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Changing circulation structure and precipitation characteristics in Asian monsoon regions: greenhouse warming vs. aerosol effects

William K. M. Lau[1,2*], Kyu-Myong Kim[3] and L. Ruby Leung[4]

Abstract

Using model outputs from CMIP5 historical integrations, we have investigated the relative roles of anthropogenic emissions of greenhouse gases (GHG) and aerosols in changing the characteristics of the large-scale circulation and rainfall in Asian summer monsoon (ASM) regions. Under GHG warming, a strong positive trend in low-level moist static energy (MSE) is found over ASM regions, associated with increasing large-scale land–sea thermal contrast from 1870s to present. During the same period, a mid-tropospheric convective barrier (MCB) due to widespread reduction in relative humidity in the mid- and lower troposphere is strengthening over the ASM regions, in conjunction with expanding areas of anomalous subsidence associated with the Deep Tropical Squeeze (Lau and Kim in Proc Natl Acad Sci 12:3630–3635, 2015). The opposing effects of MSE and MCB lead to enhanced total ASM rainfall, but only a partial strengthening of the southern portion of the monsoon meridional circulation, coupled to anomalous multi-cellular overturning motions over ASM land. Including anthropogenic aerosol emissions strongly masks MSE but enhances MCB via increased stability in the lower troposphere, resulting in an overall weakened ASM circulation with suppressed rainfall. Analyses of rainfall characteristics indicate that under GHG, overall precipitation efficiency over the ASM region is reduced, manifesting in less moderate but more extreme heavy rain events. Under combined effects of GHG and aerosols, precipitation efficiency is unchanged, with more moderate, but less extreme rainfall.

Background

Despite the large number of recent studies, the relative roles of anthropogenic greenhouse warming vs. aerosols on Asian monsoon (ASM) climate change remain mired as a subject of debate and continued intense research (Ramanathan et al. 2001; Chung and Ramanathan 2006; Lau et al. 2006, 2008; Meehl et al. 2008; Ramanathan and Carmichael 2008; Wang et al. 2009, 2012, 2017; Li et al. 2010, 2016; Bollasina et al. 2011; Lee and Wang 2012; Turner and Annamalai 2012; IPCC 2013; Krishnan et al. 2013; Song et al. 2014; Jin and Wang 2017). One of the main reasons for the slow progress is that ASM climate change is an immensely complex phenomenon, involving global-scale forcing, coupled to regional- and local-scale feedbacks arising from natural variability in the atmosphere–ocean–land system, as well as human activities. Another is the imperative to understand climate impacts such as droughts and floods on local and human scales, where application of climate model results is deficient, due to limitations of resolution and inadequate physical process representation. This is particularly true for ASM modeling, where even the simulation skills of seasonal climatology and intraseasonal variability of rainfall are still wanting (Webster et al. 1998; Wang 2006; Lau and Waliser 2012; Sperber et al. 2013; Ashfaq et al. 2016).

On the other hand, Coupled Model Intercomparison Project (CMIP) ensemble climate models have provided significant advance in understanding the thermodynamic and dynamical effects of greenhouse warming on

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*Correspondence: wkmlau@umd.edu
[2] Department of Atmospheric and Oceanic Sciences, University of Maryland, College Park, MD 20740, USA
Full list of author information is available at the end of the article

circulation, temperature, moisture, and rainfall pattern consistent with the basic governing principles of the ocean–atmosphere general circulations (Held and Soden 2006; Vecchi and Soden 2007; Xie et al. 2009; Sherwood et al. 2010; Tokinaga et al. 2012; Santer et al. 2012; Lau et al. 2013; Lau and Kim 2015). These global-scale changes will undoubtedly have impacts on key monsoon drivers, e.g., sea surface temperature, hemispheric and land–sea thermal contrasts, regional moist static energy, and tropospheric relative humidity (Fasullo 2012; Murugavel et al. 2012; Roxy et al. 2015; Li et al. 2015; Zhang and Li 2016). Knowing the impacts of greenhouse warming vs. aerosols on these monsoon drivers will provide better understanding, at a more fundamental level, of their roles in affecting structural changes (shifting, deepening, narrowing, and widening) in the monsoon regional circulation and in characteristics (types, duration, and intensity) of monsoon rainfall. Provided that statistics are taken with multi-model ensembles, and over large-scale domain, e.g., the entire Asian monsoon, or subcontinental domains (South Asia or East Asia), as opposed to local (human) scales, climate models have higher fidelity to the real world. This is not to say that the human scales are unimportant, but rather focusing on global- and regional-scale forcing and response will provide an intermediate step, where climate models can be used to inform downscaling studies to better understand ASM climate change on human scales (Fowler et al. 2007).

