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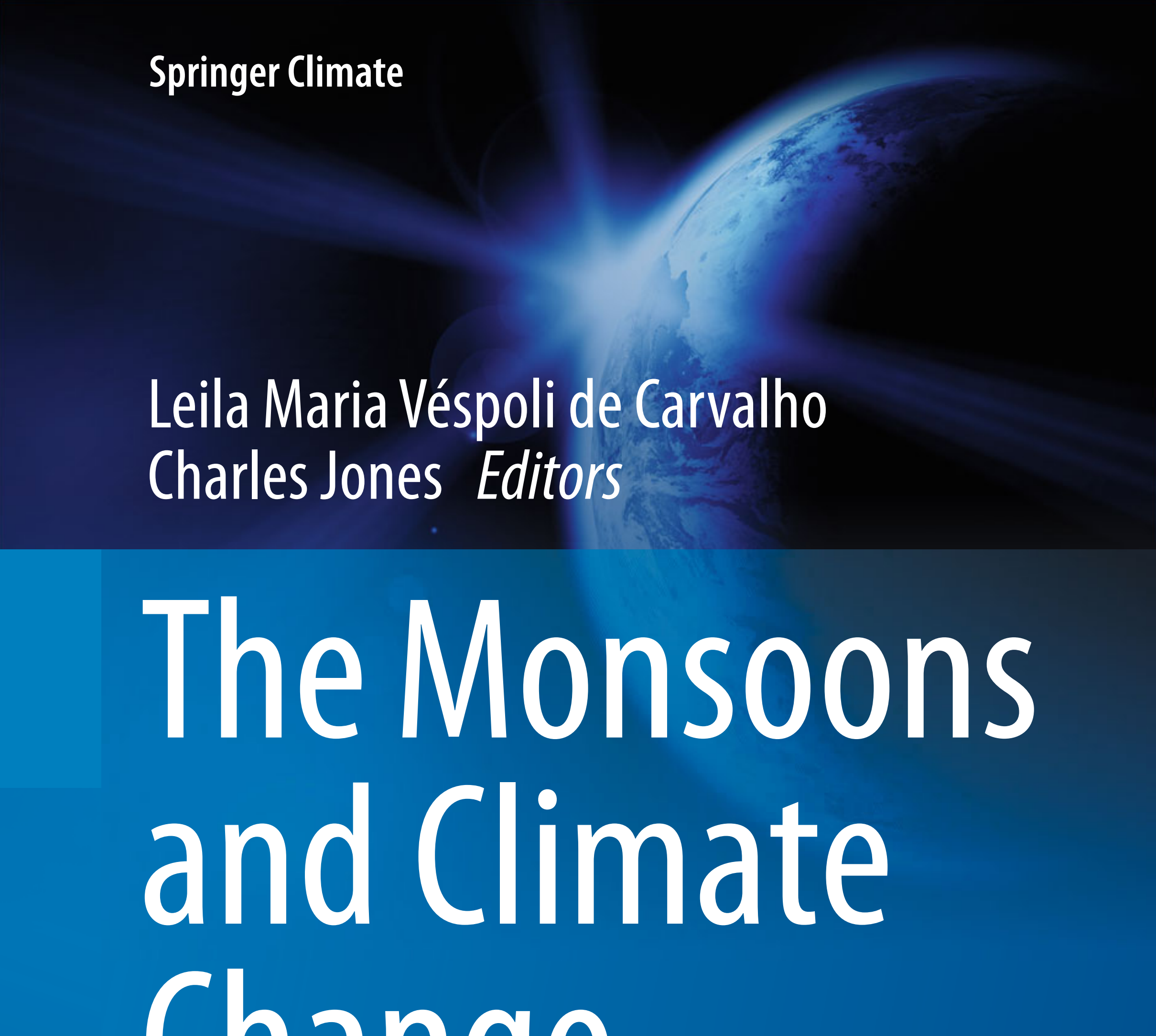

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The Monsoons and Climate Change

Observations and Modeling

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Preface

Monsoon systems are unique features of the climate of the Earth. While monsoons were historically defined as a “reversal in the surface winds accompanied by changes in precipitation” over the Bay of Bengal and Arabian Sea, modern studies in fact show that, except for the Polar Regions, monsoons occur in Africa, Asia, Indonesia, Australia, and the Americas. Driven primarily by the thermal contrast between large land masses and surrounding oceans, the monsoons exhibit a phenomenal range of spatial and temporal variability. The annual onset of the rainy season and its demise, for instance, show considerable changes from year to year in each monsoon system. Similarly, the intensity of the monsoons varies on subseasonal, inter-annual, decadal, and centennial time scales. It is, therefore, widely recognized that the monsoons play a vital role for humans and the environment. Often the occurrence of extreme events, such as heavy precipitation or droughts, can have significant impacts on millions of people who live in monsoon regions and rely on water for human consumption, agriculture, energy, and transportation.

Observational and theoretical evidence points to the undeniable fact that the Earth’s climate is changing rapidly, and anthropogenic activities have been an important component of this change. Climate variability and change pose significant challenges for humans to develop adaptation strategies that can minimize negative impacts. This is the case in particular when important uncertainties in projections of regional climate change exist. While the monsoons have been investigated for many decades and the understanding of the physical mechanisms associated with them has progressed steadily over the years, there are many unresolved questions of how the continual warming of the planet will affect the monsoons.

This book originated from the conference session entitled “The Global Monsoons and Climate Change: Observations, Models and Projections” held at the fall meeting of the American Geophysical Union (AGU) in 2012 in San Francisco, California. A significant portion of the material presented here includes results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations, which contributed to the Fifth Assessment of the Intergovernmental Panel on

Climate Change (IPCC) finalized in 2013. Thus, the main goal of this book is to provide a concise and timely assessment of the monsoons and climate change.

