific monsoons

The reproduction of the western North Pacific summer monsoon by CMIP3 models has been evaluated by Inoue and Ueda (2009). Inadequate simulation of the oceanic monsoon over the western North Pacific in some models results in large inter-model variability in the lower-tropospheric circulation. Models have difficulty in reproducing the stepwise eastward progress of the convection center from the Indian Ocean toward the western North Pacific during the maturing process of the monsoon. Siew et al. (2014) examined the Southeast Asian winter monsoon as simulated by CMIP5 models and found that models simulated the broad spatial patterns of winter monsoon precipitation but with a large spread of wet bias.

(4) Historical trend

Observational records reveal the decadal variability and/or trends in monsoon precipitation. Whether climate models can appropriately reproduce the historical trend of monsoon precipitation is another branch of model evaluation. Multiple observational records show a decreasing trend in continental Indian summer (JJAS) precipitation during 1951–2005 but an increasing trend for a larger domain including the nearby ocean (Ramesh and Goswami 2014). Local aerosol abundance (Ramanathan et al. 2005; Bollasina et al. 2011) and/or SST changes in the Indo–Pacific Ocean (Annamalai et al. 2013) may explain the decreasing rainfall trend.

The CMIP3 simulations capture the observed weakening trend of the South Asian summer monsoon circulation over the past half century, although they underestimate this trend; however, they are unable to reproduce the observed slight decrease in precipitation (Fan et al. 2010). The CMIP5 ensemble mean shows a slight negative trend, as observed. Note that most models have trends that lie outside the observed uncertainty. By investigating other metrics, Ramesh and Goswami (2014) concluded that CMIP5 models are no better than CMIP3 models at simulating the historical trend of the Indian monsoon. Interestingly, the historical simulations using the Laboratoire Meteorologie Dynamique zoomed (LMDZ) AGCM, which has enhanced resolution (~35 km) over South Asia, appear to capture the decreasing trend of the Indian summer monsoon precipitation during the post-1950s in response to anthropogenic forcing (Krishnan et al. 2016; Singh 2016).

In the CMIP5 experiments, in addition to the "Historical" run that includes all forcing, experiments are performed for climate change detection and attribution studies. The "HistoricalNat" experiment uses only natural forcing; i.e., volcanoes and solar variability. The "HistoricalGHG" experiment uses GHG forcing only. The response to aerosols can be estimated as a residual of these three experiments. Neither of the experiments with GHG forcing or natural forcing reproduces the observed decreasing trend simulated by the all-forcing case. Attribution studies show that anthropogenic aerosol has been the dominant influence on NH monsoon precipitation over the second half of the 20th century (Polson et al. 2014; Salzmann et al. 2014; Song et al. 2014). Regionally, changes in circulation and precipitation are opposite. The combination of various aerosols in the historical climate simulation of CMIP5 models leads to a weakened East Asian summer monsoon circulation, while the increase of GHG contributes to enhanced summer monsoon precipitation (Song et al. 2014). Li et al. (2015b) also show that aerosol forcing contributed to a reduction in Asian summer monsoon precipitation in the 20th century. Guo et al. (2015) show that indirect effects are the major driver of the decreasing precipitation trend of the South Asian monsoon during the 20th century. In contrast, Kim et al. (2008) suggested that volcanic forcing was an important factor in past precipitation variability of the global monsoon.

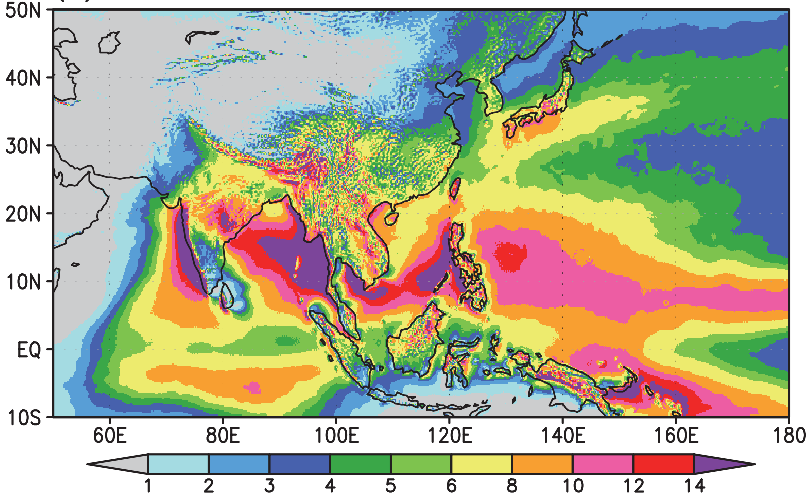
Note that large uncertainty exists in the forcing agents in historical experiments with climate models; in particular, it is unknown whether the aerosol forcing is appropriate in the historical experiment. There have been significant LULCCs in the historical period, mainly associated with agricultural development. Whether these LULCCs are properly specified as boundary conditions is also unclear.

b. *High-resolution AGCMs*

Climatemodels with higher resolution generally reproduce a better spatial pattern of the global monsoon precipitation than do lower-resolution models (Kim et al. 2008; Wang et al. 2011; Mizuta et al. 2012; Watterson et al. 2014). Among CMIP models, higher-resolution models tend to give better precipitation climatology, frequency and intensity over the East Asian summer (Chen and Sun 2013a; Kusunoki and Arakawa 2015). Boos and Hurley (2013) show that CMIP models have a systematic bias over South Asia where the upper tropospheric temperature maximum is too weak and shifted southeast of its observed location. They suggested that this is caused by a smoothed topography west of the Tibetan Plateau, which allows the intrusion of dry air from the west, suppressing moist convection. Sabin et al. (2013) also reported the importance of high resolution over the Hindu Kush Himalayan region. These results suggest the requirement for high-resolution models to represent local topographic effects (Chakraborty et al. 2006). Higher-resolution models better reproduce the East African Highlands, which results in improved representation of the Somali Jet and thus moisture transport (Johnson et al. 2016). The importance of a better representation of local topography has also been shown by many other authors (e.g., Xie et al. 2006; Rajendran and Kitoh 2008; Li et al. 2015a).

The simulation of heavy precipitation during the East Asian summer rainy season is improved by the use of global models (Kusunoki et al. 2006) and regional models (Gao et al. 2006; Kanada et al. 2008; Kitoh et al. 2009) with horizontal resolution less than

(a) MRI−AGCM3.2S JJAS P



(b) MRI−AGCM3.2S JJAS F−P2

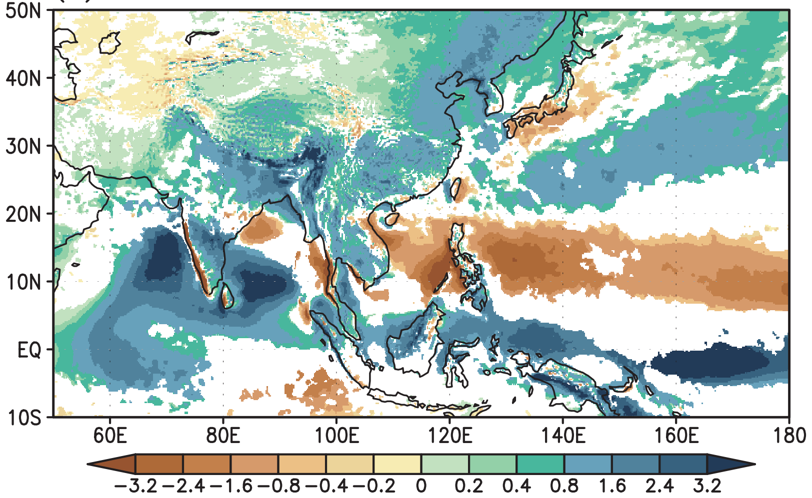


Fig. 4. June–September mean precipitation (mm day^{-1}) from the 20-km mesh MRI-AGCM3.2. (a) Present-day climatology corresponding to the period 1979–2003. (b) Future changes for 2075–2099 using the CMIP5 MME SST changes. Data from Kitoh and Endo (2016a, b).

100 km. Kitoh and Kusunoki (2008) and Kusunoki et al. (2011) show that a 20-km mesh MRI-AGCM reproduces well not only orographic rainfall but also the Baiu rain band (Fig. 4a). Endo et al. (2012) show that a 60-km mesh version of the MRI-AGCM3 has comparable abilities to the 20-km model version in reproducing monsoon precipitation and used it for multi-physics and multi-SST ensemble experiments.

The variable-grid AGCM is another approach to dynamical downscaling, employing a regionally increased resolution over a target region and a coarse resolution outside this region. Sabin et al. (2013) used the variable resolution LMDZ AGCM and showed that the simulation of the monsoon was significantly improved, especially the representation of the southwesterly monsoon flow and the heavy precipitation along the narrow orography of the Western Ghats, the northeastern mountain slopes and northern Bay of Bengal, and the monsoon synoptic disturbances along the monsoon trough.

Moist processes are the core of the tropical atmosphere but are difficult to handle in climate models with cumulus parameterization schemes. The global Non-hydrostatic Icosahedral Atmospheric Model

(NICAM) has been developed to run with a horizontal resolution on the order of kilometers (Satoh et al. 2014), where clouds are explicitly calculated using a cloud microphysics scheme without cumulus parameterization. The seasonal march of the Asian monsoon is well reproduced by the 20-year climatology of the 14-km mesh NICAM (Kodama et al. 2015). However, the model still has a northward bias in the location of the summer monsoon westerlies. The boreal summer mean precipitation bias resembles that of the CMIP5 MME.

4. Future projections of monsoons

TIn Section 2, the main agents that affect monsoons were reviewed. Some of them will be further altered by human activity in the coming century. Figure 5 shows schematically how future monsoons will be changed by human activity (Christensen et al. 2013). As the land surface warms faster than the ocean surface, the land–sea temperature contrast increases. Future changes in monsoon precipitation are derived from changes in moisture flux convergence and local evaporation, with the former generally being larger than the latter (Endo and Kitoh 2014). Owing to the rise in surface and tropospheric temperatures, water vapor content in the atmosphere increases. Large-scale atmospheric circulation will change as a result of the warming. Atmospheric circulation slows down, but water vapor transport from ocean to land and its convergence over the monsoon regions increase as the moistening effect (thermodynamic component) dominates the effect of the weakening circulation (dynamic component). An increase in atmospheric water vapor (precipitable water) leads to increasing potential for heavy precipitation. Changes in aerosols and land use can affect the absorption of solar radiation, thereby influencing the land–sea temperature contrast. Aerosols can also modify precipitation amount through cloud-producing processes.