Using the aforementioned approach, Lau and Kim (2017), hereafter referred to as LK, studied the competing influences of greenhouse warming vs. aerosols on Asian monsoon climate. LK identified, under a historical GHG-only warming scenario, an increasing land–sea temperature difference between 5°S and 30°N since the 1950s, dubbed the Warm-Ocean-Warmer-Land (WOWL) effect, as a primary driver of the ASM climate change, enhancing moisture transport from ocean to the ASM land, including strong cross-equatorial transport of moisture via the Somali jet, from the colder (southern) to the warmer (northern) hemisphere. They found that GHG also induces an increase in mid-tropospheric dryness which acts as a barrier to deep convection, suppressing monsoon rainfall over ASM regions. Furthermore, a warmer upper troposphere over the Indo-Pacific warm pool under global warming tends to inhibit the northward advance of the ASM. The net result is that under GHG, while the overall ASM rainfall is increased, the monsoon meridional circulation (MMC) is weakened. LK found that aerosols strongly mask the GHG effects, reducing the WOWL effect by 50–60%. Additionally, aerosols increase atmospheric stability over ASM land region, alluding to the presence of a convective barrier, which may further suppress monsoon rainfall and weaken the MMC. This paper is an extension of LK to further elucidate the GHG vs. aerosol impacts on monsoon circulation structure and rainfall characteristics. Specifically, we investigate the possible effects of a mid-level convective barrier, associated with structural changes in the Asian MMC under GHG, and modulation by anthropogenic aerosol forcing. Possible relationship of the convective barrier to the changing nature of precipitation under GHG and under the combined effects of GHG and aerosol forcing will also be investigated.

Methodology and data

We used outputs from 135-year historical simulations (1870–2005) of 19 CMIP5 coupled models, with prescribed anthropogenic emissions of (a) greenhouse gases (GHG) only and (b) GHG and aerosols (ALL). Each model is integrated starting from its own equilibrium pre-industrial climate. All model outputs have been interpolated to a common grid of 2.5 × 2.5 latitude–longitude. To focus on the forced response of the ASM to anthropogenic emission forcing, we minimize the impacts of natural variability by constructing the Multi-Model mean (MMM) of all key quantities for the boreal summer season (June–July–August). Anomalies are defined as the last 25 years (1981–2005), relative to pre-industrial equilibrium climate. The MMM anomalies of the GHG integrations will be used to establish the baseline for the ASM climate forcing and response. By comparing ALL to GHG, the extent to which GHG-induced anomalies are modulated by aerosols will be assessed. Changes in rainfall characteristics will be explored using scale analysis based on water balance requirement (Sugiyama et al. 2010; Lu et al. 2014) and quantile regression analysis (Buchinsky 1998; Lau and Wu 2006, 2011), as well as compared observations from APHRODITE (Yatagai et al. 2012).

Results

We first examine the global-scale forcing of the ASM, from the perspective of changes of the global mid-tropospheric vertical motions. Under GHG, the distribution of mean and anomalous vertical motions at 500 hPa (Fig. 1a) shows anomalous ascent over the equatorial central Pacific and an intensification on the equatorward flank of the Inter-Tropical Convergence Zone (ITCZ) in the eastern Pacific. As shown in LK, this is the boreal summer manifestation of the Deep Tropical Squeeze (DTS)—a narrowing and intensification of deep convective zone over the equatorial central and eastern Pacific (region marked by the red-lined rectangle in Fig. 1a), in conjunction with a widening of the subsiding branch of the Hadley Circulation (HC), under global warming (Lu