The book has 11 chapters. Chapter 1 introduces the main intent of the book. A global view of the monsoons and its change are presented in Chap. 2. Chapters 3 and 4 discuss the Asian Monsoon variability and the projected changes in the twenty-first century. Chapter 5 covers the Australian summer monsoon and potential changes in upcoming decades, and the monsoon systems in South America and North America are discussed in Chaps. 6 and 7, respectively. Chapter 8 explores the seasonal variation of the Indo-Pacific monsoon circulation and interactions with the climate of East Africa. Connections between the North American and South American Monsoon systems are covered in Chap. 9. Since all monsoon systems exhibit significant variability on intra-seasonal time scales, Chap. 10 discusses future changes in the Madden-Julian Oscillation (MJO). Lastly, Chap. 11 analyzes the importance of the monsoon systems on glaciers in the central Andes and Himalayas.

The completion of this book was possible with the contributions of several authors who are experts in the research of monsoons and climate change. Their efforts and dedication are greatly appreciated, and we also thank Forest Cannon, Abheera Hazra, and Jesse Norris for their kind help in proofreading several sections of the book. Finally, we express our sincere appreciation for the support and professionalism of the editorial staff of Springer International Publishing.

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Chapter 1
The Monsoons and Climate Change

Leila Maria Véspoli de Carvalho

Abstract Monsoon systems are unique features of the climate of the Earth and the reality of global warming has important implications for the environment and human society. This chapter provides a brief overview of this important topic.

Keywords Monsoons · Climate change · Population · IPCC · CMIP5

Monsoon systems are among the most extraordinary and intriguing phenomena on our planet. The word "monsoon" comes from the Arabic word "*mawsim,*" meaning "season." Historically, the term monsoon" describes the seasonal variation in surface winds that played significant roles in navigation and maritime trades, particularly with India (Tripati and Raut 2006). Today, this term is used in a much broader context. Monsoons are considered planetary manifestations of pronounced thermal contrasts between large land masses and ocean basins enhanced by the existence of high elevations and plateaus, such as the Tibetan Plateau in Asia and the Andes in South America. These efficient engines pump moisture from large ocean basins across great distances in meandering flows that reach tropical lands during summer to drive the most powerful precipitating systems on Earth.

Monsoon regions are globally distributed over all tropical continents and in tropical oceans in the eastern and western North Pacific, and in the southern Indian Ocean. Figure 1.1 represents the geographical distribution of these monsoon regions by the relative contribution of summer precipitation to the total annual precipitation. Six monsoon systems have been recognized: the African, South Asian, East Asian, Australian, North American, and South American Monsoons. Although the American monsoon system has not been clearly identified with wind reversals (Webster et al. 1998), when the long-term mean is removed, an evident seasonal reversal in circulation emerges (Vera et al. 2006; Zhou and Lau 1998). These magnificent systems regulate the hydrological cycle in large portions of the

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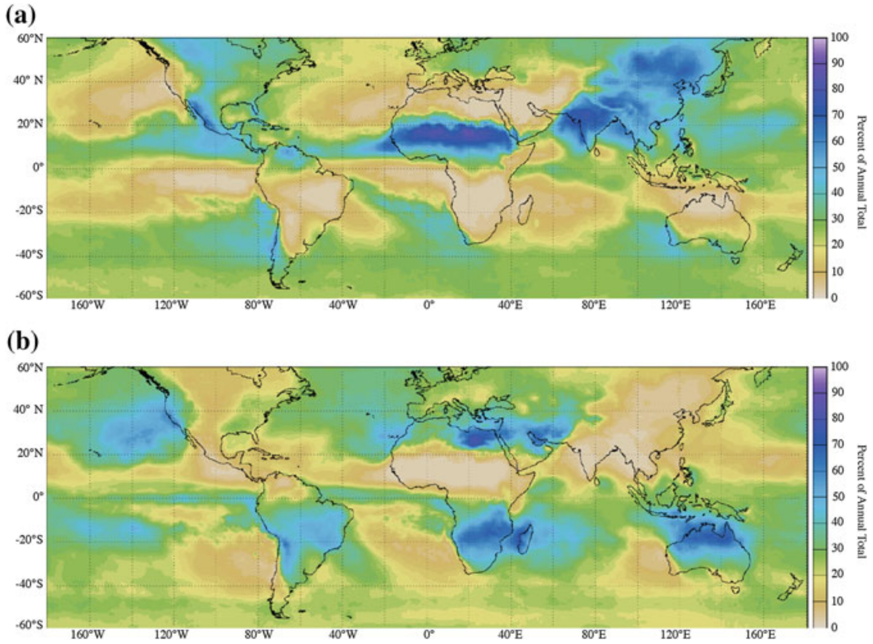

Fig. 1.1 Percent of annual precipitation during the summer peak in the northern hemisphere (June, July, August) and southern hemisphere summer (December, January, February). Precipitation data is from the Tropical Rainfall Measurement Mission (TRMM) at 25° resolution. **a** Percent of annual precipitation during June, July and August. **b** Percent of annual precipitation during December, January and February

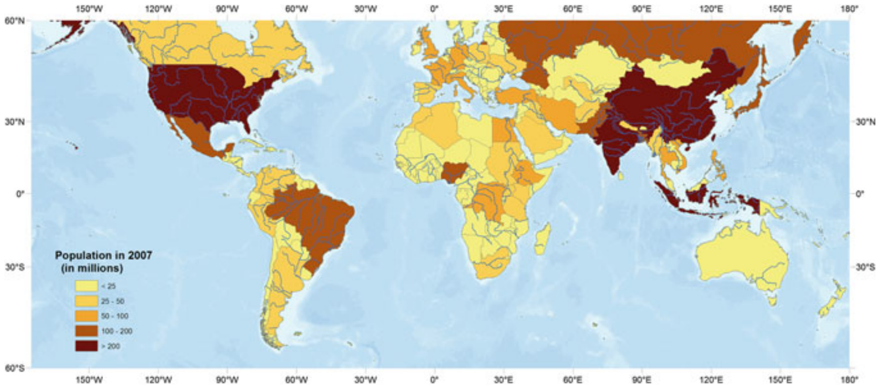

Fig. 1.2 World's population (in millions of inhabitants) as of 2007, and major river systems. *Data source* Environmental Systems Research Institute (ESRI)

tropics and are essential for creating the Earth's most diverse ecosystems and allowing the development of agriculture and human settlements throughout time.

