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Global monsoon : Concept and dynamic response to anthropogenic warming

BIN WANG*, **, CHUNHAN JIN***, # and JIAN LIU##, $, $$

**Department of Atmospheric Sciences and International Pacific Research Center,*
School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii 96825, USA

***Earth System Modeling Center, Nanjing University of Information Science and Technology, Nanjing 210044, China*

****College of Geography and Remote Sensing Science, Xinjiang University, Urumqi 830046, China*

#Xinjiang Key Laboratory of Oasis Ecology, Xinjiang University, Urumqi 830046, China

##Key Laboratory for Virtual Geographic Environment of Ministry of Education/ State Key Laboratory of Geographical Evolution of Jiangsu Provincial Cultivation Base/Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, School of Geography Science, Nanjing Normal University, Nanjing, 210023, China

$Open Studio for the Simulation of Ocean-Climate-Isotope, Pilot National Laboratory for Marine Science and Technology, Qingdao, 266237, China

$$Jiangsu Provincial Key Laboratory for Numerical Simulation of Large Scale Complex System, School of Mathematical Science, Nanjing Normal University, Nanjing, 210023, China

(**e mail : wangbin@hawaii.edu)**

सार – सदियों से मानसून का अध्ययन किया गया है, फिर भी हाल ही में क्षेत्रीय मानसून को वैश्विक प्रणाली के रूप में मान्यता दी गई है। यह पेपर ग्लोबल मॉनसून की अवधारणा और संबंधित बहस के मुद्दों के साथ शुरू होता है। हमारा तर्क है कि जीएम हैडली सर्कुलेशन, इंटरट्रॉपिकल कन्वर्जेंस ज़ोन और उपोष्णकटिबंधीय उच्च और शुष्क जलवायु क्षेत्रों के वार्षिक चक्रों को चलाता है। भूमि मानसून वर्षा (LMR) दुनिया की लगभग 70% आबादी के लिए जल संसाधन प्रदान करती है। यहां हम युग्मित मॉडल इंटरकंपेरिसन प्रोजेक्ट (CMIP6) के चरण छह में भाग लेने वाले मॉडलों द्वारा अनुमानित परिवर्तनों के लिए जिम्मेदार महत्वपूर्ण भौतिक प्रक्रियाओं पर ध्यान केंद्रित करते हुए मानवजनित वार्मिंग के लिए वैश्विक और क्षेत्रीय एलएमआर की जलवायु संवेदनशीलता की समीक्षा करते हैं। सिद्धांत रूप में, मध्य-क्षोभमंडलीय चढ़ाई और 850-एचपीए विशिष्ट आर्द्रता के उत्पाद में परिवर्तनों के साथ-साथ वाष्पीकरण से मध्यम योगदान से क्षेत्रीय माध्य एलएमआर परिवर्तनों का अनुमान लगाया जा सकता है। ग्रीनहाउस गैसों (जीएचजी) के दबाव से नमी की मात्रा बढ़ जाती है लेकिन वातावरण स्थिर हो जाता है; दो थर्मोडायनामिक प्रभाव एक दूसरे को ऑफसेट करते हैं, जिसके परिणामस्वरूप LMR पर मध्यम थर्मोडायनामिक प्रभाव पड़ता है। जीएचजी-प्रेरित क्षैतिज रूप से विभेदक वार्मिंग के परिणामस्वरूप मजबूत "उत्तरी गोलार्ध (एनएच) -दक्षिणी गोलार्ध की तुलना में गर्म (एसएच)", "भूमि-गर्म-से-महासागर" और एक एल नीनो-जैसे वार्मिंग पैटर्न होता है। बढ़ी हुई एनएच-एसएच थर्मल कंट्रास्ट एनएच मानसून वर्षा को बढ़ाएगी और एसएच मानसून वर्षा को कम करेगी। बढ़ी हुई भूमि-महासागर थर्मल कंट्रास्ट एशियाई-उत्तरी अफ्रीकी मानसून क्षेत्रों में मानसून की वर्षा को बढ़ाएगी। अनुमानित पूर्वी प्रशांत वार्मिंग उत्तरी अमेरिकी मानसून को कम कर देगी। अंतर-मॉडल प्रसार विश्लेषण से पता चलता है कि जीएचजी-प्रेरित संचलन परिवर्तन (गतिशील प्रभाव) मुख्य रूप से क्षेत्रीय अंतर के लिए जिम्मेदार हैं। अंतिम खंड आगे बढ़ने के बोधगम्य तरीकों पर चर्चा करता है।