Future climate projections have been made using several scenarios in CMIP3 and CMIP5 simulations. The global mean surface air temperature will change throughout the 21st century, depending on the accumulated anthropogenic CO_2 emissions (IPCC 2013). Global precipitation will increase with increasing global mean surface temperature, but there will be substantial spatial variations in the change in precipitation. The contrast of annual mean precipitation between dry and wet regions will increase as will the contrast between wet and dry seasons (Collins et al. 2013; Seth et al. 2013). There is a large inter-model spread in projected regional precipitation in the tropics (Christensen et al. 2013). Efforts have been made to understand this inter-model spread. The spatial pattern of the total precipitation changes will roughly follow the "wet-gets-wetter" pattern (Held and Soden 2006) or, over the ocean, the warmer-gets-wetter pattern (Xie et al. 2010; Chadwick et al. 2013). The increase in specific humidity in a warmer atmosphere results in more moisture convergence in

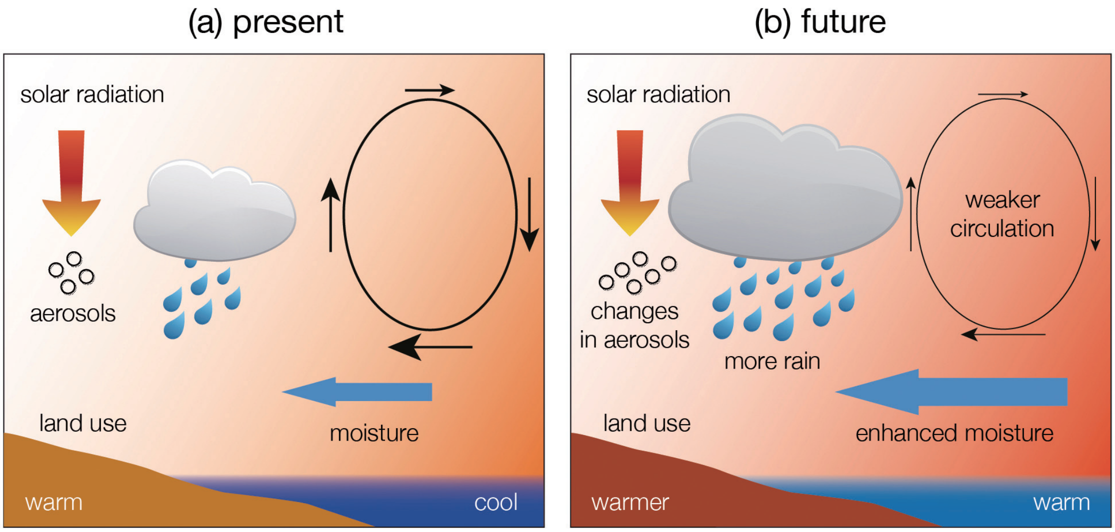


Fig. 5. Schematic diagram illustrating the main ways that human activity influences monsoon rainfall. Adapted from Christensen et al. (2013).

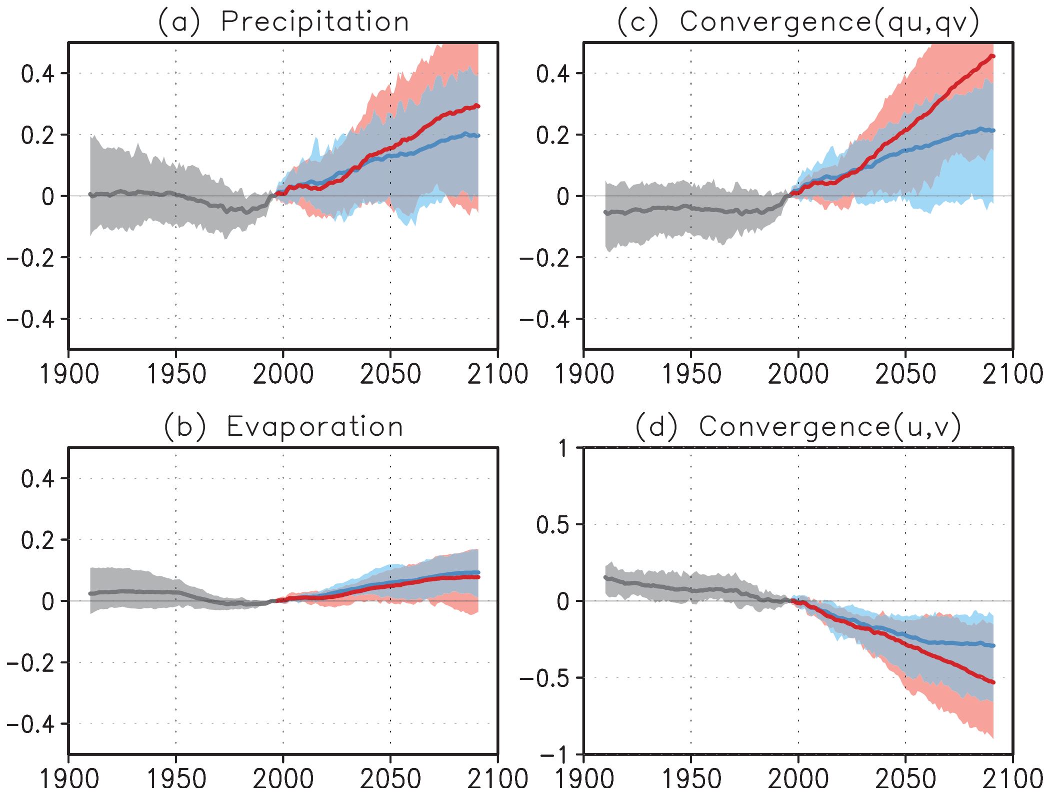


Fig. 6. Time series of simulated anomalies over the global land monsoon domain for (a) precipitation (mm d^{-1}), (b) evaporation (mm d^{-1}), (c) water vapor flux convergence in the lower (below 500 hPa) troposphere (mm d^{-1}) and (d) wind convergence in the lower troposphere (10^{-3} kg m^{-2} s^{-1}), relative to the base period average (1986–2005), based on 23 CMIP5 model monthly outputs. Historical (gray), RCP4.5 (blue), and RCP8.5 (red) simulations are shown by the 10th and 90th percentiles (shading), and by all-model averages (thick lines). Adapted from Kitoh et al. (2013).

climatologically wet regions and more moisture divergence in climatologically dry regions, thus leading to the "wet-gets-wetter" pattern. Changes in atmospheric circulation modify this mechanism to produce different precipitation anomalies. Over the tropical ocean, precipitation increases where the SST warming exceeds the tropical mean and vice versa ("warmer-gets-wetter" pattern). Oueslati et al. (2016) show that circulation differences from different cloud radiative effects result in the inter-model spread over oceans and continental coasts, while differences in water vapor increase that originate from differences in evaporation result in the spread over inland regions.

4.1 Global monsoon

CMIP5 models project a future increase in the global monsoon area (Chen and Sun 2013b; Hsu et al. 2013; Kitoh et al. 2013; Lee and Wang 2014; Hsu 2016). The CMIP5 MME shows an expansion of the global monsoon domain over the central to eastern tropical Pacific, the southern Indian Ocean and East Asia. The median change of GMA is 5.4 % and 9.4 % for RCP4.5 and RCP8.5, respectively, between the present (1986–2005) and the future (2080–2099) (Fig. 3; Kitoh et al. 2013). These results are essentially consistent with CMIP3 model results (Hsu et al. 2012, 2013) but with some regional differences (Lee and Wang 2014). Different values for the GMA change can be obtained depending on the scenarios, both for selected CMIP5 models (Lee and Wang 2014) and high-resolution AGCMs (Hsu et al. 2012). In fact, inter-model spread is large: the 10th and 90th percentile changes of CMIP5 models in GMA for RCP8.5 are 0.4 % and 17.4 %, respectively (Kitoh et al. 2013). An increased contrast between wet and dry seasons may be responsible for the future expansion of the GMA. Seth et al. (2013) noted a redistribution of precipitation from early to late rainy season.

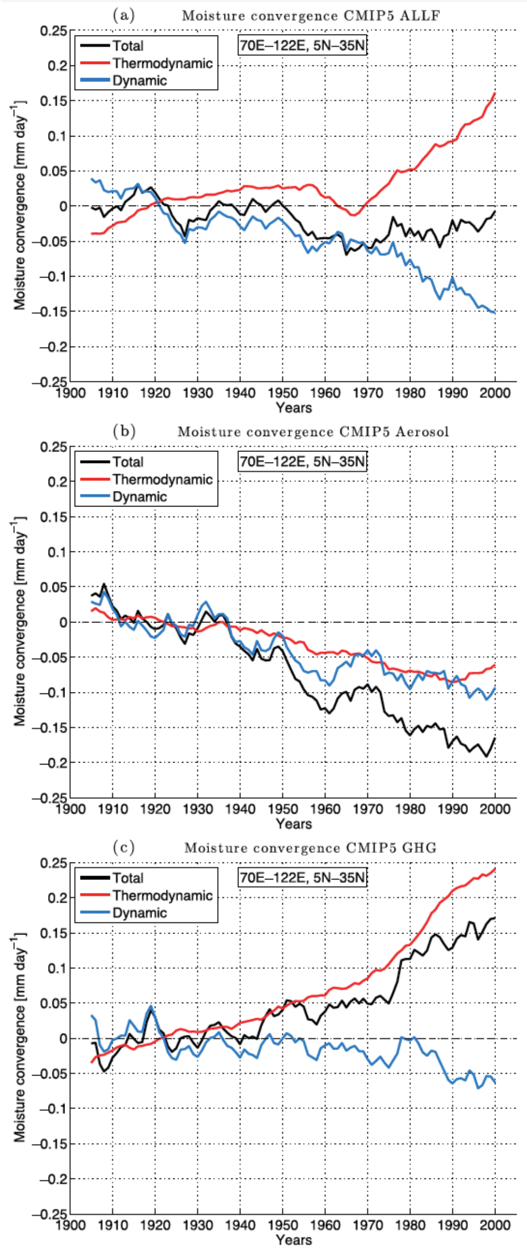


Fig. 7. Time series of area-averaged anomalies of June–August total mean moisture convergence (black), the thermodynamic component (red), and the dynamic component (blue) over the land area within 5–35°N, 70–122°E for CMIP5 nine-model MME historical (a) all-forcing, (b) aerosol-forcing, and (c) GHG-forcing simulations from 1900 to 2005. The anomalies are calculated with respect to the 1900–1949 climatology. The time series are smoothed with an 11-yr running average. Units are mm d^{-1}. Adapted from Li et al. (2015b).

In a future warmer climate, GMI will strengthen (Hsu et al. 2013; Kitoh et al. 2013; Wang et al. 2014). The CMIP5 models project a 3.6 % (5.5 %) change in GMI for RCP4.5 (RCP8.5) (Kitoh et al. 2013). Again, uncertainty among models is large, with some models showing negative or no change in GMI. As both GMA and GMI are projected to increase in a future warmer world, the monsoon area will receive more rainfall (GMP will increase much more). The GMP changes of the CMIP5 model median at the end of the 21st century are 9.0 % and 16.6 % for RCP4.5 and RCP8.5, respectively.

Using a precipitation threshold to define a rainy season in CMIP5 models, Kitoh et al. (2013) show that monsoon onset dates will advance and retreat dates will be delayed, resulting in a longer duration for future South and East Asian summer monsoons. The same changes are projected in CMIP3 models for East Asia (Kitoh and Uchiyama 2006) and South Asia (Krishna Kumar et al. 2011). However, different definitions of the monsoon may yield different results.

The projected proportional changes in precipitation extremes are much greater than those in the total precipitation amount. Under the RCP8.5 scenario, the multi-model median of the simple precipitation daily intensity index (SDII), defined as the total precipitation divided by the number of days with precipitation ≥1 mm, will increase by 8.9 %, while the seasonal maximum precipitation total in five consecutive days (Rx5d) will increase by 19.5 % over the global monsoon domain (Kitoh et al. 2013). The proportional changes in Rx5d under the RCP8.5 scenario are largest over the South Asian monsoon domain, followed by the East Asian domain (Kitoh et al. 2013). Freychet et al. (2015) show that the changes in vertical circulation and moisture advection explain the changes in frequency and intensity of precipitation extremes.

Atmospheric circulation is projected to weaken in the tropics (Vecchi and Soden 2007). Using the intensity of the kinematic circulation associated with the monsoon system in terms of the 200 hPa velocity potential, Tanaka et al. (2005) show a 20 % weakening in the boreal summer monsoon circulation at the end of the 21st century in the 15-model CMIP3 MME under the SRES A1B scenario.