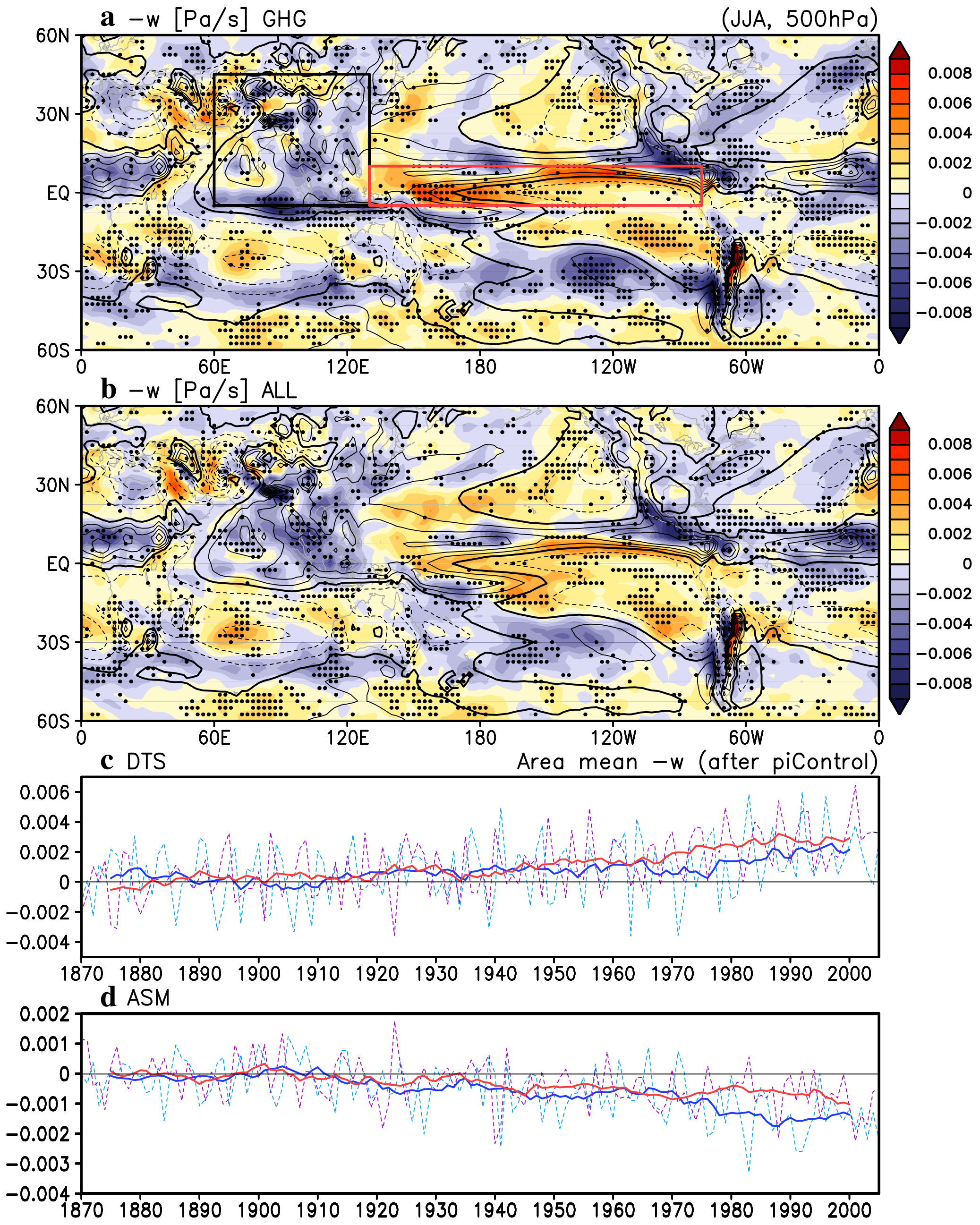

Fig. 1 Upper panels showing spatial distribution of anomalous 500 hPa negative *p*-velocity (hPa s^{-1}) for (**a**) GHG only and (**b**) ALL. Contours indicate pre-industrial climatology, with positive (warm color) and negative (blue color) values indicating anomalous ascending and descending motions, respectively. Grid points where 12 or more out of 19 models agree in the sign of the anomaly are indicated by black circles. Lower panels showing time series (1870–2005) of negative p-velocity averaged over (**c**) the DTS domain (rectangle outlined red) and (**d**) the AMS domain (rectangle outlined black), for GHG (red line) and ALL (blue line) respectively. Thick lines indicate 5-year running mean