ABSTRACT. Monsoon has been studied for centuries, yet only recently have regional monsoons been recognized as a global system. This paper begins with are view of the concept of Global Monsoon and related debating issues. We argue that GM drives annual cycles of Hadley circulation, Intertropical Convergence Zone and subtropical high and dry climate regions. Land monsoon rainfall (LMR) provides water resources for about 70% of the world's population. Here we review the climate sensitivity of global and regional LMR to anthropogenic warming projected by models participating in phase six of the Coupled Model Intercomparison Project (CMIP6), focusing on critical physical processes responsible for projected changes. In theory, regional mean LMR changes can be approximated by the changes in the product of the mid-tropospheric ascent and 850-hPa specific humidity, plus moderate contribution from evaporation. The greenhouse gases (GHGs) forcing increases moisture content but stabilizes the atmosphere; the two thermodynamic effects offset each other, resulting in a moderate thermodynamic impact on LMR. The GHGs-induced horizontally differential warming results in robust "northern hemisphere (NH)-warmer than-southern hemisphere (SH)", "land-warmer-than-ocean" and an El Nino-like warming pattern. The enhanced NH-SH thermal contrast will increase NH monsoon rainfall and reduce SH monsoon rainfall. The enhanced land-ocean thermal contrast will increase monsoon rainfall over the Asian-northern African monsoon regions. The projected eastern Pacific warming will reduce the North American monsoon. The Inter-model spread analysis suggests that the GHGs-induced circulation changes (dynamic effects) are primarily responsible for the regional differences. The last section discusses conceivable ways forward.

Key words – Monsoon, Anthropogenic forcing, Dynamics, Climate change.

1. Introduction

Projecting future changes in monsoon rainfall is essential for water resource management, food security, disaster mitigation and infrastructure planning. Monsoon studies have focused on regional scales for centuries due to their indigenous properties and practical applications. Only recently the regional monsoons been recognized as a global system. Investigation of the response of global monsoon (GM) to anthropogenic forcing has started since the Intergovernmental Panel on Climate Change (IPCC) phase 5 by using the models' simulations of the Coupled Model Intercomparison Project (CMIP5). The GM area, intensity and precipitation are likely or very likely to increase by the end of the twenty-first century (Hsu *et al*., 2013; Christensen *et al*., 2013). The onset dates will be earlier or unchanged and the retreat will be delayed, so the GM season will likely increase in length (Christensen *et al*., 2013; Lee and Wang, 2014). The monsoon will dominantly increase in the northern hemisphere (NH) (Kitoh *et al*., 2013) and the stronger signal in the NH was related to the temperature difference between the NH and southern hemisphere (SH) (Lee and Wang, 2014). However, fundamental drivers for the complex pattern of GM precipitation change have yet to be fully understood. Understanding the integrated property of GM could link paleo-monsoon, modern monsoon and future monsoon studies.

Future changes in the regional monsoon projected by CMIP5 showed that the South Asia (SA) summer monsoon rainfall was consistently projected to increase (Menon *et al*., 2013; Sharmila *et al*., 2015; Kitoh *et al*., 2013). The precipitation sensitivity (percentage change scaled to one degree Celsius of global warming) is about 5.0%/°C for the SA monsoon and 6.4%/°C for the East Asian (EA) monsoon under the RCP 4.5 anthropogenic warming scenario (Wang *et al*., 2014). The duration of the EA rainy season may be lengthened due to advanced onset and delayed retreat (Kitoh *et al*., 2013; Moon and Ha, 2017). The projected Asian-Australian monsoon low-level circulation tends to weaken significantly (by about 2.3%/°C) due to atmospheric stabilization, but the EA subtropical monsoon circulation increases by 4.4%/°C. The projected northern African (NAF) monsoon generally gets a wetter late season (except for the west coast) and delayed cessation of the rains (Biasutti, 2013; Roehrig *et al.*, 2013). North American (NAM) monsoon will likely have an early-to-late redistribution. While mean precipitation remains unchanged in the traditional NAM region (Cook and Seager, 2013), Central American precipitation will experience a substantial reduction (Colorado-Ruiz *et al*., 2018). Nevertheless, there is low confidence in the NAM projections as large uncertainties are involved (Bukovsky *et al*., 2015; Meyer and Jin, 2017; Pascale *et al*., 2017). In the SH, the total Australian-Indonesian monsoon precipitation will increase by 2.6%/°C. The projected change in the South American (SAM) precipitation is chaotic as the results presented by Seth *et al*. (2013) show little change in the total precipitation but a delay and shortening of the monsoon season; However, Jones and Carvalho (2013) suggests an early onsets, late demises and lengthening duration SAM monsoon.

In this article, we will first review aspects of the emerging concept of GM, followed by a review of the CMIP6 models' projected future changes and discuss the causes of the projected changes in the global and regional monsoons under anthropogenic forcing, focusing on land monsoon rainfall (LMR).