The lower-tropospheric wind weakens throughout the 21st century, and the magnitude of the convergence over the monsoonal rain area decreases. However, owing to increased moisture content associated with increasing air temperature, the moisture flux convergence will increase in the future. Surface

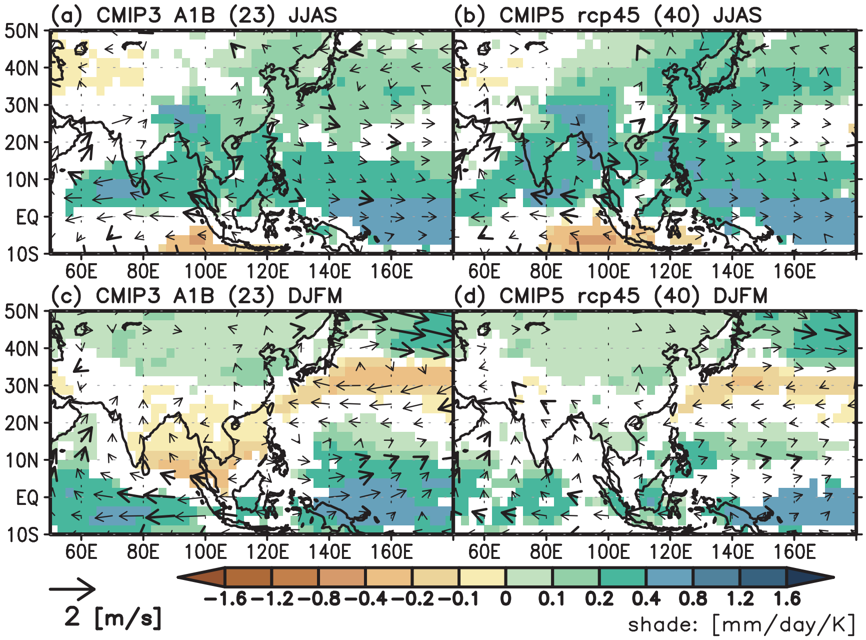


Fig. 8. Future changes in (a, b) June–September, and (c, d) December–March mean precipitation and 850 hPa wind fields. (a, c) A 23-model CMIP3 MME under the SRES A1B scenario, and (b, d) 40-model CMIP5 MME under the RCP4.5 scenario with a common 2.5° by 2.5° grid. Grid points where two-thirds of models agree on the sign of the changes are shaded for precipitation and shown in bold vectors for both zonal and meridional winds.

evaporation also increases owing to warmer surface temperature. Therefore, the projected increase of the global monsoon precipitation can be attributed to an increase in moisture convergence owing to increased surface evaporation and water vapor in the air column, although this is offset to a certain extent by weakening of the monsoon circulation (Fig. 6; Kitoh et al. 2013).

Regional precipitation changes can be divided into thermodynamic and dynamic effects. During the 20th century, the contribution from aerosol forcing dominates that from GHGs, leading to the general drying in the Asian summer monsoon region (Song et al. 2014; Li et al. 2015b). The relative contributions of aerosols and GHGs vary in the 21st century, when the thermodynamic effect dominates the dynamic effect (Fig. 7; Li et al. 2015b). As local moisture content increases rather uniformly over the global monsoon domain, regional differences in rainfall change are largely explained by differences in the dynamic effect. In the Asian monsoon regions, monsoon circulation slows down at a much lower rate than in the other monsoon regions, and surface evaporation increases at a higher rate, resulting in a much larger increase in rainfall (Endo and Kitoh 2014).

4.2 Asian monsoon

a. AOGCMs

Figure 8 shows projected future changes in boreal summer (JJAS) and winter (December–March) mean precipitation and 850 hPa wind fields from the CMIP3 MME mean under the SRES A1B scenario and CMIP5 MME mean under the RCP4.5 scenario. As described later, overall projections are similar between the CMIP3 and CMIP5 models, but differences exist in local changes in precipitation and 850 hPa winds.

(1) South Asian monsoon

Previous studies with a single model or multimodels have shown that the South Asian summer monsoon precipitation is projected to increase in a future warmer world (Meehl and Washington 1993; Lal et al. 1994, 2001; Bhaskaran et al. 1995; Kitoh et al. 1997; Hu et al. 2000b; Douville et al. 2000; May 2002, 2011; Meehl and Arblaster 2003; Turner et al. 2007; Stowasser et al. 2009; Cherchi et al. 2011). Not only will the long-term mean precipitation but also its interannual variability and extremes increase. The meridional temperature gradient (MTG) in the mid to upper troposphere between the Indian Ocean and the Tibetan Plateau is an important index of the South Asian monsoon (Li and Yanai 1996; Dai et al. 2013). Reversals of the MTG are concurrent with the onset and withdrawal of the Asian summer monsoon. A greater warming in the mid to upper troposphere over the tropical Indian Ocean than over the Asian continent results in a weakening of the MTG in a future warmer world (Ueda et al. 2006). Despite a weakening of the monsoon vertical wind shear index, which is often used as an index of dynamical monsoon strength, the Indian summer monsoon precipitation will increase with global warming owing to increased moisture content in the atmosphere (Bhaskaran et al. 1995; Kitoh et al. 1997; Douville et al. 2000; Ashrit et al. 2003; Meehl and Arblaster 2003; Ueda et al. 2006; Stowasser et al. 2009).

When the CO_2 reaches double its pre-industrial concentration, in the experiment with the idealized 1 % per year compound increase, the CMIP3 MME projects an 8 % increase in summer rainfall for the South Asian region (Kripalani et al. 2007b). An increasing tendency of the Indian summer monsoon rainfall is also obtained by CMIP3 models under SRES scenarios (Krishna Kumar et al. 2011; Sabade et al. 2011; Fan et al. 2012; Turner and Annamalai 2012).

The CMIP5 MME is more skilful than the CMIP3 MME at simulating the present-day monsoon climatology (Sperber et al. 2013). The CMIP5 models simulate stronger seasonal mean rainfall in the future compared with that in the historical period (Chaturvedi et al. 2012; Menon et al. 2013). The interannual variability of the Indian monsoon rainfall also shows a positive trend. The MTG in the Indian sector is reduced in both CMIP3 and CMIP5 projections, in association with enhanced heating in the upper troposphere over the equatorial region (Ogata et al. 2014; Sooraj et al. 2015). The increase in atmospheric moisture content owing to atmospheric warming, resulting from increasing moisture flux convergence, acts to enhance precipitation despite the weakening of the circulation (Endo and Kitoh 2014; Li et al. 2015b; Mei et al. 2015). Mei et al. (2015) further show that the remote Indian Ocean and local recycling are the largest and second largest sources for precipitation over India at present, respectively, but the strengthening remote source (warmer Indian Ocean) is a robust driver of precipitation change in the 21st century. Sabeerali et al. (2015) argue that CMIP5 models overestimate convective precipitation compared with stratiform precipitation in their present climate simulations (cf. Dai 2006), thus producing too much convection and consequently too much warming in the tropical upper troposphere in the future climate.

Srivastava and DelSole (2014) analyze 23 CMIP5 models and report a robust response in South Asian summer monsoon precipitation under the RCP8.5 scenario, characterized by enhanced precipitation in South Asia and diminished precipitation over the Maritime Continent. This zonal dipole pattern becomes clear by the middle of the 21st century. Jayasankar et al. (2015) show an increase in Indian summer monsoon precipitation but with large model-to-model spread. They also report that nearly half of the models project an increase in interannual variability while the others project a decrease. By selecting a sub-set of models with good performance in representing the mean seasonal cycle in the present climate, an increase in projected mean and interannual variability in Indian summer monsoon precipitation is obtained, with an increase in high-to-extreme precipitation. An intensification of the hydrological cycle is reported over South Asia, mainly in precipitation and moisture flux convergence (Prasanna 2015). Strong Indian summer monsoons will be more active and weak monsoons will be drier owing to longer active and break spells, and both extreme wet and dry episodes will intensify (Sharmila et al. 2015).

Ogata et al. (2014) compare changes in the Asian monsoon in the CMIP3 SRES A1B simulations and the CMIP5 RCP4.5 simulations between 1981–2000 and 2081–2100. The CMIP3 MME projected increases in precipitation and attenuation of circulation over broad regions in Asia. In contrast, the CMIP5 MME projected an acceleration of climatological low-level monsoon westerlies, particularly in subtropical regions (10–20°N). To the south (0–20°N), models agree on easterly wind anomalies at 850 hPa; i.e., a weakening of the climatological surface monsoon westerlies in the future climate. A poleward shift of low-level westerlies is another aspect of the weakening of the monsoon circulations (Sandeep and Ajayamohan 2015).

(2) East Asian monsoon

Both the circulation and precipitation of the East Asian summer monsoon are projected to strengthen through the 21st century under various scenarios. Some earlier multi-model studies show summer precipitation increase over East Asia but the inter-model scatter is large (Giorgi et al. 2001; Hu et al. 2003). Increased heavy precipitation is also projected

(Kimoto et al. 2005; Kitoh et al. 2005). The MME of four skilful AOGCMs shows that East Asia will experience wetter summers in the 21st century under the SRES A2 and B2 scenarios, with a larger increase over the continent than over the ocean (Min et al. 2004). The CMIP3 models projected increased and more intense East Asian summer monsoon precipitation owing to enhanced moisture convergence in a warmer climate (Kimoto 2005; Kripalani et al. 2007a; Chen and Sun 2009; Kim and Byun 2009; Sun and Ding 2010; Lee et al. 2011; Li et al. 2011; Jiang et al. 2012; Kusunoki and Arakawa 2012). Lu and Fu (2010) report an increase in the interannual variability of summer monsoon precipitation.

The increase of the East Asian summer monsoon precipitation is associated with projected intensification of the North Pacific subtropical high (Kripalani et al. 2007a). Kusunoki and Arakawa (2012) show that the all-model MME projects greater precipitation intensity over almost all of East Asia under the SRES A1B scenario. Sometimes an ensemble of models that perform better for a particular aspect is used; i.e., a best models ensemble rather than the all models ensemble. When the five best models are used for the MME, the spatial pattern of precipitation intensity change is similar to that of the all-model MME but the local magnitudes of change are different. Seo and Ok (2013) selected the six best-performing CMIP3 models for the East Asian summer monsoon. An ensemble of these six models projects a 10–20 % increase in East Asian summer monsoon precipitation under the SRES A1B scenario for the period 2079–2099 over the present period 1979–1999, while the all-model ensemble gives only half this increase. They found that an increase in moisture flux convergence owing to a significant increase in atmospheric water vapor, rather than a change in monsoonal low-level circulation, is responsible for the enhanced precipitation in the future climate. Kitoh and Uchiyama (2006) found a late withdrawal of the Baiu in the CMIP3 MME, as observed in eastern and western Japan (Endo 2011).

Seo et al. (2013) examined CMIP5 models under the RCP6.0 scenario, which is close to the SRES A1B scenario and obtained a marked precipitation increase of 10–15 % toward the end of the 21st century over the major monsoonal front region. They show that CMIP5 models project a statistically significant precipitation increase over the Baiu region and to the north and northeast of the Korean Peninsula. The change in the latter relatively dry region is not seen in CMIP3 models. A northwestward intensification of the western North Pacific subtropical high may be related to this feature, which is not present in CMIP3 projections. There is a lack of consensus on changes in the western North Pacific subtropical high. He and Zhou (2015) show that approximately half of the CMIP5 models project an enhanced western North Pacific subtropical high, while approximately half of the models project a weakened subtropical high. Models with a significant increased subtropical high also tend to give a significant increase in the East Asian monsoon precipitation and vice versa. Using eddy geopotential height as a definition of the western North Pacific subtropical high, He et al. (2015) discuss a weakening and an eastward retreat of the western North Pacific subtropical high under global warming, accompanied by an eastward expansion of the East Asian rain belt along the northwestern flank of this high.

Ogata et al. (2014) analyze CMIP5 RCP4.5 simulations and obtain JJA mean maximum precipitation changes to the south of Japan, concurrent with a southward shift of the Baiu rain band. This feature is consistent with the CMIP3 models (Kitoh and Uchiyama 2006; Inoue and Ueda 2012). In contrast, Seo et al. (2013) report little movement of the monsoonal major rain band. Both the increased moisture over the climatological ascent region and increased evaporation contribute to increased summer rainfall in East Asia (Qu et al. 2014).