Figure 1.2 shows the geographic distribution of the world's population and evidences the remarkable importance of monsoon systems for the subsistence of billions of people. The Earth's population in 2013 was estimated to be 7,162 billion people, with about 43 % of this population living in four countries largely affected by monsoonal regimes: China (first in the rank), India (second), Indonesia (third), and Brazil (fourth). According to projections of the United Nations (2013), the world's population is estimated to reach over 10 billion by the end of the twenty-first century, with India leading the rank and the most populated countries exhibiting territory partially or totally influenced by monsoon systems. Therefore, more than 50 % the Earth's population will be directly or indirectly influenced by monsoon systems and will be mostly susceptible to the effects of global warming and climate change in these regions. With the growth in population, the demand for food is expected to increase proportionally. Rice is among the most important crops that feeds the world (Seck et al. 2012), and countries influenced by the South Asia and East Asia monsoons lead rice production (http://www.geohive.com/). Climate change in monsoon regions increases the risks of infectious diseases that are usually exacerbated in developing countries due to inadequate sanitary conditions, malnutrition, and insufficient access to health services, clean water, and other basic necessities (Jones et al. 2008; Patz et al. 2005). Thus, variations and changes in intensity, frequency, and regularity of monsoonal precipitation are and will continue to be crucial for food and health security.

The abundant rainfall produced by summer convective systems over land controls soil moisture and the extent of wetlands and river flows, creates feedback (Douville et al. 2001; Eltahir 1998; Small 2001) and regulate carbon cycles (Richey et al. 2002). The dry period during the winter months following the wet season reinvigorates crop cycles, which are relevant for carbon sequestration (Carvalho et al. 2009). The dry season is also the period of intense biomass burning, particularly from rainforests and pasture, a practice that is very common in all monsoon regions (Crutzen and Andreae 1990; Fearnside 2000; Hao and Liu 1994; Haywood et al. 2008; Lestari et al. 2014). Hobbs et al. (1997) estimate that about 80 % of all biomass burning occurs in the tropics. Biomass burning from anthropogenic or natural origin releases large quantities of CO, CO_2, acetonitrile, methyl chloride, hydrocarbons, NO, O_3, and aerosols in the atmosphere, which are transported through long distances affecting air quality across the globe and causing complex feedback in the climate system that have yet to be identified and properly quantified (Andreae et al. 1988; Andreae et al. 2001; Freitas et al. 2005). Global warming may cause regional variations in monsoonal circulation and modify the length of the wet and dry seasons, resulting in variations in the distribution of precipitation and cloudiness that can accelerate climate change by modifying carbon cycles (Luo 2007; White et al. 1999) and radiation budgets, among other processes. The anthropogenic component of these changes is difficult to evaluate as society evolves and exerts significant pressure on the environment by intensifying land-use-land-cover-change and releasing greenhouse gases and aerosols in the atmosphere (Karl and Trenberth 2003; Trenberth 2011).

The increase in surface temperatures also has important implications for the hydrological cycle in regions where the water supply depends on the melting of snow and ice, such as the Andes and the Himalayas. There is evidence that the South American Monsoon and the Indian Monsoon are essential for supplying moisture and precipitation to high elevations (Barnett et al. 2005; Bird et al. 2011), and possibly controlling surface temperatures through cloud radiative transfer processes. In addition, changes in precipitation affect the volume and timing of runoff with dramatic impacts for populations living downslope of these mountains (Bookhagen and Burbank 2010; Bookhagen and Strecker 2012).

Understanding and assessing the anthropogenic influence on the monsoons is especially challenging for several reasons: vast areas covered by rain forests and complex terrain with limited access to instrumentation; intermittent and scarce observations, particularly for periods extending before the satellite era; and monsoon regions dominated by developing and least developing countries (according to the United Nations) that provide limited support for installing and maintaining meteorological stations. Although monitoring climate variations in monsoon regions has considerably improved since the advent of satellites, long-term trends and regional to local climate change signals are virtually unknown in large areas under the influence of monsoon systems.

The compelling evidence of warming of the climate system since the twentieth century and the anthropogenic interference in this process motivated the United Nations to create the Intergovernmental Panel on Climate Change (IPCC). The IPCC is a scientific intergovernmental body that was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNE), with the goal of producing reports that support the United Nations Framework Convention on Climate Change, which is considered the main international treaty on climate change. The IPCC reports "cover the scientific, technical and socio-economic information relevant to understanding the scientific basis of the risk of human-induced climate change, its potential impacts and options for adaptation and mitigation" (www.ipcc.ch). The completion of the Fifth Assessment Report of (AR5) the Intergovernmental Panel on Climate Change (IPCC 2013) provided the most updated scientific understanding of climate change and its implications.