2. Delineation of monsoon domain

The monsoon concept has evolved since Halley (1686) first documented the Indian monsoon by land-ocean thermal contrast-induced seasonal reversal of surface winds. Since then, the quantitative delineation of

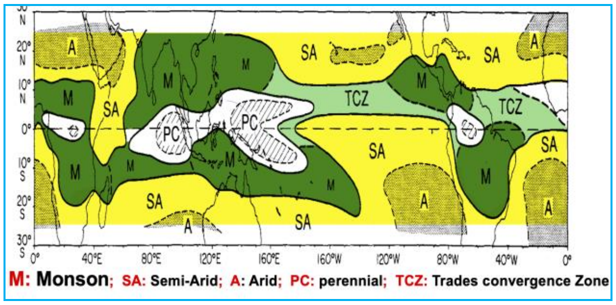


Fig. 1. Climatic regime diagram for tropical convection/rainfall derived from OLR data (1974-1989). Reproduced from Wang (1994)

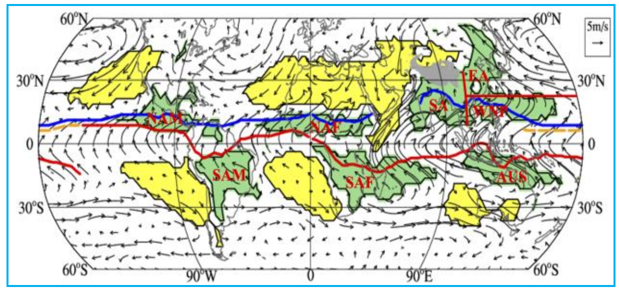


Fig. 2. The GM precipitation domain defined by the local summer-minus-winter precipitation rate exceeds 2 mm/day and the local summer precipitation exceeds 55% of the annual total (in green). Summer denotes May through September for the NH and November through March for the SH. The dry regions, where the local summer precipitation is less than 1mm/day, are shown (yellow). The arrows show August-minus-February 925 hPa winds. The blue lines indicate the ITCZ position for August and the red lines indicate the ITCZ position for February (solid for monsoon trough and dashed for trade wind convergence). The Global Precipitation Climatology Project data and ERA interim data were used for 1979-2012. Eight regional monsoons are indicated. The SA, EA and WNP monsoon regions are separated by 105° E and 22.5° N. Modified from Wang *et al*. (2014b)

the monsoon regime has been based solely on the annual reversal of the prevailing surface winds (Hann, 1908; Khromov, 1957; Ramage, 1971; Li and Zeng, 2000). The resultant monsoon domains were primarily confined to the Eastern Hemisphere.

Monsoon climate is characterized by both annual reversals of surface winds and contrasting rainy summer and dry winter (Webster, 1987; Webster *et al.*, 1999). Monsoon rainfall imposes the most significant impact on humans and society. Monsoon precipitation heating essentially drives atmospheric general circulation. Thus, delineating the monsoon domain by precipitation characteristics is of incomparable advantage. With the availability of satellite remote sensing techniques and outgoing longwave radiation (OLR) data over the ocean, Wang (1994) first attempted to delineate the monsoon climate regime over the global tropics using OLR as a proxy for tropical rainfall (Fig. 1). The monsoon precipitation domain defined by rainfall characteristics covers the global tropics, extending monsoon domain from traditional Asia-Australian-west African monsoon to the North and South American monsoons and the southern African monsoon. Monsoons entail substantial oceanic regions. Using rainfall observations, Wang and Ding (2008) proposed a qualitative way to identify the global monsoon precipitation domain. The delineation was based on the contrast between rainy summer and dry winter measured by the annual range (AR) that is defined by the local summer-minus-winter precipitation (Fig. 2). There are eight regional monsoons in NAF, SA, EA, western North Pacific (WNP), NAM, southern Africa, Australia, SAM.

3. Global monsoon : Concept and impact on global climate

Monsoons vary considerably from region to region. Each regional monsoon has unique features due to its specific land-ocean and topographic configuration, remote forcings and atmosphere-ocean-land interaction processes. The regional monsoon (RM) directly affects people; therefore, monsoon studies have been primarily focused on regional scales.

However, all regional monsoons are driven and synchronized by the annual cycle of solar radiation and the global divergent circulation bonds them. Therefore, the regional monsoons should be studied as an entity. Considering the physical principle of conservation of mass, moisture and energy as it applies to the global atmosphere and its exchange of energy with the underlying surfaces, analysis of overall monsoon variability and changes from a global perspective is imperative and advantageous for understanding fundamental monsoon dynamics (Trenberth *et al.,* 2000).

GM represents the dominant mode of annual variation of the global tropical precipitation and circulation, a defining feature of the Earth's climatology. GM can be quantitatively defined by the first two principal empirical orthogonal modes of the annual variation of global precipitation and low-level (850 hPa) winds (Wang and Ding, 2008). The first mode, which accounts for 71% of the total annual variance, describes June-July-August-September (JJAS) minus December-January-February-March (DJFM) precipitation and circulation pattern. It is called solstitial mode, which reflects the impact of antisymmetric annual solar forcing with a one-to-two-month phase delay in the atmospheric response. The second mode (13% of total variance) also has an annual period, with the maximum and minimum