Chen and Sun (2013a) show that the CMIP5 MME averages under the RCP4.5 scenario project increases in precipitation and its intensity over almost all of East Asia in the near future (2016–2035), while the precipitation frequency is projected to decrease over eastern China and around Japan, and increase in other regions. At the end of the 21st century, the CMIP5 best-model MME projects a statistically significant increase in total precipitation, with intense precipitation frequency over the Baiu rain band to the south of Japan. Changes in intense precipitation frequency are not significant over Japan, Korea, and East China. Jiang and Tian (2013) show a slight strengthening of southerly flow in East China.

CMIP5 projections also indicate an increase in the magnitude of heavy precipitation events (SDII and Rx5d). Based on 29 CMIP5 models, median values of total precipitation (Pav), SDII, and Rx5d show increases of 5.3 %, 7.3 %, and 10.1 % under RCP4.5 and of 6.8 %, 14.1 %, and 18.9 % under RCP8.5, respectively, over the domain of the East Asian land monsoon (Kitoh et al. 2013). Endo and Kitoh (2014) show that the thermodynamic effect (increase in moisture content) overwhelms the dynamic effect (decrease in dynamic wind convergence), resulting in a large increase in precipitation in East Asia.

Few studies have considered multi-model future changes of the Asian winter monsoon compared with its summer counterpart. Global warming gives more land surface warming than ocean warming, thereby reducing the contrast of near-surface temperature and sea-level pressure in winter between the Asian continent and the Pacific Ocean. However, there is a local exception, around the northern North Pacific where a reduction in sea ice causes greater warming over the Okhotsk Sea and the Bering Sea.

Some earlier studies have shown model-dependent changes in the Asian winter monsoon owing to global warming (Boer et al. 2000; Giorgi and Francisco 2000; Hu et al. 2000a; Lal and Harasawa 2001). The CMIP3 MME shows weakening of the East Asian winter monsoon winds, associated with weakening intensity of both the Aleutian Low and the Siberian High (Kimoto 2005; Hori and Ueda 2006). CMIP3 models under the SRES A2 and B2 scenarios exhibit large inter-model variability in projected changes of East Asian winter precipitation, although the CMIP3 MME tends to exhibit reduced winter precipitation (Min et al. 2004). Three AOGCMs show a decrease in annual and seasonal maximum wind speeds over China in the 21st century owing to both the reduced intensity of cold surges and the reduced intensity of winter monsoons (Jiang et al. 2013). Regarding the uncertainty of CMIP3 model future projections, Yamaguchi and Noda (2006) noted the opposing influences on circulation changes in this region from the positive AO-like change at high latitudes and the El Niño-like SST change at low latitudes. The AO-like change tends to be associated with positive sea-level pressure anomalies whereas the El Niño-like SST change is associated with negative sea-level pressure anomalies in the North Pacific.

Figures 8c and 8d show the December–March mean wind anomalies at 850 hPa for the CMIP3 and CMIP5 MME mean. In the northwestern Pacific, westerly and easterly wind anomalies are observed around 45°N and 30°N, respectively. Based on the surface meridional wind strength index, the ensemble mean of CMIP3 and CMIP5 models shows a weakening (strengthening) East Asian winter monsoon circulation north (south) of approximately 25°N, associated with the northward shift of the Aleutian Low, and decreased northwest–southeast thermal and sea level pressure differences across Northeast Asia (Jiang and Tian 2013). The CMIP5 MME projects significant intensification and a northward shift of the Aleutian Low, associated with strong warming over the high-latitude North Pacific owing to a reduction of sea ice in the Bering Sea and the Okhotsk Sea (Ogata et al. 2014; Hong et al. 2016; Xu et al. 2016). A cyclonic circulation anomaly north of 40°N and an anticyclonic anomaly south of 40°N in the North Pacific are consistent with the positive trend of the AO. Thus, northwesterly monsoonal winds will be enhanced over coastal regions of high-latitude northeastern Asia, while those around the Korean Peninsula and south of Japan will weaken.

(3) Southeast Asian and western North Pacific monsoons

The CMIP3 models project decreasing precipitation during June–August over the Indonesian region owing to an eastward shift of convection areas associated with El Niño-like Pacific SST changes (Ose and Arakawa 2011). The CMIP5 MME projects a moderate increase in precipitation in Southeast Asia and the western North Pacific region, and a decrease in the Indonesian region neighboring the southeast Indian Ocean during boreal summer (Christensen et al. 2013). However, there is no consensus on precipitation changes over the Maritime Continent (Jourdain et al. 2013). Northeasterly winds over Southeast Asia and the northern South China Sea will increase (Xu et al. 2016) with cyclonic circulation anomalies over the South China Sea (Siew et al. 2014). Associated with these cyclonic anomalies, a northward and southward expansion of the ITCZ is projected, with rainfall increasing at ~10°N and ~5°S (Siew et al. 2014).

b. High-resolution AGCMs

(1) South Asian monsoon

High-resolution models can resolve well the regional details of precipitation changes associated with orographic rainfall (Fig. 4b). The MRI 20-km mesh AGCM has been used in a time-slice manner to project future monsoon precipitation changes (Rajendran and Kitoh 2008; Rajendran et al. 2012, 2013; Krishnan et al. 2013). With an experiment using the CMIP3 MME mean SST changes under the SRES A1B scenario, Rajendran and Kitoh (2008) noted an increase in the simulated monsoon rainfall over the interior of the Indian subcontinent and a significant reduction in orographic rainfall over the west coasts of Kerala and Karnataka. The rainfall reduction over the west coast was mostly to the south of 15°N and was accompanied by a marked reduction in the southwesterly winds over the eastern Arabian

Sea. By comparing 20-, 60-, 120-, and 180-km mesh versions of MRI-AGCM, Rajendran et al. (2013) show that a high resolution is crucial not only for realistic mean summer monsoon simulation but also for obtaining useful future projections of the Indian summer monsoon and extremes, as lower-resolution models fail to capture the observed characteristics of present-day monsoon rainfall and its spatial heterogeneity. As shown in Fig. 4b, a reduction in JJAS mean precipitation over the western coast of the Indian subcontinent is a robust feature of the 20-km mesh MRI-AGCM. Using four-member 20-km mesh MRI-AGCM experiments, Kitoh and Endo (2016a) show that the largest extreme precipitation increases are found in South Asia. A robust increase in the frequency of heavy precipitation (>100 mm d^{-1}) over central India is projected by the high-resolution LMDZ model (Krishnan et al. 2016).

Endo et al. (2012) assess the uncertainty of future changes in mean and extreme precipitation by conducting 12 ensemble projections using 60-km mesh MRI AGCMs. Three different cumulus schemes and four different SST change patterns were used. Mean and extreme precipitation generally increase in future climate simulations in South Asia but their changes show marked differences among the projections, suggesting some uncertainty. Further investigation by analysis of variance revealed that the uncertainty in the precipitation changes is derived mainly from differences in the cumulus schemes.

(2) East Asian monsoon

A series of global warming experiments using 20-km and 60-km mesh AGCM (MRI-AGCM) has been used to investigate future changes in precipitation extremes (Kitoh et al. 2009, 2016). These experiments show that the higher-resolution model better reproduces the Baiu rain band (Kusunoki et al. 2006; Kitoh and Kusunoki 2008) and tropical cyclones (Murakami et al. 2012). The 20-km AGCM shows increases in precipitation amounts and intensity over the Yangtze River valley, the East China Sea, Western Japan, and the ocean to the south of Japan (Kamiguchi et al. 2006; Kusunoki et al. 2006, 2011; Kusunoki and Mizuta, 2008; Kitoh and Endo 2016a). Over South Korea, the number of heavy precipitation events such as days with precipitation greater than 100 mm will increase not only in summer but also in winter (Lee et al. 2013). Increased water vapor convergence associated with the intensified subtropical high is thought to be responsible for these future precipitation changes.

Three-member ensemble simulations with a 60-km mesh MRI AGCM for the period 1872–2099 revealed a monotonic increase in annual mean precipitation, SDII, and Rx5d averaged over East Asia through the 21st century (Kusunoki and Mizuta 2013). Intense rainfall will increase over northern and southern China in the late 21st century. The proportional change in precipitation per 1°C rise in surface air temperature for SDII and Rx5D is much larger than that for total precipitation during the 21st century, suggesting that extreme rainfall events will increase more than moderate rainfall events for a given temperature rise. Endo et al. (2012) assessed the uncertainty of future changes in mean and extreme precipitation using 60-km mesh MRI AGCMs. Over East Asia, mean precipitation changes are consistent among the projections. Over South China and Japan, the rate of change of SDII and Rx5d is higher than that for mean precipitation, whereas the reverse holds over North China. The uncertainty in the precipitation changes in South China comes mainly from differences in the cumulus schemes.

Chen et al. (2011) used the variable-grid LMDZ model, which has approximately 60 km resolution over China, to investigate changes in precipitation extremes in China. With four experiments for future climate, they obtained 6–7 % and 10–13 % increases in SDII and Rx5d, respectively, in southeast China in the middle of the 21st century under the SRES A2 scenario.

(3) Southeast Asian and western North Pacific monsoons

Endo et al. (2012) found that mean as well as extreme precipitation will increase in Southeast Asia, but their changes show marked differences among ensemble members. Winter monsoon precipitation is projected to decrease in the Indochina peninsula. The uncertainty in the precipitation changes over Southeast Asia is derived mainly from differences in the cumulus schemes used, while that over the Maritime Continent originates primarily from the differences in the future SST anomaly patterns used. A decrease in tropical cyclone activity means that climatological mean heavy precipitation such as Rx1d will only modestly increase in the western North Pacific, but its interannual variability will significantly increase at the end of the 21st century (Kitoh and Endo 2016b).

5. Concluding remarks

This review article has focused on climate modeling studies of the Asian monsoon and its future changes. In recent decades, modeling capabilities have developed with the incorporation of sophisticated parameterizations and an increase in horizontal and vertical resolution. However, current GCMs still have various biases in simulating many aspects of monsoons. As the monsoon is a complex atmosphere–land–ocean coupled system, every effort is needed to improve climate models not only in each sub-system but also the interaction among sub-systems. Although the speed of climate model development is slow, models have been improving and will improve further. The next phase of CMIP (CMIP6) has already begun (Eyring et al. 2016), and the results of those simulations will become available in a few years.

The Asian summer monsoon precipitation is projected to increase into the 21st century owing to global warming. In general, the thermodynamic and dynamic effects oppose each other, with the former enhancing and the latter reducing monsoon precipitation. During the 20th century, the contribution from aerosol forcing dominated that from GHGs, leading to the general drying of the Asian summer monsoon precipitation. The contribution of GHGs is predicted to dominate the 21st century when a middle- or high-CO_2 concentration scenario is realized. However, there are uncertainties regarding the contribution of aerosols and atmospheric circulation changes to regional precipitation projections. These uncertainties need further study.

Dynamical downscaling by a nested RCM is one approach to obtain regionally fine-scale information for climate change. In this review article, simulations by RCMs are intentionally omitted. As the boundary conditions of RCMs come from the GCMs, the large-scale component of the projections will not change much from that of the parent GCMs. For this reason, downscaling by RCMs is not reviewed in this article. Recently, some RCMs have employed horizontal resolution of a few kilometers and a non-hydrostatic convection-permitting scheme. Together with better representation of topography and underlying land surface, with even an urban canopy scheme in some models, these RCMs have the ability to add value to the simulated output from the parent GCMs (Kitoh et al. 2016; Takayabu et al. 2016).

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References

Abe, M., A. Kitoh, and T. Yasunari, 2003: An evolution of the Asian summer monsoon due to mountain uplift – Simulation with the MRI atmosphere-ocean coupled GCM–. *J. Meteor. Soc. Japan,* **81**, 909-933.

Abe, M., T. Yasunari, and A. Kitoh, 2004: Effect of large-scale orography on the atmosphere-ocean coupled system in the tropical Indian and Pacific sector in boreal summer. *J. Meteor. Soc. Japan,* **82**, 745-759.