The main purpose of this book is to provide a concise and timely assessment of monsoons and climate change based on the AR5 and other recent scientific contributions; its 11 chapters cover the monsoons from a global perspective as well as each individual monsoon system. A global view of the monsoons and their changes are presented in Chap. 2. Chapters 3 and 4 discuss the Asian Monsoon variability and the projected changes in the twenty-first century, while Chap. 5 covers the Australian summer monsoon and potential changes in the coming decades. The monsoon systems in South America and North America are discussed in Chaps. 6 and 7, respectively. Chapter 8 explores the seasonal variation of the Indo-Pacific monsoon circulation and interactions with the climate of East Africa. Connections between the North American and South American Monsoon systems are discussed in Chap. 9. Since all monsoon systems exhibit significant variability on intra-seasonal time scales, Chap. 10 discusses future changes in the Madden-Julian Oscillation (MJO). Finally, Chap. 11 analyzes the importance of the monsoon for glacier systems.

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Chapter 2
Global Monsoon in a Changing Climate

Pang-Chi Hsu

Abstract Monsoons, the most energetic tropical climate system, exert a great social and economic impact upon billions of people around the world. This chapter reviews recent progress in our understanding of the global monsoon (GM) system and its associated precipitation changes in the present and future warming climates. The GM can be viewed as an integrated system of all regional monsoons over the globe that are driven by solar forcing and bounded by the planetary-scale overturning circulation. The GM precipitation (GMP), defined as the total summer monsoon precipitation amount within the GM area (GMA), experienced multi-decadal variability in the twentieth century. The observed GMP over land shows a slightly increasing trend from 1900 throughout the 1940s, and then a downward trend from the 1950s until the end of the 1970s; there was no clear trend after 1980. The GMP over the ocean has had more uncertainty over the past three decades, and trends are inconsistent among different global rainfall datasets. In the twenty-first century, the GMP is expected to increase robustly, based on the projections by the state-of-the-art coupled models that participated in Phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5). The change in GMP under global warming is primarily due to changes to the hydrological cycle induced by warmer temperatures. The increase in water vapor contributes positively to moisture convergence and surface evaporation over the GMA, but is partly offset by the weakening of the monsoon circulation.

Keywords Global monsoon · Monsoon precipitation variability · Global warming · CMIP3 · CMIP5

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2.1 Introduction

"Monsoon" is conventionally defined as the seasonal reversal in lower-tropospheric winds (Ramage 1971), and its associated precipitation is characterized by a contrast between wet summers and dry winters (Webster 1987). The contrast is induced by the annual cycle of solar heating and seasonal changes in large-scale continent-ocean thermal contrast. Monsoons occur around the globe: in Asia, Australia, Africa, and throughout the Americas (Webster et al. 1998). From a regional perspective, an individual monsoon system evolves according to the local land-sea configuration, orography, and feedback with the distinct elements of the climate system. The features and variations of each regional monsoon have been extensively studied over the past three decades (e.g., Davidson et al. 1983; McBride 1987; Tao and Chen 1987; Webster 1987; Ding 1994; Higgins et al. 1997; Webster et al. 1998; Sultan and Janicot 2003; Goswami 2005; Vera et al. 2006).

More recently, an emerging concept of the global monsoon (GM) has been proposed to describe the combined variability of monsoon systems around the world. Considering that all regional monsoons are associated with the annual cycle of solar heating and that the global-scale circulation is necessitated by mass conservation, Trenberth et al. (2000) depicted the GM system as a persistent global-scale overturning of the tropical atmosphere that varies with seasons. In a dynamic sense, the rainfall distributions reflect the tropospheric heat sources that drive the circulation in the tropics; thus, the planetary-scale overturning circulation is closely associated with the seasonal variation of precipitation. Wang and Ding (2008) documented that in the climatological context, the GM system is the dominant mode of annual precipitation and 850 hPa winds in the tropics. Applying a multi-variable empirical orthogonal function (EOF) analysis to climatological monthly precipitation and low-level wind fields, two leading modes—accounting for 84 % of the annual variance—were obtained. The first mode, called the solstitial mode, represents the atmospheric response to the meridional differential of annual solar forcing. The second mode, the equinoctial asymmetry mode, reflects the asymmetric patterns between spring and autumn. Both modes characterize the seasonality of tropical climate (Wang and Ding 2008).

In short, the GM is a response of the coupled climate system to the annual cycle of solar forcing. From this global perspective, the precipitation over each monsoon region combines to form the GM system, which is associated with a planetary-scale overturning circulation throughout the tropics (Trenberth et al. 2000, 2006).

2.2 Delineations of Global Monsoon Precipitation, Area, and Intensity

The monsoon climate features the seasonal variations in both wind and precipitation. Earlier studies used the reversal in wind direction and speed to identify a monsoon domain (Ramage 1971). Such monsoon domains are found mainly over the Eastern Hemisphere because the seasonal wind reversal is less significant over the Americas. Besides the wind field, precipitation is another fundamental variable used to delineate the monsoon climate. Monsoon precipitation is characterized by a concentration of yearly rainfall in the local summer and a dry period in the local winter (Webster 1987). Using a simple parameter based on precipitation, Wang and Ding (2006) defined the global monsoon area (GMA) as the regions in which the annual range (AR—the local summer-minus-winter rainfall) of rainfall exceeds 180 mm and the summer-to-annual rainfall ratio is greater than 35 %. In the Northern Hemisphere (NH), the summer is defined as June to August (JJA) and the winter is defined as December to February (DJF). In the Southern Hemisphere (SH), the definitions are reversed. Figure 2.1 shows the derived GMA based on the climatological monthly rainfall averaged from the Global Precipitation Climatology Project (GPCP; Adler et al. 2003) and the CPC Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) datasets. The known monsoon systems around the world, including the Asian, Australian, northern and southern African, and North and South American Monsoons, are well identified.