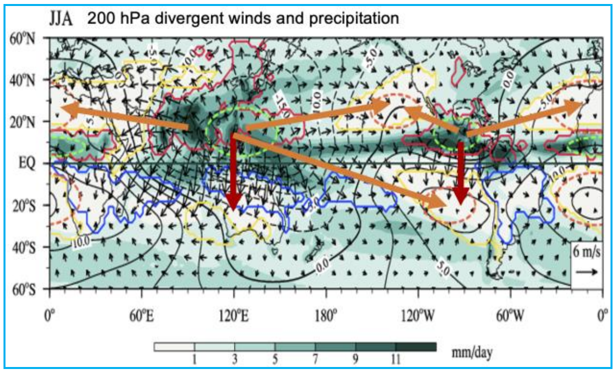
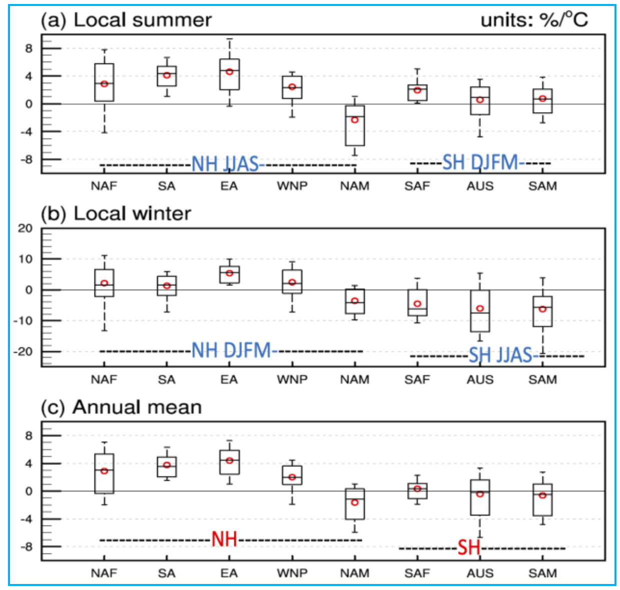


Fig. 3. Global monsoon divergent circulation. Climatological mean (a) JJA precipitation (shading in units of mm/day) and upper-tropospheric velocity potential (contours in units of 106 m^2/s) and divergent component of vector winds (unit, m/s) at 200 hPa (~12 km). Local summer (winter) monsoon regions are outlined by red (blue) curves. The dry regions, where the local summer precipitation is less than 1mm/day are outlined by yellow curves. The upper-level divergence (convergence) centers are indicated by green (brown) dashed circles. The rainfall and wind data are derived from GPCP and NCEP-DOE, respectively. Modified from Wang *et al*. (2017)



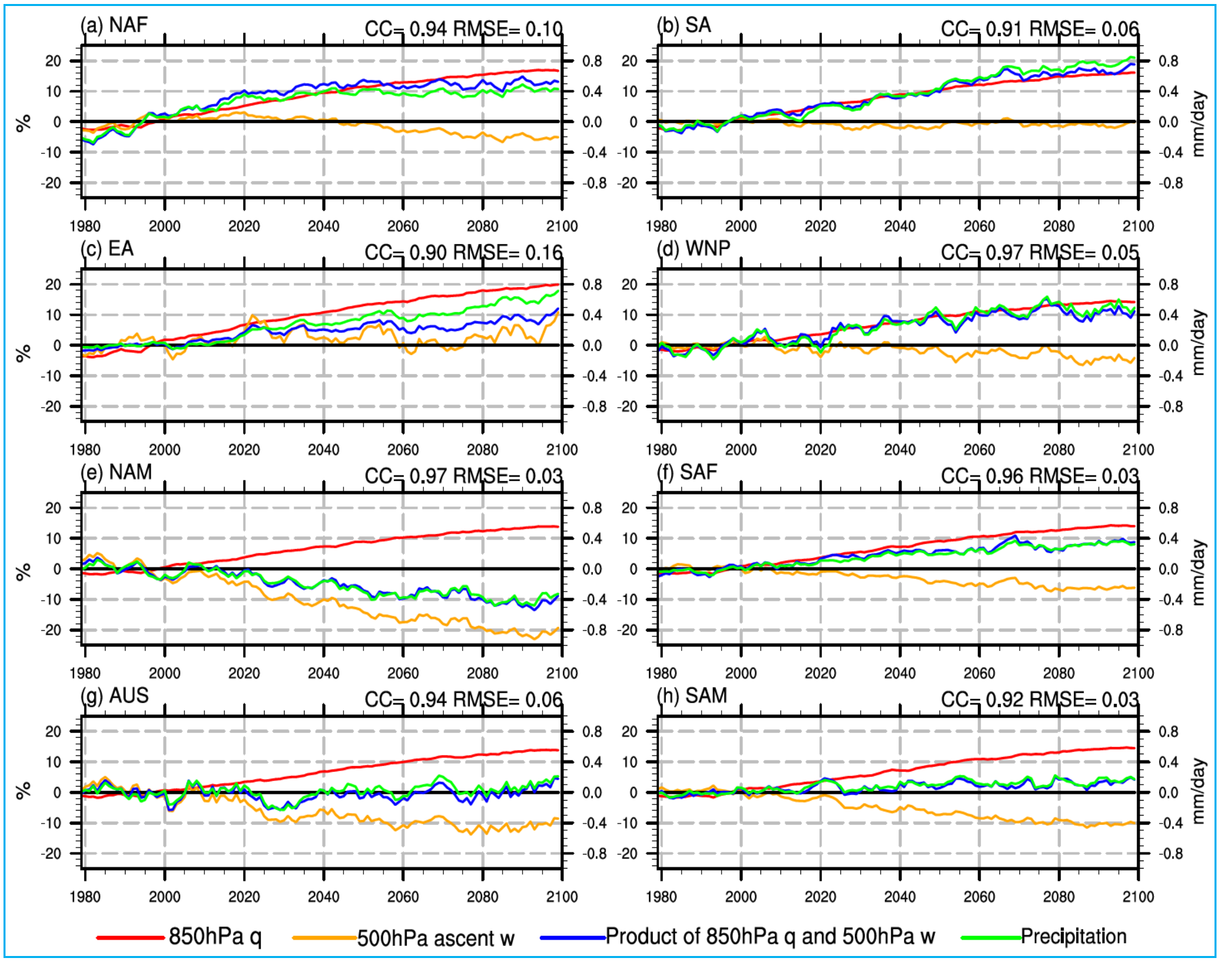
Figs. 4(a-c). Projected regional land monsoon precipitation sensitivity under the SSP2-4.5, *i.e*., the percentage change (2065-2100 relative to 1979-2014) per 1 7°C global warming (%/°C) derived from 24 CMIP6 models for (a) local summer, (b) local winter and (c) annual mean land monsoon precipitation at each regional monsoon. The upper (lower) edge of the boxes represents the 83rd (17th) percentile, so the box contains 66% of the model projection data and represents the "likely" range. The horizontal line within the box is the median. The red circle is the mean. The whiskers denote the "very likely" range from 5% to 95%. Adopted from Jin *et al.* (2020)