Abe, M., M. Hori, T. Yasunari, and A. Kitoh, 2013: Effects of the Tibetan Plateau on the onset of the summer monsoon in South Asia: The role of the air-sea interaction. *J. Geophys. Res.,* **118**, 1760-1776.

Annamalai, H., J. Hafner, K. P. Sooraj, and P. Pillai, 2013: Global warming shifts the monsoon circulation, drying South Asia. *J. Climate,* **26**, 2701-2718.

Ashrit, R. G., H. Douville, and K. Rupa Kumar, 2003: Response of the Indian monsoon and ENSO-monsoon teleconnection to enhanced greenhouse effect in the CNRM coupled model. *J. Meteor. Soc. Japan,* **81**, 779-803.

Bhaskaran, B., J. F. B. Mitchell, J. R. Lavery, and M. Lal, 1995: Climatic response of the Indian subcontinent to doubled CO_2 concentrations. *Int. J. Climatol.,* **15**, 873-892.

Boer, G. J., G. Flato, and D. Ramsden, 2000: A transient climate change simulation with greenhouse gas and aerosol forcing: Projected climate to the twenty-first century. *Climate Dyn.,* **16**, 427-450.

Bollasina, M. A., Y. Ming, and V. Ramaswamy, 2011: Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *Science,* **334**, 502-505.

Boo, K.-O., G. Martin, A. Sellar, C. Senior, and Y.-H. Byun, 2011: Evaluating the East Asian summer monsoon circulation in climate models. *J. Geophys. Res.,* **116**, D01109, doi:10.1029/2010JD014737.

Boos, W. R., and J. V. Hurley, 2013: Thermodynamic bias in the multimodel mean boreal summer monsoon. *J. Climate,* **26**, 2279-2287.

Braconnot, P., B. Otto-Bliesner, S. Harrison, S. Joussaume, J.-Y. Peterchmitt, A. Abe-Ouchi, M. Crucifix, E. Driesschaert, Th. Fichefet, C. D. Hewitt, M. Kageyama, A. Kitoh, A. Laine, M.-F. Loutre, O. Marti, U. Merkel, G. Ramstein, P. Valdes, S. L. Weber, Y. Yu, and Y. Zhao, 2007: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: Experiments and large-scale features. *Climate Past,* **3**, 261-277.

Broccoli, A. J., and S. Manabe, 1992: The effects of orography on midlatitude Northern Hemisphere dry climates. *J. Climate,* **5**, 1181-1201.

Chadwick, R., I. Boutle, and G. Martin, 2013: Spatial patterns of precipitation change in CMIP5: Why the rich do not get richer in the tropics. *J. Climate,* **26**, 3803-3822.

Chakraborty, A., R. S. Nanjundiah, and J. Srinivasan, 2006: Theoretical aspects of the onset of Indian summer monsoon from perturbed orography simulations in a GCM. *Ann. Geophys.,* **24**, 2075-2089.

Chakraborty, A., R. S. Nanjundiah, and J. Srinivasan, 2009: Impact of African orography and Indian summer monsoon on the low-level Somali Jet. *Int. J. Climatol.,* **29**, 983-992.

Chang, C.-P., Y. Ding, N.-C. Lau, R. H. Johnson, B. Wang, and T. Yasunari, 2011: *The Global Monsoon System: Research and Forecast, 2nd edition.* World Scientific Series on Asia–Pacific Weather and Climate, **5**, World Scientific Publication Company, 594 pp.

Chaturvedi, R. K., J. Joshi, M. Jayaraman, G. Bala, and N. H. Ravindranath, 2012: Multi-model climate change projections for India under representative concentration pathways. *Curr. Sci.,* **103**, 791-802.

Chen, H.-P. and J.-Q. Sun, 2009: How the "best" models project the future precipitation change in China. *Adv. Atmos. Sci.,* **26**, 773-782.

Chen, H.-P., and J.-Q. Sun, 2013a: Projected change in East Asian summer monsoon precipitation under RCP scenario. *Meteorol. Atmos. Phys.,* **121**, 55-77.

Chen, H.-P., and J.-Q. Sun, 2013b: How large precipitation changes over global monsoon regions by CMIP5 models? *Atmos. Oceanic Sci. Lett.,* **6**, 306-311.

Chen, W., Z. Jiang, L. Li, and P. Yiou, 2011: Simulation of regional climate change under the IPCC A2 scenario in southeast China. *Climate Dyn.,* **36**, 491-507.

Cherchi, A., A. Alessandri, S. Masina, and A. Navarra, 2011: Effects of increased CO_2 levels on monsoons. *Climate Dyn.,* **37**, 83-101.

Christensen, J. H., K. Krishna Kumar, E. Aldrian, S.-I. An, I. F. A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D. B. Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.), Cambridge University Press, Cambridge, UK and New York, USA, 1217-1308.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver, and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.), Cambridge University Press, Cambridge, UK and New York, USA, 1029-1120.

Crowley, T. J., and K. C. Burke, 1998: *Tectonic Boundary Conditions for Climate Reconstructions.* Oxford University Press, New York, USA, 285 pp.

Dai, A., 2006: Precipitation characteristics in eighteen coupled climate models. *J. Climate,* **19**, 4605-4630.

Dai, A., H. Li, Y. Sun, L.-C. Hong, LinHo, C. Chou, and T. Zhou, 2013: The relative roles of upper and lower tropospheric thermal contrasts and tropical influences in driving Asian summer monsoon. *J. Geophys. Res.,* **118**, 7024-7045.

Dallmeyer, A., and M. Claussen, 2011: The influence of land cover change in the Asian monsoon region on present-day and mid-Holocene climate. *Biogeosciences,* **8**, 1499-1519.

Ding, Y., Y. Liu, Y. Song, and J. Zhang, 2015: From MONEX to the global monsoon: A review of monsoon system research. *Adv. Atmos. Sci.,* **32**, 10-31.

Douville, H., J.-F. Royer, J. Polcher, P. Cox, N. Gedney, D. B. Stephenson, and P. J. Valdes, 2000: Impact of CO_2 doubling on the Asian summer monsoon: Robust versus model-dependent response. *J. Meteor. Soc. Japan,* **78**, 421-439.

Endo, H., 2011: Long-term changes of seasonal progress in Baiu rainfall using 109 years (1901-2009) daily station data. *SOLA,* **7**, 5-8.

Endo, H., and A. Kitoh, 2014: Thermodynamic and dynamic effects on regional monsoon rainfall changes in a warmer climate. *Geophys. Res. Lett.,* **41**, 1704-1710.

Endo, H., and A. Kitoh, 2016: Projecting Changes of the Asian Summer Monsoon through the Twenty-First Century. *The Monsoons and Climate Change: Observations and Modeling.* Carvalho, L. M. V., and C. Jones (eds.), Springer, 47-66.

Endo, H., A. Kitoh, T. Ose, R. Mizuta, and S. Kusunoki, 2012: Future changes and uncertainties in Asian precipitation simulated by multi-physics and multi-sea surface temperature ensemble experiments with high-resolution Meteorological Research Institute atmospheric general circulation models (MRI-AGCMs). *J. Geophys. Res.,* **117**, D16118, doi:10.1029/2012JD017874.

Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation. *Geosci. Model Dev.,* **9**, 1937-1958.

Fan, F., M. E. Mann, S. Lee, and J. L. Evans, 2010: Observed and modeled changes in the South Asian summer monsoon over the historical period. *J. Climate,* **23**, 5193-5205.

Fan, F., M. E. Mann, S. Lee, and J. L. Evans, 2012: Future changes in the South Asian summer monsoon: An analysis of the CMIP3 multimodel projections. *J. Climate,* **25**, 3909-3928.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S. C. Chou, W. J. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.), Cambridge University Press, Cambridge, UK and New York, USA, 741-866

Freychet, N., H.-H. Hsu, C. Chou, and C.-H. Wu, 2015: Asian summer monsoon in CMIP5 projections: A link between the change in extreme precipitation and monsoon dynamics. *J. Climate,* **28**, 1477-1493.

Gao, X., Y. Xu, Z. Zhao, J. S. Pal, and F. Giorgi, 2006: On the role of resolution and topography in the simulation of East Asia precipitation. *Theor. Appl. Climatol.,* **86**, 173-185.

Gilchrist, A, 1977: The simulation of the Asian summer monsoon by general circulation models. *Pure Appl. Geophys.,* **115**, 1431-1448.

Giorgi, F., and R. Francisco, 2000: Evaluating uncertainties in the prediction of regional climate change. *Geophys. Res. Lett.,* **27**, 1295-1298.

Giorgi, F., P. H. Whetton, R. G. Jones, J. H. Christensen, L. O. Mearns, B. Hewitson, H. von Storch, R. Francisco, and C. Jack, 2001: Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings. *Geophys. Res. Lett.,* **28**, 3317-3320.

Gong, H., L. Wang, W. Chen, R. Wu, K. Wei, and X. Cui, 2014: The climatology and interannual variability of the East Asian winter monsoon in CMIP5 models. *J. Climate,* **27**, 1659-1678.

Guo, L., A. G. Turner, and E. J. Highwood, 2015: Impacts of 20th century aerosol emissions on the South Asian monsoon in the CMIP5 models. *Atmos. Chem. Phys.,* **15**, 6367-6378.

Hahn, D. G., and S. Manabe, 1975: The role of mountains in the south Asian monsoon circulation. *J. Atmos. Sci.,* **32**, 1515-1541.

He, C., and T. Zhou, 2015: Response of the western North Pacific subtropical high to global warming under RCP4.5 and RCP8.5 scenarios projected by 33 CMIP5 models: The dominance of tropical Indian Ocean-tropical western Pacific SST gradient. *J. Climate,* **28**, 365-380.

He, C., T. Zhou, A. Lin, B. Wu, D. Gu, C. Li, and B. Zheng, 2015: Enhanced or weakened Western North Pacific Subtropical High under global warming? *Sci. Rep.,* **5**, 16771, doi:10.1038/srep16771.

Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming, *J. Climate,* **19**, 5686-5699.

Hong, J.-Y., J.-B. Ahn, and J.-G. Jhun, 2016: Winter climate changes over East Asian region under RCP scenarios using East Asian winter monsoon indices. *Climate Dyn.,* doi:10.1007/s00382-016-3096-5.

Hori, M. E., and H. Ueda, 2006: Impact of global warming on the East Asian winter monsoon as revealed by nine coupled atmosphere-ocean GCMs. *Geophys. Res. Lett.,* **33**, L03713, doi:10.1029/2005GL024961.

Hsu, P.-C., 2016: Global monsoon in a changing climate. *The Monsoons and Climate Change: Observations and Modeling.* de Carvalho, L. M. V., and C. Jones (eds.), Springer, 7-24.

Hsu, P.-C., T. Li, and B. Wang, 2011: Trends in global monsoon area and precipitation in the past 30 years. *Geophys. Res. Lett.,* **38**, L08701, doi:10.1029/2011GL046893.

Hsu, P.-C., T. Li, J.-J. Luo, H. Murakami, A. Kitoh, and M. Zhao, 2012: Increase of global monsoon area and precipitation under global warming: A robust signal? *Geophys. Res. Lett.,* **39**, L06701, doi:10.1029/2012GL051037.

Hsu, P.-C., T. Li, H. Murakami, and A. Kitoh, 2013: Future change of the global monsoon revealed from 19 CMIP5 models. *J. Geophys. Res.,* **118**, 1247-1260.

Hu, Z.-Z., L. Bengtsson, and K. Arpe, 2000a: Impact of the global warming on the Asian winter monsoon in a coupled GCM. *J. Geophys. Res.,* **105**, 4607-4624.

Hu, Z.-Z., M. Latif, E. Roeckner, and L. Bengtsson, 2000b: Intensified Asian summer monsoon and its variability in a coupled model forced by increasing greenhouse gas concentrations. *Geopys. Res. Lett.,* **27**, 2681-2684.

Hu, Z.-Z., S. Yang, and R. Wu, 2003: Long-term climate variations in China and global warming signals. *J. Geophys. Res.,* **108**, 4614, doi:10.1029/2003JD003651.