Following the approach of Wang and Ding (2006), other studies modified the lengths of summer and winter seasons and the criteria of rainfall indices. For example, Liu et al. (2009) used a longer length of local summer (May to September (MJJAS) for the NH) and winter (November to March (NDJFM) for the NH) months. The two criteria for GMA were modified as the AR (MJJAS and NDJFM difference) exceeding 2 mm day^{-1} and the ratio of summer-to-annual rainfall exceeding 55 %. The defined GMA (Fig. 2 in Liu et al. 2009) is almost identical to that shown in Fig. 2.1. The GMA presented in Wang et al. (2011) was based on alternative criteria—AR (JJA and DJF difference) exceeding 2 mm day^{-1} and 70 % of the annual mean, and it also agrees with the results shown in Fig. 2.1 and other similar studies (Wang and Ding 2008; Liu et al. 2009). Therefore, the defined GMA is not very sensitive to the two criteria with some modifications.

Total rainfall amount during a local summer (JJA for the NH, and DJF for the SH) is the major factor determining the amplitude of AR. Generally, a larger AR (wet-dry season contrast) reflects a more active monsoon. Therefore, the total GM

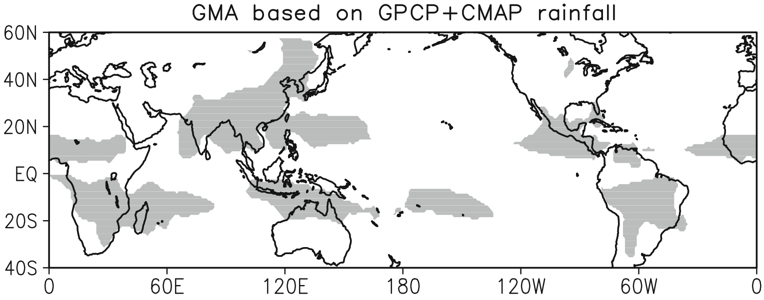

Fig. 2.1 Observed global monsoon area (*shaded area*) derived from the average of GPCP and CMAP climatological rainfall for 1979–2008

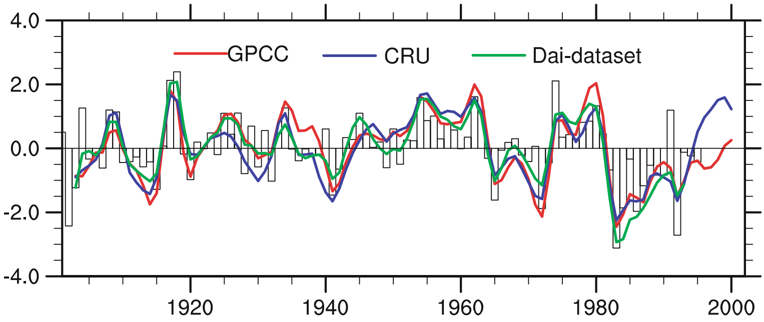

Fig. 2.2 Time series of normalized global land monsoon precipitation anomalies. The bars denote the GMP over land based on the data compiled by Dai (*Dai-dataset*). The anomalies are calculated relative to the mean of 1951–1979, using the precipitation datasets developed by the Global Precipitation Climatology Centre (*GPCC*) and by the Climate Research Unit (*CRU*), and the Dai-dataset. The *red*, *blue*, and *green curves* are 5-year running means of GPCC, CRU and Dai-dataset, respectively. According to Zhang and Zhou (2011)

precipitation (GMP)—the sum of summer rainfall within the GMA—is proposed to describe the monsoon strength (Wang and Ding 2006, 2008; Liu et al. 2009). Given that the global circulation and the land-sea surface-temperature contrast may experience significant changes from one climate condition to another, induced by sea-surface-temperature (SST) anomalies or anthropogenic forcing, the GMA may be subject to some temporal/spatial variability. To describe the GMP change associated with a varying GMA, the global monsoon intensity (GMI) index, which measures the GMP amount per unit area, was introduced (Zhou et al. 2008a; Hsu et al. 2011; Wang et al. 2011). Because the area in each grid box varies with latitude, an area-conserving metric is applied when calculating the GMA and GMP. The long-term variability of GMA, GMP, and GMI over the past decades and their projected changes under certain global warming scenarios, are reviewed in the following two sections, respectively.

2.3 Observed Changes in Global Monsoon Activity

2.3.1 Trends in GM Precipitation in the Twentieth Century

After the concept of the GM was proposed, a number of researchers began to investigate the variability of GMP over continental monsoon areas inhabited by billions of people. Chase et al. (2003) analyzed the variation of land precipitation along with surface pressure and upper-level divergence in the Asian, Australian, and African monsoon regions between 1950 and 1998. Consistent reductions in land rainfall and monsoonal circulations have been detected over the monsoon regions globally since 1950. However, this decreasing trend has leveled off since 1979, when the strongest global warming has been reported in terms of averaged surface temperature. Using four sets of rain gauge observations for the 1948–2003 period, Wang and Ding (2006) also pointed out an overall downward trend in rainfall over land within global monsoon domains, particularly before 1980. The weakening of GMP over land was mainly attributed to the decreased summer monsoon rainfall in the NH because the monsoon rainfall in the SH showed no significant trend over the same period (Wang and Ding 2006). Zhou et al. (2008a) further pointed out that not only the monsoon precipitation intensity, but also the total monsoon area, contributed to this weakening trend in global land monsoon rainfall from 1949 to 2002.