occurring around April and October, respectively. It represents an equinoctial asymmetric mode or the spring-fall asymmetry of the seasonal variation in the tropical and monsoon circulation.

Physically, GM is a forced response of the coupled atmosphere-land-ocean-cryosphere-biosphere system to annual variation of solar radiative forcing. GM system is a global-scale annual reversal of the three-dimensional monsoon circulation accompanied by the seasonal migration of heavy precipitation. This generic definition is particularly relevant to the paleo-monsoon study on the orbital time scale (Milankovitch cycle) and when the land-ocean distribution differs from today.

GM plays a pivotal role in driving the annual variation of the Intertropical Convergence Zone (ITCZ). As shown in Fig. 2, ITCZ consists of a monsoon convergence zone between westerly and easterly and a trade wind convergence zone between meridional wind convergence. About three-quarters of the ITCZ are embedded within the monsoon convergence zone. The annual migration of ITCZ is large (10-30 degrees of latitude) over the monsoon regions while small (less than 5 degrees of latitude) in the trade wind convergence zone. Thus, monsoon drives the annual variation of ITCZ.GM also drives annual variations of Hadley circulation and Walker circulation. In theory, monsoon heating can induce Hadley and Walker Circulation by generating vertical motion and exciting equatorial kelvin and Rossby waves (Gill, 1980). Walker cell is induced by Kelvin wave response and Hadley cell is induced by Rossby wave response. As shown in Fig. 3, the "lateral monsoons" (Webster *et al*., 1999) form the backbone of the Hadley circulation. The **"**transverse monsoon**"** contributes to Pacific Walker circulation. During NH summer, Subtropical High is driven by the transverse monsoon**,** not the Hadley cell. Interannual variation of total precipitation in the NH Monsoon and desert regions vary out of phases, indicating Monsoon-Desert coupled variability (Wang *et al*., 2012).

GM is also central to the global hydrological cycle whose significance remains to be more understood, particularly in paleoclimatology. GM precipitation (GMP) is a sensible measure of global climate variations in the last millennium. On the centennial-millennial timescale, the change of the GMP follows the effective radiative forcing better than the change of global mean surface air temperature, suggesting that the GMP is a valuable gauge for global climate change. On the centennial-millennial timescale, the change of the GMP follows the effective radiative forcing better than the change of global mean surface air temperature, suggesting that the GMP is a valuable gauge for global climate change.