et al. 2007; Seidel et al. 2008; Hu et al. 2011; Lau and Kim 2015). Elsewhere, anomalous subsiding motions are found over extensive areas in the tropics and subtropics, most pronounced over land regions of Asia, the Maritime continent, and the North American/Mexico monsoon regions and subtropical belt (35–40°S) of the Southern Hemisphere. Comparing to the climatology, changes within 5°S–20°N signal a weakened Walker circulation (WC), while the anomalous subsidence poleward of 30°N mostly over land in the Northern Hemisphere and near

35°S in the Southern Hemisphere reflects a widening of the subsiding zone of the HC. The extensive subsidence regions coincide with regions of reduced mid-tropospheric relative humidity (Lau and Kim 2015). Under ALL, the anomalous vertical motion pattern (Fig. 1b) is similar on the global scale, but substantially weaker than GHG, with less tight gradients, except over the ASM domain (marked by the box outlined in black in Fig. 1a), where the regions of anomalous descent area have expanded.

The inverse relationship between the anomalous vertical motion over the ASM and the DTS domain (box outlined in red) can be seen in the time series plots of area mean p-velocity over each domain. Figure 1c shows that the mid-tropospheric anomalous ascent has been trending positive in the DTS region since the 1930s, with faster rate under GHG compared to ALL, reflecting the aerosol masking effect (Ramanathan and Feng 2008; LK). During the same period, the anomalous vertical motion has been trending negative over the ASM domain, but with a faster rate under ALL than GHG (Fig. 1d). The changes in the vertical motion in the two regions signal a weakening of the climatological WC under GHG warming (Vecchi and Soden 2007; Tokinaga et al. 2012; LK). Under ALL, a “masked” anomalous ascent over the DTS would have led to “weakened” anomalous descent over the ASM, if the WC were the only dominant driver of the ASM. Apparently, this is *not* the case. Over ASM land region, cooling of the land surface by attenuation of solar radiation by aerosols can lead to a spin-down of the ASM circulation (Ramanathan et al. 2001). Furthermore, the presence of abundant absorbing aerosols (BC, OC, and dust) in monsoon regions increases stability in the lower troposphere by warming above and cooling near the surface (Menon et al. 2002; Lau et al. 2006, 2008, 2016; Fan et al. 2008; Wang et al. 2013). These aerosol effects result in substantial “masking” of the WOWL effect, resulting in weakened anomalous moisture transport from ocean to monsoon land under ALL compared to GHG (see LK for details).