Huang, D.-Q., J. Zhu, Y.-C. Zhang, and A.-N. Huang, 2013: Uncertainties on the simulated summer precipitation over Eastern China from the CMIP5 models. *J. Geophys. Res.,* **118**, 9035-9047.

Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff, 2007: The TRMM multi-satellite precipitation analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at finer scale. *J. Hydrometeor.,* **8**, 38-55.

Huffman, G. J., R. F. Adler, D. T. Bolvin, and G. Gu, 2009: Improving the global precipitation record: GPCP Version 2.1. *Geophys. Res. Lett.,* **36**, L17808, doi:10.1029/2009GL040000.

Inoue, T., and H. Ueda, 2009: Evaluation for the seasonal evolution of the summer monsoon over the Asian and western North Pacific sector in the WCRP CMIP3 multi-model experiments. *J. Meteor. Soc. Japan,* **87**, 539-560.

Inoue, T., and H. Ueda, 2012: Delay of the Baiu withdrawal in Japan under global warming condition with relevance to warming patterns of SST. *J. Meteor. Soc. Japan,* **90**, 855-868.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.), Cambridge University Press, Cambridge, UK and New York, USA, 996 pp.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, USA, 1535 pp.

Jayasankar, C. B., S. Surendran, and K. Rajendran, 2015: Robust signals of future projections of Indian summer monsoon rainfall by IPCC AR5 climate models: Role of seasonal cycle and interannual variability. *Geophys. Res. Lett.,* **42**, 3513-3520.

Jiang, D. B., and Z. P. Tian, 2013: East Asian monsoon change for the 21st century: Results of CMIP3 and CMIP5 models. *Chinese Sci. Bull.,* **58**, 1427-1435.

Jiang, Y., Y. Luo, and Z. Zhao, 2013: Maximum wind speed changes over China. *Acta Meteor. Sinica,* **27**, 63-74.

Jiang, Z., J. Song, L. Li, W. Chen, Z. Wang, and J. Wang, 2012: Extreme climate events in China: IPCC-AR4 model evaluation and projection. *Climate Change.* **110**, 385-401.

Johnson, S. J., R. C. Levine, A. G. Turner, G. M. Martin, S. J. Woolnough, R. Schiemann, M. S. Mizielinski, M. J. Roberts, P. L. Vidale, M.-E. Demory, and J. Strachan, 2016: The resolution sensitivity of the South Asian monsoon and Indo-Pacific in a global 0.35° AGCM. *Climate Dyn.,* **46**, 807-831.

Jourdain, N. C., A. S. Gupta, A. S. Taschetto, C. C. Ummenhofer, A. F. Moise, and K. Ashok, 2013: The Indo-Australian monsoon and its relationship to ENSO and IOD in reanalysis data and the CMIP3/CMIP5 simulations. *Climate Dyn.,* **41**, 3073-3102.

Kamiguchi, K., A. Kitoh, T. Uchiyama, R. Mizuta, and A. Noda, 2006: Changes in precipitation-based extremes indices due to global warming projected by a global 20-km-mesh atmospheric model. *SOLA,* **2**, 64-67.

Kanada, S., M. Nakano, S. Hayashi, T. Kato, M. Nakamura, K. Kurihara, and A. Kitoh, 2008: Reproducibility of maximum daily precipitation amount over Japan by a high-resolution non-hydrostatic model. *SOLA,* **4**, 105-108.

Kanae, S., T. Oki, and K. Musiake, 2001: Impact of deforestation on regional precipitation over the Indochina Peninsula. *J. Hydrometeor.,* **2**, 51-70

Kim, D.-W. and H.-R. Byun, 2009: Future pattern of Asian drought under global warming scenario. *Theor. Appl. Climatol.,* **98**, 137-150.

Kim, H.-J., B. Wang, and Q. Ding, 2008: The global monsoon variability simulated by CMIP3 coupled climate models. *J. Climate,* **21**, 5271-5294.

Kimoto, M., 2005: Simulated change of the east Asian circulation under global warming scenario. *Geophys. Res. Lett.,* **32**, L16701, doi:10.1029/2005GL023383.

Kimoto, M., N. Yasutomi, C. Yokoyama, and S. Emori, 2005: Projected changes in precipitation characteristics around Japan under the global warming. *SOLA,* **1**, 85–88.

Kitoh, A., 1997: Mountain uplift and surface temperature changes. *Geophys. Res. Lett.,* **24**, 185-188.

Kitoh, A., 2002: Effects of large-scale mountains on surface climate: A coupled ocean-atmosphere general circulation model study. *J. Meteor. Soc. Japan,* **80**, 1165-1181.

Kitoh, A., 2004: Effect of mountain uplift on East Asian summer climate investigated by a coupled atmosphere-ocean GCM. *J. Climate,* **17**, 783-802.

Kitoh, A., 2006: Asian monsoons in the future. *The Asian Monsoon,* Wang, B. (ed), Springer-PRAXIS, Berlin, 631-649.

Kitoh, A., 2011: Impact of climate change on Asian monsoon characteristics. *The Global Monsoon System: Research and Forecast, 2nd edition*. World Scientific Series on Asia-Pacific Weather and Climate- vol. 5, Chang, C.-P., Y. Ding, N.-C. Lau, R. H. Johnson, B. Wang, and T. Yasunari (eds.), World Scientific Publication Company, 557-568.

Kitoh, A., and T. Uchiyama, 2006: Changes in onset and withdrawal of the East Asian summer rainy season by multi-model global warming experiments. *J. Meteor. Soc. Japan,* **84**, 247-258.

Kitoh, A., and S. Kusunoki, 2008: East Asian summer monsoon simulation by a 20-km mesh AGCM. *Climate Dyn.,* **31**, 389-401.

Kitoh, A., and H. Endo, 2016a: Changes in precipitation extremes projected by a 20-km mesh global atmospheric model. *Wea. Climate Extremes,* **11**, 41-52.

Kitoh, A., and H. Endo, 2016b: Future changes in rainfall extremes associated with El Niño projected by a global 20-km mesh atmospheric model. *SOLA,* **12A**, 1-6.

Kitoh, A., S. Yukimoto, A. Noda, and T. Motoi, 1997: Simulated changes in the Asian summer monsoon at times of increased atmospheric CO_2. *J. Meteor. Soc. Japan,* **75**, 1019-1031.

Kitoh, A., M. Hosaka, Y. Adachi, and K. Kamiguchi, 2005: Future projections of precipitation characteristics in East Asia simulated by the MRI CGCM2. *Adv. Atmos. Sci.,* **22**, 467-478.

Kitoh, A., T. Ose, K. Kurihara, S. Kusunoki, M. Sugi, and KAKUSHIN Team-3 Modeling Group, 2009: Projection of changes in future weather extremes using super-high-resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. *Hydrol. Res. Lett.,* **3**, 49-53.

Kitoh, A., H. Endo, K. Krishna Kumar, I. F. A. Cavalcanti, P. Goswami, and T. Zhou, 2013: Monsoons in a changing world: a regional perspective in a global context. *J. Geophys. Res.,* **118**, 3053-3065.

Kitoh, A., T. Ose, and I. Takayabu, 2016: Dynamical downscaling for climate projection with high-resolution MRI AGCM-RCM. *J. Meteor. Soc. Japan,* **94A**, 1-16.

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan,* **93**, 5-48.

Kodama, C., Y. Yamada, A. T. Noda, K. Kikuchi, Y. Kajikawa, T. Nasuno, T. Tomita, T. Yamaura, H. G. Takahashi, M. Hara, Y. Kawatani, M. Satoh, and M. Sugi, 2015: A 20-year climatology of a NICAM AMIP-type simulation. *J. Meteor. Soc. Japan,* **93**, 393-424.

Kripalani, R. H., J. H. Oh, and H. S. Chaudhari, 2007a: Response of the East Asian summer monsoon to doubled atmospheric CO_2: Coupled climate models simulations and projections under IPCC AR4. *Theor. Appl. Climatol.,* **87**, 1-28.

Kripalani, R. H., J. H. Oh, A. Kulkarni, S. S. Sabade, and H. S. Chaudhari, 2007b: South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4. *Theor. Appl. Climatol.,* **90**, 133-159.

Krishna Kumar, K., K. Kamala, B. Rajagopalan, M. P. Hoerling, J. K. Eischeid, S. K. Patwardham, G. Srinivasan, B. N. Goswami, and R. Nemani, 2011: The once and future pulse of Indian monsoonal climate. *Climate Dyn.,* **36**, 2159-2170.

Krishnan, R., T. P. Sabin, D. C. Ayantika, A. Kitoh, M. Sugi, H. Murakami, A. G. Turner, J. M. Slingo, and K. Rajendran, 2013: Will the South Asian monsoon overturning circulation stabilize any further? *Climate Dyn.,* **40**, 187-211.

Krishnan, R., T. P. Sabin, R. Vellore, M. Mujumdar, J. Sanjay, B. N. Goswami, F. Hourdin, J.-L. Dufresne, and P. Terray, 2016: Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. *Climate Dyn.,* **47**, 1007-1027.

Kusunoki, S., and R. Mizuta, 2008: Future changes in the Baiu rain rand projected by a 20-km mesh global atmospheric model: sea surface temperature dependence. *SOLA,* **4**, 85–88.

Kusunoki, S., and O. Arakawa, 2012: Change in the precipitation intensity of the East Asian summer monsoon projected by CMIP3 models. *Climate Dyn.,* **38**, 2055-2072.

Kusunoki, S., and R. Mizuta, 2013: Changes in precipitation intensity over East Asia during the 20th and 21st centuries simulated by a global atmospheric model with a 60 km grid size. *J. Geophys. Res., Atmos.,* **118**, 11007-11016.

Kusunoki, S., and O. Arakawa, 2015: Are CMIP5 models better than CMIP3 models in simulating precipitation over East Asia? *J. Climate,* **28**, 5601-5621.

Kusunoki, S., J. Yoshimura, H. Yoshimura, A. Noda, K. Oouchi, and R. Mizuta, 2006: Change of Baiu rain band in global warming projection by an atmospheric general circulation model with a 20-km grid size. *J. Meteor. Soc. Japan,* **84**, 581–611.

Kusunoki, S., R. Mizuta, and M. Matsueda, 2011: Future changes in the East Asian rain band projected by global atmospheric models with 20-km and 60-km grid size. *Climate Dyn.,* **37**, 2481-2493.

Kutzbach, J. E., P. J. Guetter, W. F. Ruddiman, and W. L. Prell, 1989: Sensitivity of climate to late Cenozoic uplift in southern Asia and the American west: Numerical experiment. *J. Geophys. Res.,* **94**, 18393-18407.

Kutzbach, J. E., W. L. Prell, and W. F. Ruddiman, 1993: Sensitivity of Eurasian climate to surface uplift of the Tibetan Plateau. *J. Geol.,* **101**, 177-190.

Lal, M., and H. Harasawa, 2001: Future climate change scenarios for Asia as inferred from selected coupled atmosphere-ocean global climate models. *J. Meteor. Soc. Japan,* **79**, 219-227.

Lal, M., U. Cubasch, and B. D. Santer, 1994: Effect of global warming on Indian monsoon simulated with a coupled ocean-atmosphere genera circulation model. *Curr. Sci.,* **66**, 430-438.

Lal, M., U. Cubasch, R. Voss, and J. Waszkewitz, 1995: Effect of transient increase in greenhouse gases and sulphate aerosols on monsoon climate. *Curr. Sci.,* **69**, 752-763.

Lal, M., T. Nozawa, S. Emori, H. Harasawa, K. Takahashi, M. Kimoto, A. Abe-Ouchi, T. Nakajima, T. Takemura, and A. Numaguti, 2001; Future climate change: Implications for Indian summer monsoon and its variability. *Curr. Sci.,* **81**, 1196-1207.