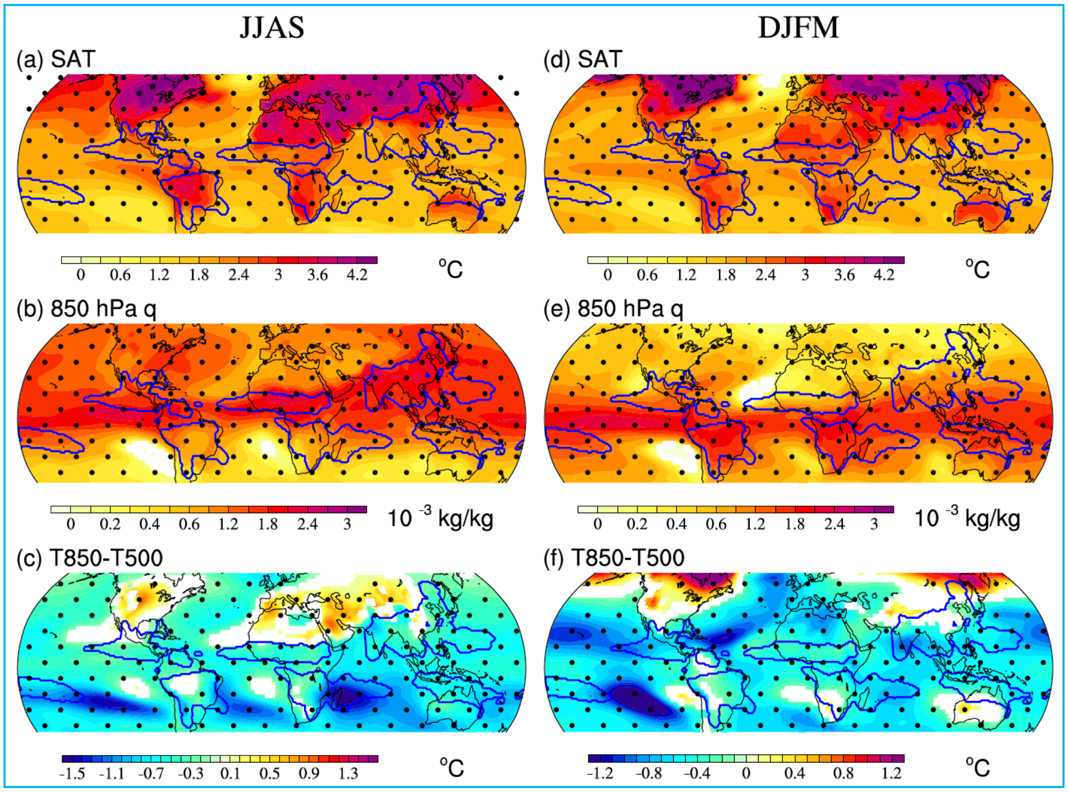


Figs. 5(a-h). Transient responses of the 850-hPa q (specific humidity; red lines), 500-hPa ascent w (the negative vertical pressure velocity at 500 hPa), product of 850-hPa q and 500-hPa w (the diagnosed precipitation; blue line) and the simulated precipitation (green line) obtained from the 24MME for the historical run period (1979-2014) and the SSP2-4.5 run period (2015-2100) in each regional monsoon. The q and v are shown in percentage changes, *i.e.*, the anomalies normalized by its corresponding mean during 1979-2014. The diagnosed and simulated precipitation (mm/day) are anomalies with reference to their corresponding mean values during 1979-2014. The PCC and RMSE in the top-right corners are between diagnosed and simulated precipitation. A 5-yr moving average was applied to all time series. Adapted from Jin *et al*. (2020)

4. Global and regional LMR response to anthropogenic forcing

The multi-models' ensemble projects that, under the shared socioeconomic pathway (SSP) 2-4.5, the total land monsoon rainfall will likely increase in the NH by about 2.8%/°C in contrast to little change in the SH (-0.3%/°C) (Wang *et al.*, 2020b). Figs. 4(a-c) show the regional land monsoon precipitation (LMP) sensitivity to global warming (%/°C). The confidence level of the 24 multi-models' ensemble follows the likelihood presented in the IPCC Fifth Assessment Report (Mastrandrea *et al.*, 2010). The projected summer mean LMP will very likely increase in SA (4.1%/°C) and EA (4.6%/°C), likely increase in NAF (2.9%/°C) and likely decrease in NAM (-2.3%/°C). The SH summer and winter changes are in opposite directions, resulting in insignificant changes in the annual mean precipitation [Fig. 4(c)]. The projected SH LMP changes will likely decrease due to enhanced NH summer monsoon, which drives descent over the SH monsoon regions through Hadley circulation.

The processes influencing the future change of regional monsoon rainfall under anthropogenic forcing are complex. However, circulation changes play the most critical role in changing regional monsoon precipitation. In theory, regional mean LMR changes can be approximated by the changes in the product of the mid-tropospheric ascent and 850 hPa specific humidity, plus moderate contribution from evaporation. This simplified



Figs. 6(a-f). Changes in thermodynamic fields. (a)-(c) Changes in JJAS mean surface (a) air temperature (SAT), (b) 850 hPa specific humidity and (c) atmospheric static stability at the lower troposphere measured by the temperature difference between 850 and 500 hPa (T850-T500). (d)-(f) Same as in (a) to (c) except for the DJFM mean changes. Adapted from Wang *et al*. (2020b)

theoretical framework for the attribution of precipitation changes stems from the moisture conservation equation for a steady motion:

$$P = E - \left\langle \omega \frac{\partial q}{\partial p} \right\rangle - \left\langle V_h \cdot \nabla_q \right\rangle$$

Taking a two-layer approximation of the troposphere with the interface at 500-hPa, assuming the mean specific humidity in the lower troposphere equals the q_{850} and neglecting upper tropospheric q, we have