Regional monsoon controls

In this subsection, we examine changes in two major controls of the ASM, i.e., low-level moist static energy (MSE) and mid-tropospheric relative humidity (ΔRH). Under GHG, an increasing potential for deep convection and precipitation is evidenced in a positive trend in ASM domain averaged (MSE) since 1950–1960s (Fig. 2a). This trend is almost identical to, and can be identified with, the WOWL effect (see Fig. 1 in LK) of increasing land–sea temperature contrast and moisture transport from ocean to ASM land. Under ALL, the MSE positive trend is substantially weakened, with the aerosol masking nearly 50–60% of GHG trend in the 1960–2000s, reflecting the large increase in aerosol emissions, due to the rapid modernization taking place over Asia during this period. Contemporaneously, a “mid-tropospheric convective barrier” (MCB) represented by decreasing trend in mid-tropospheric RH can be seen under both GHG and ALL (Fig. 2b) since the early 1900s. The negative trends stem from moist adiabatic lapse-rate feedback and remote forcing from anomalous subsidence associated with the DTS under GHG warming (see LK for details). Briefly, warm moist air parcel ascending from low levels via the moist adiabatic will conserve moist static energy and experience larger warming in the upper and mid-troposphere relative to the lower troposphere. Based on the differential form of the Clausius–Clapeyron equation relating to relative humidity R_h, i.e., $\delta R_h = \delta q/q_s - \alpha R_h \delta T$, where $\alpha = L(R_v T^2)^{-1} \sim 6\%\ \mathrm{K}^{-1}$, q and T represents the ambient specific humidity and temperature, respectively, and q_s is the saturated humidity, it can be seen that an increase in δT in the mid- and upper troposphere larger than $\delta q/q_s$ due to vertical transport can lead to a reduction in R_h, i.e., drying. Additionally, drier air from above transported by anomalous downward motion under GHG remote forcing over the ASM domain (see Fig. 1) can further dry the mid- and lower troposphere. The presence of the MCB tends to inhibit deep convection, suppress rainfall, and limit the upward transport of moisture locally, providing a positive feedback to the remote forcing. During the later period (1970–2000s), the MCB is actually stronger (more negative RH) under ALL compared to GHG as a result of aerosol effects in increasing atmospheric stability in the mid- and lower troposphere and limiting deep convection (Fan et al. 2008; Wang et al. 2013).

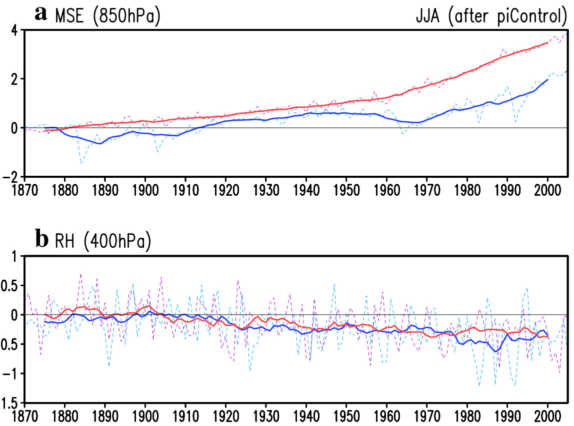

Fig. 2 Time series (1870–2005) of ASM domain-averaged anomalies of (**a**) 850 hPa MSE and (**b**) 400 hPa RH. Solid red (blue) lines indicate 5-year running means for GHG (ALL)

Monsoon meridional circulation (MMC)

In this subsection, MMC anomalies over the ASM are examined in relation to changes in MSE, MCB, and rainfall (Fig. 3). Under GHG warming, the MMC shows alternating anomalous ascent and descent over the ASM domain. The influence of the anomalous Walker circulation can be seen in the strong anomalous descent near 5°S and moderate descent near 10°N (Fig. 3a, see also Fig. 1a). Poleward of 30°N and S, anomalous subsidence reflects the expansion of the subtropical subsidence zone of the HC, in association with the DTS (Lau and Kim 2015; LK). While the increased MSE over monsoon land enhances convective potential, deep convection with ascent throughout the troposphere can only break out where it can overcome the MCB (Fig. 3b). Judging from the distribution of the anomaly relative to the climatological mean vertical motions, GHG warming appears to have produced only limited enhancement of the ascending motions over the ASM land, as evident in the alternating descent and ascent north of 10°N. On the other hand, the descent branch appears to have deepened and widened, with enhanced subsidence near 40°S, but weakened near the climatological descending center (20–30°S). Consistent with the vertical motion changes, rainfall is enhanced (decreased) in the climatological rising (sinking branch) of the MMC, with rates commensurate with a steady rise in MSE from ocean to land, against the opposing tendency by the mid-tropospheric drying (MCB) across the MMC. This is particularly noteworthy, over the ASM land in subtropical and higher latitudes, where precipitation increase is only moderate (Fig. 3b). Under ALL (Fig. 3c, d), inclusion of aerosols leads to an overall weakened MMC, accentuating regions of anomalous subsidence under GHG warming over the ASM land domain (10–30°N). ASM rainfall is suppressed in conjunction with a muted increase in MSE, but increased MCB (negative ΔRH) over ASM land (10–30°N) compared to GHG.