Lau, K.-M., M. K. Kim, and K. M. Kim, 2006: Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. *Climate Dyn.,* **26**, 855-864.

Lau, K.-M., V. Ramanathan, G.-X. Wu, Z. Li, S. C. Tsay, C. Hsu, R. Sikka, B. Holben, D. Lu, G. Tartari, M. Chin, P. Koudelova, H. Chen, Y. Ma, J. Huang, K. Taniguchi, and R. Zhang, 2008: The joint aerosol-monsoon experiment. *Bull. Amer. Meteor. Soc.,* **89**, 369-383.

Lee, J.-Y., and B. Wang, 2014: Future change of global monsoon in the CMIP5. *Climate Dyn.,* **42**, 101-119.

Lee, S., D.-H. Bae, and C.-H. Cho, 2013: Changes in future precipitation over South Korea using a global high-resolution climate model. *Asia-Pacific J. Atmos. Sci.,* **49**, 619-624.

Lee, T.-C., K.-Y. Chan, H.-S. Chan, and M.-H. Kok, 2011: Projections of extreme rainfall in Hong Kong in the 21st century. *Acta Meteor. Sinica,* **25**, 691-709.

Levine, R. C., A. G. Turner, D. Marathayil, and G. M. Martin, 2013: The role of northern Arabian Sea surface temperature biases in CMIP5 model simulations and future projections of Indian summer monsoon rainfall. *Climate Dyn.,* **41**, 155-172.

Li, C., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast. *J. Climate,* **9**, 358-375.

Li, H., L. Feng, and T. Zhou, 2011: Multi-model projection of July-August climate extreme changes over China under CO_2 doubling. Part I: Precipitation. *Adv. Atmos. Sci.,* **28**, 433-447.

Li, J., R. Yu, W. Yuan, H. Chen, W. Sun, and Y. Zhang, 2015a: Precipitation over East Asia simulated by NCAR CAM5 at different horizontal resolutions. *J. Adv. Model. Earth Syst.,* **7**, 774-790.

Li, X., M. Ting, C. Li, and N. Henderson, 2015b: Mechanisms of Asian summer monsoon changes in response to anthropogenic forcing in CMIP5 models. *J. Climate,* **28**, 4107-4125.

Li, Y., N. C. Jourdain, A. S. Taschetto, C. C. Ummenhofer, K. Ashok, and A. Sen Gupta, 2012: Evaluation of monsoon seasonality and the tropospheric biennial oscillation transitions in the CMIP models. *Geophys. Res. Lett.,* **39**, L20713, doi:10.1029/2012GL053322.

Lin, J.-L., K. M. Weickman, G. N. Kiladis, B. E. Mapes, S. D. Schubert, M. J. Suarez, J. T. Bacmeister, and M.-I. Lee, 2008: Subseasonal variability associated with Asian summer monsoon simulated by 14 IPCC AR4 coupled GCMs. *J. Climate,* **21**, 4541-4567.

Liu, X.-D., and B. W. Dong, 2013: Influence of the Tibetan Plateau uplift on the Asian monsoon-arid environment evolution. *Chinese Sci. Bull.,* **58**, 4277-4291.

Lu, R., and Y. Fu, 2010: Intensification of East Asian summer monsoon rainfall interannual variability in the twenty-first century simulated by 12 CMIP3 coupled models. *J. Climate,* **23**, 3316-3331.

Manabe, S., and T. B. Terpstra, 1974: The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments. *J. Atmos. Sci.,* **31**, 3-42.

Manabe, S., D. G. Hahn, and L. Holloway, Jr., 1974: The seasonal variation of the tropical circulation as simulated by a global model of the atmosphere. *J. Atmos. Sci.,* **31**, 43-83.

Marengo, J. A., B. Liebmann, A. M. Grimm, V. Misra, P. L. Silva Dias, I. F. A. Cavalcanti, L. M. V. Carvalho, E. H. Berbery, T. Ambrizzi, C. S. Vera, A. C. Saulo, J. Nogues-Paegle, E. Zipser, A. Seth, and L. M. Alves, 2012: Recent developments on the South American monsoon system. *Int. J. Climatol.,* **32**, 1-21.

May, W., 2002: Simulated changes of the Indian summer monsoon under enhanced greenhouse gas concentrations in a global time-slice experiment. *Geophys. Res. Lett.,* **29**, 1118, doi:10.1029/2001GL013808.

May, W., 2011: The sensitivity of the Indian summer monsoon to a global warming of 2°C with respect to pre-industrial times. *Climate Dyn.,* **37**, 1843-1868.

Meehl, G. A., and W. M. Washington, 1993: South Asian summer monsoon variability in a model with doubled atmospheric carbon dioxide concentration. *Science,* **260**, 1101-1104.

Meehl, G. A., and J. M. Arblaster, 2003: Mechanisms for projected future changes in south Asian monsoon precipitation. *Climate Dyn.,* **21**, 659-675.

Meehl, G. A., W. M. Washington, D. J. Erickson III, B. P. Briegleb, and P. J. Jaumann, 1996: Climatechange from increased CO_2 and direct and indirect effects of sulfate aerosols. *Geophys. Res. Lett.,* **23**, 3755-3758.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007: The WCRP CMIP3 multi-model dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.,* **88**, 1383-1394.

Mei, R., M. Ashfaq, D. Rastogi, L. R. Leung, and F. Dominguez, 2015: Dominating controls for wetter South Asian summer monsoon in the twenty-first century. *J. Climate,* **28**, 3400-3419.

Menon, A., A. Levermann, J. Schewe, J. Lehmann, and K. Frieler, 2013: Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models. *Earth Syst. Dyn.,* **4**, 287-300.

Min, S.-K., E.-H. Park, and W.-T. Kwon, 2004: Future projections of East Asian climate change from multi-AOGCM ensembles of IPCC SRES scenario simulations. *J. Meteor. Soc. Japan,* **82**, 1187-1211.

Mitchell, J. F. B., T. C. Johns, J. M. Gregory, and S. F. B. Tett, 1995: Climateresponse to increasing levels of greenhouse gases and sulphate aerosols. *Nature,* **376**, 501-504.

Mizuta, R., H. Yoshimura, H. Murakami, M. Matsueda, H. Endo, T. Ose, K. Kamiguchi, M. Hosaka, M. Sugi,

S. Yukimoto, S. Kusunoki, and A. Kitoh, 2012: Climatesimulations using MRI-AGCM3.2 with 20-km grid. *J. Meteor. Soc. Japan,* **90A**, 233-258.

Murakami, H., Y. Wang, H. Yoshimura, R. Mizuta, M. Sugi, E. Shindo, Y. Adachi, S. Yukimoto, M. Hosaka, S. Kusunoki, T. Ose, and A. Kitoh, 2012: Future changes in tropical cyclone activity projected by the new high-resolution MRI-AGCM. *J. Climate,* **25**, 3237-3260.

Ninomiya, K., 2012: Characteristics of intense rainfalls over southwestern Japan in the Baiu season in the CMIP3 20th century simulation and 21st century projection. *J. Meteor. Soc. Japan,* **90A**, 327-338.

Ogata, T., H. Ueda, T. Inoue, M. Hayasaki, A. Yoshida, S. Watanabe, M. Kira, M. Ooshiro, and A. Kumai, 2014: Projected future changes in the Asian monsoon: A comparison of CMIP3 and CMIP5 model results. *J. Meteor. Soc. Japan,* **92**, 207-225.

Ose, T., and O. Arakawa, 2011: Uncertainty of future precipitation change due to global warming associated with sea surface temperature change in the tropical Pacific. *J. Meteor. Soc. Japan,* **89**, 539-552.

Oueslati, B., S. Bony, C. Risi, and J.-L. Dufresne, 2016: Interpreting the inter-model spread in regional precipitation projections in the tropics: Role of surface evaporation and cloud radiative effects. *Climate Dyn.,* **47**, 2801-2815.

Pielke, Sr., R. A., A. Pitman, D. Niyogi, R. Mahmood, C. McAlpine, F. Hossain, K. K. Goldewijk, U. Nair, R. Betts, S. Fall, M. Reichstein, P. Kabat, and N. de Noblet, 2011: Land use/land cover changes and climate: modeling analysis and observational evidence. *WIREs Climate Change,* **2**, 828-850.

Polson, D., M. Bollasina, G. C. Hegerl, and L. J. Wilcox, 2014: Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols. *Geophys. Res. Lett.,* **41**, 6023-6029.

Prasanna, V., 2015: Regional climate change scenarios over South Asia in the CMIP5 coupled climate model simulations. *Meteorol. Atmos. Phys.,* **127**, 561-578.

Qu, X., G. Huang, and W. Zhou, 2014: Consistent responses of East Asian summer mean rainfall to global warming in CMIP5 simulations. *Theor. Appl. Climatol.,* **117**, 123-131.

Rajendran, K., and A. Kitoh, 2008: Indian summer monsoon in future climate projection by a super high-resolution global model. *Curr. Sci.,* **95**, 1560-1569.

Rajendran, K., A. Kitoh, J. Srinivasan, R. Mizuta, and R. Krishnan, 2012: Monsoon circulation interaction with Western Ghats orography under changing climate: Projection by an ultra-high resolution global model. *Theor. Appl. Climatol.,* **110**, 555-571.

Rajendran, K., S. Sajani, C. B. Jayasankar, and A. Kitoh, 2013: How dependent is climate change projection of Indian summer monsoon rainfall and extreme events on model resolution? *Curr. Sci.,* **104**, 1409-1418.

Ramage, C. S., 1971: *Monsoon Meteorology.* Academic Press, 296 pp.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, 2001: Aerosols, climate, and the hydrological cycle. *Science,* **294**, 2119-2124.

Ramanathan, V., C. Chung, D. Kim, T. Bettge, L. Buja, J. T. Kiehl, W. M. Washington, Q. Fu, D. R. Sikka, and M. Wild, 2005: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proc. Natl. Acad. Sci.,* **102**, 5326-5333.

Ramstein, G., F. Fluteau, J. Besse, and S. Joussaume, 2007: Effect of orography, plate motion and land-sea distribution on Eurasian climate change over the past 30 million years. *Nature,* **386**, 788-795.

Ramesh, K. V., and P. Goswami, 2014: Assessing reliability of regional climate projections: The case of Indian monsoon. *Sci. Rep.,* **4**, 4071, doi:10.1038/srep04071.

Reichler, T., and J. Kim, 2008: How well do coupled models simulate today's climate? *Bull. Amer. Meteor. Soc.,* **89**, 303-311.

Ruddiman, W. F., 2001: *Earth's Climate Past and Future.* W. H. Freeman and Company, New York, USA, 465 pp.

Ruddiman, W. F., W. L. Prell, and M. E. Raymo, 1989: Late Cenozoic uplift in southern Asia and the American West: Rationale for general circulation modeling experiments. *J. Geophys. Res.,* **94**, 18379-18391.

Sabade, S. S., A. Kulkarni, and R. H. Kripalani, 2011: Projected changes in South Asian summer monsoon by multi-model global warming experiments. *Theor. Appl. Climatol.,* **103**, 543-565.

Sabeerali, C. T., S. A. Rao, A. R. Dhakate, K. Salunke, and B. N. Goswami, 2015: Why ensemble mean projection of south Asian monsoon rainfall by CMIP5 models is not reliable? *Climate Dyn.,* **45**, 161-174.

Sabin, T. P., R. Krishnan, J. Ghattas, S. Denvil, J.-L. Dufresne, F. Hourdin, and T. Pascal, 2013: High resolution simulation of the South Asian monsoon using a variable resolution global climate model. *Climate Dyn.,* **41**, 173-194.

Saito, K., T. Yasunari, and K. Takata, 2006: Relative roles of large-scale orography and land surface processes in the global hydroclimate. Part II: Impacts on hydroclimate over Eurasia. *J. Hydrometeor.,* **7**, 642-659.