Using a century-long observational rainfall dataset, Zhang and Zhou (2011) found that the global land monsoon precipitation exhibited a significant multi-decadal variability during the twentieth century (Fig. 2.2). A significant upward trend in the global land monsoon precipitation was shown in the first half of the century (1901–1955), followed by a downward trend in the latter half (1955–2001), as documented in other studies (Chase et al. 2003; Wang and Ding 2006; Zhou et al. 2008a). Because of this multi-decadal change, the overall trend for the twentieth century (1901–2001) was not statistically significant at the 95 % confidence level.

As discussed above, the results based on rain-gauge observations show no significant trend in rainfall over the global land monsoon areas since 1979. Was this the same for the precipitation change over the oceanic monsoon regions? Wang and Ding (2006) used the GPCP dataset to examine the GMP over oceans and found a significant increasing trend from 1979 to 2003. This change in oceanic monsoon rainfall, however, is not robust and depends on data sources (Zhou et al. 2008b; Hsu et al. 2011). In contrast to the GPCP data, the CMAP data indicate a weak declining monsoon rainfall over the global oceanic monsoon regions for the period of 1979–2008. The inconsistency of rainfall variability over the oceans between the GPCP and CMAP datasets was attributed to different algorithms used to retrieve the precipitation from the satellite data (Gruber et al. 2000).

The trends in global oceanic monsoon rainfall have dominated the trends in total GMP over the past three decades (Wang and Ding 2006; Zhou et al. 2008b; Hsu et al. 2011). The GMP showed an increasing trend from 1979 to 2008 based on the GPCP rainfall data, while it revealed a downward tendency over the same period using the CMAP dataset (Fig. 2.3). Zhou et al. (2008b) found that the oceanic monsoon rainfall derived from the GPCP dataset was highly correlated with that of the Special Sensor Microwave Imager (SSM/I), which might be the best available precipitation estimates over the ocean. This suggests that the trend in GMP obtained from the GPCP data is probably more reliable than that from the CMAP data. With a focus on the monsoon change at the hemispheric scale, Wang et al. (2013) found consistent enhancements of NH monsoon rainfall and of the Walker and Hadley circulations from 1979 to 2011.

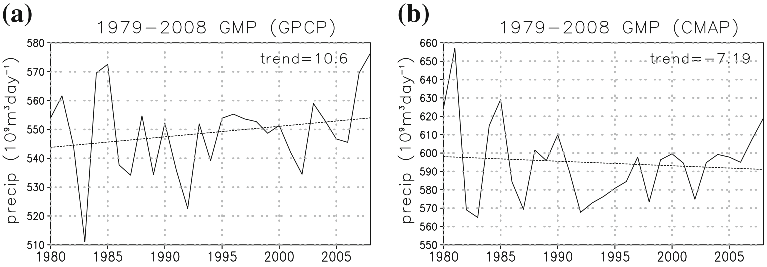

Fig. 2.3 **a** Time series of global monsoon precipitation (GMP; units: 10^{9} m^{3} day^{-1}) calculated from (s) the GPCP and **b** the CMAP datasets for 1979–2008. The linear trend of each time series is indicated by a *dotted line*, with the linear trend [units: 10^{9} m^{3} day^{-1}(29 year)$^{-1}$] noted on each panel. (Adapted from Hsu et al. 2011)

2.3.2 Factors Controlling the GMP Change

Variations in GMP can be attributed to tropical atmospheric responses to varying forcing fields, such as SST, shortwave forcing resulting from the effect of aerosols, and longwave forcing induced by growing greenhouse gas emissions. Wang et al. (2012) discussed the mechanisms regulating the NH summer monsoon rainfall over land and adjacent ocean areas. They suggested that the zonal contrast of eastern and western Pacific SST plays an important role in causing the enhanced NH monsoon precipitation. The recent trend of eastern Pacific cooling and western Pacific warming favors the high (low) pressure anomaly in the eastern (western) Pacific and the trades that transport moisture into the Asian and African monsoon regions (Wang et al. 2013). Moreover, the intensification of NH monsoon rainfall is consistent with the increased inter-hemispheric thermal contrast. The pattern associated with a warmer NH and a cooler SH over the past three decades would induce strengthened cross-equatorial flows driven by meridional pressure gradients. As a result, more moisture is transported from the SH into the NH, favoring the monsoon rainfall in the NH (Wang et al. 2012).

Long-term simulations under different forcing fields may help to clarify the factors controlling the observed GMP changes. Zhou et al. (2008b) showed that the observed weakening trend in global land monsoon precipitation over the second half of the twentieth century was successfully reproduced by the NCAR Community Atmosphere Model version 2 (CAM2) driven by observed SSTs between 1950 and 2000. The results indicated that the changes in GMP over land may have arisen from oceanic forcing. In the second half of the twentieth century (1950–2000), significant warming trends were observed over the central-eastern Pacific Ocean and the tropical Indian Ocean. Zhou et al. (2008b) further argued that the recent warming over the central-eastern Pacific Ocean and the tropical Indian Ocean contributed to the reduction of global land monsoon precipitation during the period of 1950–2000 reported by Wang and Ding (2006).

In addition to the SST influence, aerosols have been reported to have significant impacts on regional rainfall in several ways (e.g., Turner and Annamalai 2012).

Focusing on the effect of volcanic aerosols, Kim et al. (2008) analyzed the GMP changes in the twentieth-century simulations for the period of 1951–1999 from the models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). They found that among 21 CMIP3 models, those with volcanic aerosols simulated the decreasing trends of NH land monsoon rainfall since 1950, suggesting that the natural volcanic forcing could be an important contributor to the reduction of global land monsoon precipitation. The results of Kim et al. (2008) were similar to the findings of Lambert et al. (2004), who argued that variation in land precipitation was controlled more by the natural shortwave forcing of volcanic aerosols than by the longwave forcing of greenhouse gases. External forcing associated with volcanic aerosols plays a crucial role in multi-decadal variability of torrential precipitation in both observations and model simulations (Broccoli et al. 2003; Gillett et al. 2004).