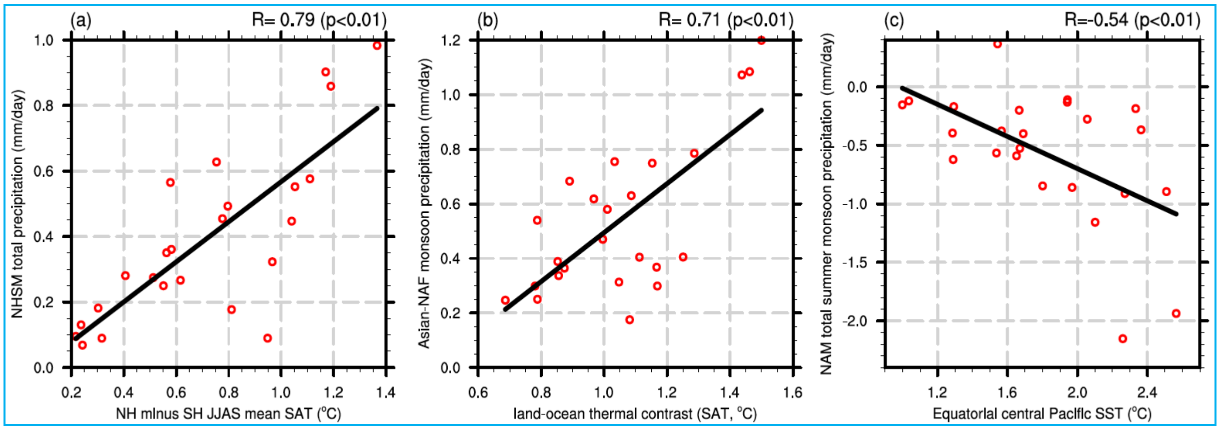
$$P \approx E - \frac{1}{g}\left(\omega_{500} \cdot q_{850}\right) - \frac{1}{g}\left(V_{850} \cdot \nabla_{q850}\right)$$

The regional mean horizontal moisture advection is often negligibly small.

Figs. 5(a-h) show that the estimated precipitation by $-\left(\omega_{500} \cdot q_{850}\right)/g$ is highly correlated with the precipitation simulated by the 24 MME for each regional monsoon. The correlation coefficients range from 0.90 to 0.97 during 2015-2100. The under estimation in EA is due to neglecting the significant contributions from surface evaporation and horizontal advection (Jin *et al*., 2020). The 850 hPa specific humidity will increase by about 15%-20% by the end of the twenty-first century, implying an increase of about 7% per degree of global warming following the Clausius-Clapeyron equation (Held and Soden, 2006). However, the increasing specific humidity in all regional summer monsoon are similar and cannot explain the markedly different precipitation changes. The circulation change must be the fundamental cause of the different LMP changes in regional monsoons (Endo and Kitoh, 2014).

5. How GHGs radiative forcing drives GM and regional monsoon changes

The answer requires scrutinizing the GHGs' radiative forcing-induced thermodynamic field changes. Figs. 6(a-f) show that in summer monsoon regions, the low-level specific humidity increases nearly uniformly across different monsoon regions, about 7% per degree of



Figs. 7(a-c). (a) The relationship between the "NH-warmer-than-SH" and the total NH summer monsoon precipitation. The NH-warmer-than-SH denotes NH and SH surface air temperature difference [(T2m, 0° N-60° N, 0-360° E) - (T2m, 40° S-0° S, 0°-360° E)]. (b) The relationship between the "land-warmer-than-ocean" and the Asian-African monsoon precipitation. The "land warmer than-ocean" is measured by the land-minus-ocean sea level pressure in the NH. (c) The relationship between the NAM JJAS precipitation and the surface air temperature (SAT) difference between the equatorial eastern Pacific (5° S-5° N, 120° W-80° W) and the tropical Atlantic (10° N-20° N, 60° W-15° W). Total of 24 CMIP6 modesare used. Reproduced from Wang *et al*. (2020b) and Jin *et al*. (2020)