Salzmann, M., H. Weser, and R. Cherian, 2014: Robust response of Asian summer monsoon to anthropogenic aerosols in CMIP5 models. *J. Geophys. Res.,* **119**, 11321-11337.

Sanap, S. D., G. Pandithurai, and M. G. Manoj, 2015: On the response of Indian summer monsoon to aerosol forcing in CMIP5 model simulations. *Climate Dyn.,* **45**, 2949-2961.

Sandeep, S., and R. S. Ajayamohan, 2015: Poleward shift in Indian summer monsoon low level jetstream under global warming. *Climate Dyn.,* **45**, 337-351.

Satoh, M., H. Tomita, H. Yashiro, H. Miura, C. Kodama, T. Seiki, A. T. Noda, Y. Yamada, D. Goto, M. Sawada, T. Miyoshi, Y. Niwa, M. Hara, T. Ohno, S. Iga, T. Arakawa, T. Inoue, and H. Kubokawa, 2014: The Non-hydrostatic Icosahedral Atmospheric Model: Description and development. *Prog. Earth Planet. Sci.,* **1**, 18., doi:10.1186/s40645-014-0018-1.

Seo, K.-H., and J. Ok, 2013: Assessing future changes in the East Asian summer monsoon using CMIP3 models: Results from the best model ensemble. *J. Climate,* **26**, 1807-1817.

Seo, K.-H., J. Ok, J.-H. Son, and D.-H. Cha, 2013: Assessing future changes in the East Asian summer monsoon using CMIP5 coupled models. *J. Climate,* **26**, 7662-7675.

Seth, A., S. A. Rauscher, M. Biasutti, A. Giannini, S. J. Camargo, and M. Rojas, 2013: CMIP5 projected changes in the annual cycle of precipitation in monsoon regions. *J. Climate,* **26**, 7328-7351.

Sharmila, S., S. Joseph, A. K. Sahai, S. Abhilash, and R. Chattopadhyay, 2015: Future projection of Indian summer monsoon variability under climate change scenario: An assessment from CMIP5 climate models. *Global Planet. Change,* **124**, 62-78.

Shashikanth, K., K. Salvi, S. Ghosh, and K. Rajendran, 2014: Do CMIP5 simulations of Indian summer monsoon rainfall differ from those of CMIP3? *Atmos. Sci. Lett.,* **15**, 79-85.

Siew, J. H., F. T. Tangang, and L. Juneng, 2014: Evaluation of CMIP5 coupled atmosphere-ocean general circulation models and projection of the Southeast Asian winter monsoon in the 21st century. *Int. J. Climatol.,* **34**, 2872-2884.

Singh, D., 2016: South Asian monsoon: Tug of war on rainfall changes. *Nat. Clim. Change,* **6**, 20-22.

Song, F., and T. Zhou, 2014a: Interannual variability of East Asian summer monsoon simulated by CMIP3 and CMIP5 AGCMs: Skill dependence on Indian Ocean–Western Pacific anticyclone teleconnection. *J. Climate,* **27**, 1679–1697.

Song, F., and T. Zhou, 2014b: The climatology and interannual variability of East Asian summer monsoon in CMIP5 coupled models: Does air-sea coupling improve the simulation? *J. Climate,* **27**, 8761-8777.

Song, F., T. Zhou, and Y. Qian, 2014: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophys. Res. Lett.,* **41**, 596-603.

Sooraj, K. P., P. Terray, and M. Mujumdar, 2015: Global warming and the weakening of the Asian summer monsoon circulation: Assessments from the CMIP5 models. *Climate Dyn.,* **45**, 233-252.

Sperber, K. R., H. Annamalai, I.-S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou, 2013: The Asian summer monsoon: An intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Climate Dyn.,* **41**, 2711-2744.

Srivastava, A. K., and T. DelSole, 2014: Robust forced response in South Asian summer monsoon in a future climate. *J. Climate,* **27**, 7849-7860.

Stowasser, M., H. Annamalai, and J. Hafner, 2009: Response of the South Asian summer monsoon to global warming: Mean and synoptic systems. *J. Climate,* **22**, 1014-1036.

Sun, Y., and Y.-H. Ding, 2010: A projection of future changes in summer precipitation and monsoon in East Asia. *Sci. China Earth Sci.,* **53**, 284-300.

Tada, R., H. Zheng, and P. D. Clift, 2016: Evolution and variability of the Asian monsoon and its potential linkage with uplift of the Himalaya and Tibetan Plateau. *Prog. Earth. Planet. Sci.,* **3**, doi:10.1186/s40645-016-0080-y.

Takata, K., K. Saito, and T. Yasunari, 2009: Changes in the Asian monsoon climate during 1700-1850 induced by preindustrial cultivation. *Proc. Natl. Acad. Sci. U.S.A.,* **106**, 9586-9689.

Takayabu, I., H. Kanamaru, K. Dairaku, R. Benestad, H. von Storch, and J. H. Christensen, 2016: Reconsidering the quality and utility of downscaling. *J. Meteor. Soc. Japan,* **94A**, 31-45.

Tanaka, H. L., N. Ishizaki, and D. Nohara, 2005: Intercomparison of the intensities and trends of Hadley, Walker and monsoon circulations in the global warming projections. *SOLA,* **1**, 77-80.

Tang, H., A. Micheels, J. T. Eronen, B. Ahrens, and M. Fortelius, 2013: Asynchronous responses of East Asian and Indian summer monsoons to mountain uplift shown by regional climate modelling experiments. *Climate Dyn.,* **40**, 1531-1549.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.,* **93**, 485-498.

Tokioka, T., and A. Noda, 1986: Effects of large-scale orography on January atmospheric circulation: A numerical experiment. *J. Meteor. Soc. Japan,* **64**, 819-840.

Trenberth, K. E., D. P. Stepaniak, and J. M. Caron, 2000: The global monsoon as seen through the divergent atmospheric circulation. *J. Climate,* **13**, 3969-3993.

Tung, Y.-S., C.-T. Chen, and P.-C. Hsu, 2014: Evolution of Asian summer monsoon in the CMIP3 and CMIP5 models. *SOLA,* **10**, 88-92.

Turner, A. G., and A. Annamalai, 2012: Climatechange and the South Asian summer monsoon. *Nat. Climate Change,* **2**, 587-595.

Turner, A. G., P. M. Inness, and J. M. Slingo, 2007: The effect of doubled CO_2 and model basic state biases on the monsoon-ENSO system. I: Mean response and interannual variability. *Quart. J. Roy. Meteor. Soc.,* **133**, 1143-1157.

Ueda, H., A. Iwai, K. Kuwako, and M. E. Hori, 2006: Impact of anthropogenic forcing on the Asian summer monsoon as simulated by eight GCMs. *Geophys. Res. Lett.,* **33**, L06703, doi:10.1029/2005GL025336.

Vecchi, G. A., and B. J. Soden, 2007: Global warming and the weakening of the tropical circulation. *J. Climate,* **20**, 4316-4340.

Vera, C., W. Higgins, J. Amador, T. Ambrizzi, R. Garreaud, D. Gochis, D. Gutzler, D. Lettenmaier, J. Marengo, C. R. Mechoso, J. Nogues-Paegle, P. L. Silva Dias, and C. Zhang, 2006: Toward a unified view of the American monsoon system. *J. Climate,* **19**, 4977-5000.

Wang, B., 2006: *The Asian Monsoon.* Springer-Praxis, Berlin, Germany, 845 pp.

Wang, B., and LinHo, 2002: Rainy season of the Asian-Pacific summer monsoon. *J. Climate,* **15**, 386-398.

Wang, B., and Q. Ding, 2006: Changes in global monsoon precipitation over the past 56 years. *Geophys. Res. Lett.,* **33**, L06711, doi:10.1029/2005GL025347.

Wang, B., and Q. Ding, 2008: Global monsoon: Dominant mode of annual variation in the tropics. *Dyn. Atmos. Oceans,* **44**, 165-183.

Wang, B., Q. Ding, X. Fu, I.-S. Kang, K. Jin, J. Shukla, and F. Doblas-Reyes, 2005: Fundamental challenge in simulation and prediction of summer monsoon rainfall. *Geophys. Res. Lett.,* **32**, L15711, doi:10.1029/2005GL022734.

Wang, B., H.-J. Kim, K. Kikuchi, and A. Kitoh, 2011: Diagnostic metrics for evaluation of annual and diurnal cycles. *Climate Dyn.,* **37**, 941-955.

Wang, B., J. Liu, H.-J. Kim, P. J. Webster, and S.-Y. Yim, 2012: Recent change of the global monsoon precipitation (1979-2008). *Climate Dyn.,* **39**, 1123-1135.

Wang, B., S.-Y. Yim, J.-Y. Lee, J. Liu, and K.-J. Ha, 2014: Future change of Asian-Australian monsoon under RCP 4.5 anthropogenic warming scenario. *Climate Dyn.,* **42**, 83-100.

Watterson, I. G., J. Bathols, and C. Heady, 2014: What influences the skill of climate models over the continents? *Bull. Amer. Meteor. Soc.,* **95**, 689-700.

Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.,* **103**, 14451-14510.

Wu, G., Y. Liu, B. He, Q. Bao, A. Duan, and F.-F. Jin, 2012: Thermal controls on the Asian summer monsoon. *Sci. Rep.,* **2**, 404, doi:10.1038/srep00404.

Xie, P.-P., and P. A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs. *Bull. Amer. Meteor. Soc.,* **78**, 2539-2558.

Xie, S.-P., H. Xu, N. H. Saji, and Y. Wang, 2006: Role of narrow mountains in large-scale organization of Asian monsoon convection. *J. Climate,* **19**, 3420-3429.

Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg, 2010: Global warming pattern formation: sea surface temperature and rainfall. *J. Climate,* **23**, 966-986.

Xu, M., H. Xu, and J. Ma, 2016: Responses of the East Asian winter monsoon to global warming in CMIP5 models. *Int. J. Climatol.,* **36**, 2139-2155.

Yamaguchi, K., and A. Noda, 2006: Global warming patterns over the North Pacific: ENSO versus AO. *J. Meteor. Soc. Japan,* **84**, 221-241.

Yasunari, T., 2011: Role of vegetation in the monsoon climate system. *The Global Monsoon System: Research and Forecast, 2nd edition.* World Scientific Series on Asia-Pacific Weather and Climate vol. 5, Chang, C. P., Y. Ding, N.-C. Lau, R. H. Johnson, B. Wang., and T. Yasunari (eds.), World Scientific Publication Company, 583-594.

Yasunari, T., A. Kitoh, and T. Tokioka, 1991: Local and remote response to excessive snow mass over Eurasia appearing in the northern spring and summer climate – A study with the MRI GCM. *J. Meteor. Soc. Japan,* **69**, 473-487.

Yasunari, T., K. Saito, and K. Takata, 2006: Relative roles of large-scale orography and land surface processes in the global hydroclimate. Part I: Impacts on monsoon systems and the tropics. *J. Hydrometeor.,* **7**, 626-641.

Zhang, H., and X. Gao, 2009: On the atmospheric dynamical responses to land-use change in East Asian monsoon region. *Climate Dyn.,* **33**, 409-426.

Zhang, L., and T. Zhou, 2011: An assessment of monsoon precipitation changes during 1901-2001. *Climate Dyn.,* **37**, 279-296.

Zhang, R., D.-B. Jiang, X-D. Liu, and Z. P. Tian, 2012: Modeling the climate effects of different subregional uplifts within the Himalaya-Tibetan Plateau on Asian summer monsoon evolution. *Chinese Sci. Bull.,* **57**, 4617-4626.

Zhou, T., R. Yu, H. Li, and B. Wang, 2008a: Ocean forcing to changes in global monsoon precipitation over the recent half-century. *J. Climate,* **21**, 3833–3852.

Zhou, T., L. Zhang, and H. Li, 2008b: Changes in global land monsoon area and total rainfall accumulation over the last half century. *Geophys. Res. Lett.,* **35**, L16707, doi:10.1029/2008GL034881.