2.4 Future Projections of Global Monsoon

The rise in the average temperature of the Earth's atmosphere and oceans—namely, global warming—has been observed since the late twentieth century and is projected with very high probability to continue in the coming century (e.g., IPCC 2007, 2013). Estimates of GM change under a warmer future climate primarily rely on projections from climate models. Thanks to great advances in computing power and numerical model developments, state-of-the-art atmospheric general circulation models (AGCMs) and ocean-atmosphere, coupled general circulation models (CGCMs) driven by various global-warming forcings, may help to provide consistent projected signals and enhance our confidence in these future GM changes. A number of robust signals related to GM change were identified from the recent modeling studies based on various multi-model ensemble (MME) approaches (Hsu et al. 2012, 2013; Chen and Sun 2013; Kitoh et al. 2013; Lee and Wang 2014). In this section, future changes in GM domain, total amount of monsoon precipitation, extreme monsoon precipitation events, timing of monsoon onset and retreat, and inter-annual variability of GM are reviewed and discussed.

2.4.1 Changes in GM Domain

Based on simulations of three high-resolution (20–50 km) AGCMs forced by various future SST warming patterns during the twenty-first century, Hsu et al. (2012) indicated a consistent increase of GMA under global warming. The GMA increased around 7–9 % from the end of the twentieth century to the end of the twenty-first century in these simulations. Marked expansions occurred over the oceans, which accounted for 80–90 % of the total contribution to the GMA change in these simulations.

The expansions of GM domain were also projected in the MMEs of CMIP3 and CMIP5 models, although the spread of individual models is large (Hsu et al. 2012, 2013; Kitoh et al. 2013; Lee and Wang 2014). As shown in Fig. 2.4, the GMA projections show a 3–6 % increase from the late twentieth century (1979–2003) to the end of the twenty-first century (2075–2099) based on many ensemble members (~20 or more) of CMIP5 models under the Representative Concentration Pathways 4.5 (RCP4.5) scenario and of CMIP3 models under the Special Report on Emissions Scenarios (SRES) A1B scenario (Chen and Sun 2013; Hsu et al. 2013; Kitoh et al. 2013). The averaged expansion of GMA was larger (~9 %) when the models were forced with the higher greenhouse gas emissions under the RCP8.5 scenario (Kitoh et al. 2013). Even so, Hsu et al. (2013) indicated that the expansion rate of GMA is not significantly correlated with the increase in global mean surface air temperature.

Rather than analyzing MMEs based on all CMIP3 or all CMIP5 models, Lee and Wang (2014) conducted an MME analysis based on the four models among 20 CMIP5 models that most accurately simulated monsoon precipitation characteristics during the period of 1980–2005. Similar to the results of all models' MME, the four best models' MME (B4MME) projects an increased GMA with a change rate of 4.6 % (2.6 % for land and 6.3 % for ocean) from the end of the twentieth century (1980–2005) to the end of the twenty-first century (2070–2095) under the RCP4.5 scenario. However, this change does not exceed the uncertainty measured by a standard deviation of inter-model spread.

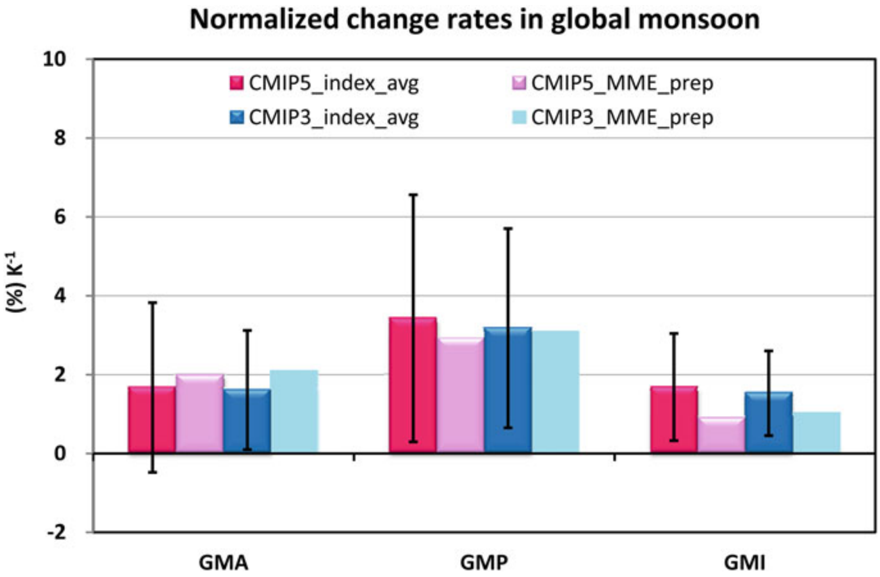

Fig. 2.4 Averages and inter-model standard deviations [*red* (*blue*) bars with whiskers] of GMA, GMP and GMI change rates between RCP4.5 (A1B) from 2075 until 2099, and historical (20C3 M) from 1979 to 2003 in 19 CMIP5 (24 CMIP3) simulations. *Pink* (*light blue*) bars show the change rates calculated from the CMIP5 (CMIP3) multi-model ensemble mean precipitation. (Adapted from Hsu et al. 2013)

According to the CMIP5 MME results, under the RCP4.5, the increased GMA will be distributed along the edges of the present-day GMA, especially for the global oceanic monsoon regions (Hsu et al. 2013). This is consistent with the B4MME results of Lee and Wang (2014), which suggested that the monsoon domain will tend to increase over oceanic monsoon regions while it will apparently not change over land except for a westward movement of Asian continental monsoon areas. Based on the RCP8.5 simulations, Kitoh et al. (2013) identified GMA expansions mainly over the central-to-eastern tropical Pacific, the southern Indian Ocean, and eastern Asia.