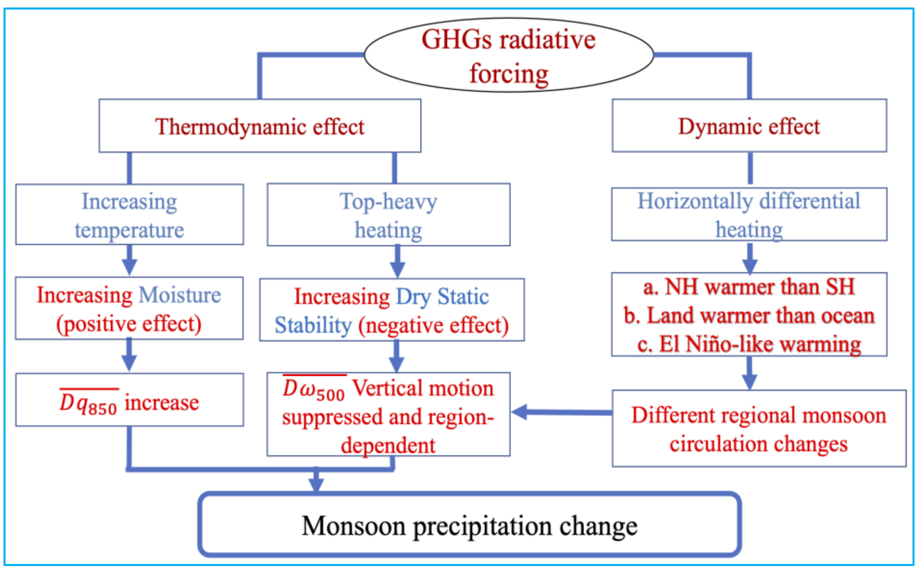


Fig. 8. Schematic diagram showing how GHG radiative forcing drives GM change

global warming. Another notable feature is that the increased atmospheric dry static stability goes hand-in-hand with the increased low-level specific humidity. The static stability increases would suppress vertical motion and reduce precipitation, implying that the two thermodynamic effects, namely moisture and static stability increases, tend to offset each other.

The GHGs induce spatially non-uniform warming patterns during both NH summer and winter [Figs. 6(a,d)]. It shows three salient characteristics: (a) the 'NH-warmer-than-SH' pattern, which tends to enhance NHM while weakens SHM, (b) the 'Land warmer-than Ocean' pattern, which enhances Asian-NAF monsoon but not NAM as the latter is largely an ocean dominate the region and (c) an El Nino-like warming, which weakens NAM and global monsoon in general.

The model physics supports the above assertions. Fig. 7(a) indicates that the models-projected NH summer monsoon precipitation increases are significantly related to the models-projected inter hemispheric temperature contrast change. The NH-warmer-than-SH pattern creates hemispheric sea-level pressure differences, generating northward cross-equatorial flows and associated moisture and energy transport, thereby enhancing the NH summer monsoon rainfall.

Why does the LMR change show increased Asian-African monsoon rainfall and decreased North American monsoon rainfall? Fig. 7(b) shows that the models that project a larger change in the land-ocean thermal contrast predict a stronger Asian-NAF summer monsoon precipitation. Over the eastern NH, pronounced warming over Eurasia and the northern African continent generates a vast low-pressure system, enhancing the climatological cyclonic monsoon circulation and transporting moisture to the African and Asian monsoon. The land-sea contrast plays a negligible role in changing North American monsoon as the ocean dominates this area. However, the projected SST change features an El Nino-like eastern Pacific warming and a relative cooling in the subtropical North Atlantic [Fig. 6(a)]. As shown in Fig. 7(c), models projecting relative warming in the equatorial eastern Pacific (5° S - 5° N, 120 - 80° W) compared tothe tropical North Atlantic (10° - 20° N, 60 - 15° W) show more significant future decreases in the North American monsoon rainfall. Physically, the El Nino-like eastern Pacific warming may shift the ITCZ and monsoon convergence zone equator ward, causing reduced precipitation over large areas of central and North American monsoon regions, including Mexico and Central America and the adjacent oceans.

The major processes by which the GHGs radiative forcing determines the GM future change are summarized in Fig. 8. GHGs radiative forcing changes mean LMR by its thermodynamic and dynamic effects. The thermal effect includes the rising temperature-induced water vapor increase (moisture effect) and the top-heavy heating-caused dry static stability increase (stabilization effect). The moisture and stabilization effects offset each other, significantly reducing the total thermodynamic effect. In the literature, the effect of increased moisture was called the thermodynamic effect. However, it is only part of the thermodynamic effect. More accurately, it should be called the moisture effect. Besides, the thermodynamic effects are nearly uniform across all regional summer monsoons (Fig. 5), unable to explain regional differences. Therefore, different regional monsoon responses must be due to the circulation change or the dynamic effect of the GHG radiative forcing.

The GHG-induced horizontally differential warming results in robust "NH-warmer than-SH" and "land-warmer-than-ocean" patterns, as well as an El Nino-like warming. The enhanced NH-SH thermal contrast favors increasing NHM rainfall and reducing SHM rainfall (Fig. 6). The enhanced land-ocean thermal contrast between the vast Eurasian-African landmass and adjacent oceans favors increased monsoon rainfall over the Asian-northern African monsoon regions. The projected eastern Pacific warming will reduce the North American monsoon.

6. Way forward

To overcome the models' common biases, improve the missing and poorly resolved physical processes and reduce sources of projected uncertainties, Wang *et al*. (2020a) suggested the following conceivable ways forward.

(*i*) Explicitly resolve deep convection and their responses to anthropogenic forcing to project extreme precipitation.

(*ii*) Better understand the contributions from the forced response and internal variability, as well as the forced change of internal variability by applying large ensembles methods (Maher *et al*., 2019) or perturbed-parameter ensembles (Murphy *et al*., 2014).

(*iii*) Develop emergent constraints applicable to monsoon ensemble projections to reduce the projection uncertainties.

(*iv*) Quantify the uncertainties in aerosol processes, water-cloud feedback, ecosystem feedbacks to climate change and elevated CO_2 and land-use impacts.

(*v*) Quantify the causes of uncertainty at the process level by coordinated simulations.

(*vi*) Theoretical advances to understand monsoon circulations in a changing climate.

(*vii*) Understanding monsoon responses to natural external forcing through study the past climate.

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