The future expansion of GMA may be attributed to both an increased annual range of precipitation under global warming (Chou and Lan 2012) and a stronger summer-to-annual rainfall ratio (Hsu et al. 2012; Lee and Wang 2014). Hsu et al. (2013) analyzed the absolute change of monthly rainfall within the GMA and found a prominent increase in local summer monsoon rainfall over the globe. Projected winter rainfall within the GMA, however, shows less significant change, with a small increase (decrease) in the NH (SH). These results indicate that global warming may induce a wetter summer over the GM regions, and enhance the contrast between rainy and dry seasons (especially in the SH).

2.4.2 Changes in GM Precipitation and Intensity

The expansion of the GMA may cause changes in GMP, as a larger monsoon domain would receive more rainfall. As shown in Fig. 2.4, the MME indicates a 6–9 % increase in GMP under the SRES A1B and RCP4.5 scenarios (Hsu et al. 2013), and much more ($\sim$16.6 %) in the RCP8.5 scenarios from the end of the twentieth century to the end of the twenty-first century (Kitoh et al. 2013). Due to a greater rate of increase of GMP than of GMA, the GM intensity, which is defined as the monsoon precipitation amount per unit area, will tend to strengthen in future warmer climate. The increase of GMI from the end of the twentieth century until the end of the twenty-first century ranges from 2 to 4 % in the CMIP3 and CMIP5 MME results, respectively (Fig. 2.4).

Precipitation extremes occurring in all regional monsoons are projected to increase at a much greater rate than the GMP (Kitoh et al. 2013). For example, GMP will increase by −6.5 to 12.9 % by the end of the twenty-first century, according to the RCP8.5 simulations, while the simple daily precipitation intensity index, defined as total precipitation divided by the number of rainy days (≥1 mm), shows—0.7 to 14.7 % increase. The index of seasonal maximum precipitation total over five consecutive days within the global monsoon areas shows an even greater increase (6.2–22.1 %) under the RCP8.5 scenario. As well as the increase in extreme precipitation events, indices of extreme dry events (such as maximum number of consecutive no-rain days) within the GMA are projected to increase (Lu and Fu 2010; Turner and Annamalai 2012). This suggests that although the frequency of precipitation events would decrease in a future warmer climate, the precipitation intensity of individual events could be greater (Kitoh et al. 2013).

Lee and Wang (2014) illustrated the spatial distribution of GMP change based on the B4MME (Fig. 2.5). The CMIP5 models projected a remarkable enhancement (reduction) of monsoon rainfall over Asia (northern America). Monsoon rainfall over Australia and Africa also show positive contributions to the increased GMP, but with less significance and robustness. The relative contributions from regional monsoons to the GMP projected by the B4MME generally agree with those derived from the CMIP5 models' MME (Kitoh et al. 2013); in other words, the Eastern-hemisphere monsoons will produce more precipitation than the Western-hemisphere monsoons, and the NH monsoons will produce more precipitation than the SH monsoons. This means that future changes in GMP can be characterized by a prominent east–west contrast and a north–south asymmetry. As with the summer mean monsoon rainfall projections, the extreme precipitation events are also projected to increase most significantly in the Asian monsoon domain, suggesting that the Asian monsoon is particularly sensitive to global warming (Kitoh et al. 2013).

To better understand the physical processes that cause the increase in GMP projected by the CMIP5 models, Hsu et al. (2013) examined a column-integrated moisture budget within the GMA in present-day and future-climate simulations, respectively.

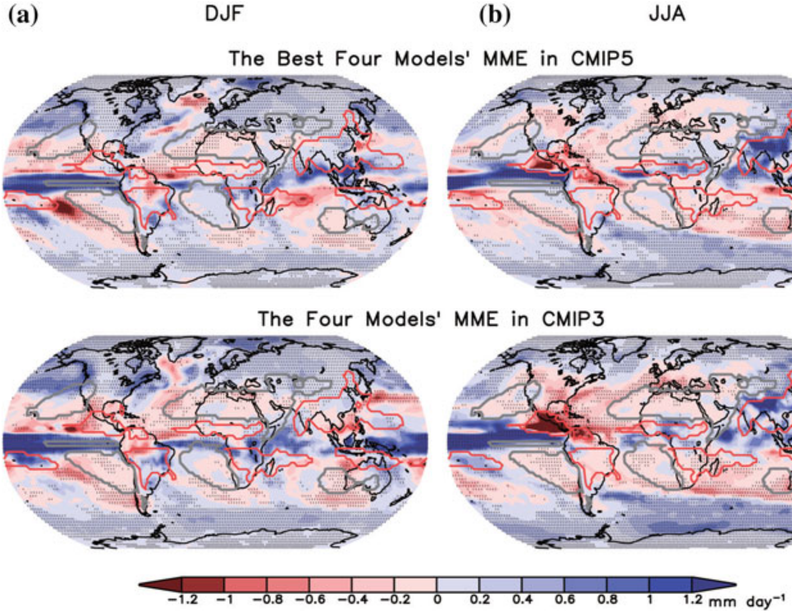

Fig. 2.5 Changes in **a** annual mean precipitation, and **b** annual range of precipitation. The annual range is defined as absolute value of JJAS mean minus DJFM mean precipitation rate. Changes are given for the RCP4.5 (A1B) simulation for 2070–2095 relative to the historical simulation for 1980–2005, in CMIP5 (CMIP3) in the *upper* (*bottom*) panels. *Red* contours delineate the GMA. (Adapted from Lee and Wang 2014)