Changing rainfall characteristics

Previous studies have shown that changes in rainfall characteristics can better reveal the underlying physical processes associated with climate change (Trenberth et al. 2003; Lau and Wu 2006, 2011; Lau et al. 2013). In this subsection, we evaluate the impacts of GHG and aerosols on rainfall characteristics in the ASM region, in

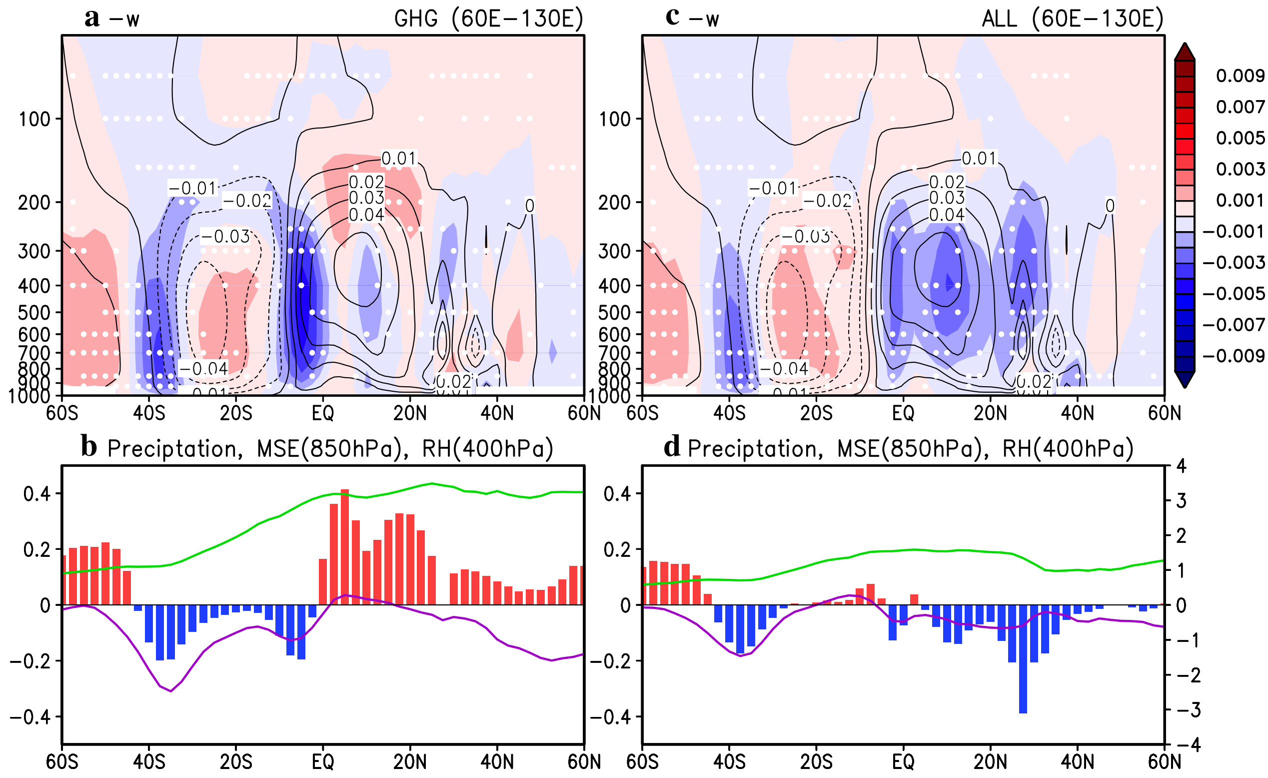

Fig. 3 Left two panels showing (**a**) latitude–height cross-sections of anomalous negative p-velocity under GHG-only forcing and (**b**) latitude profiles of anomalies of rainfall (histogram) in mm day^{-1}(left ordinate), 850 hPa MSE (green line) in kJ (right ordinate), and 400 hPa RH (purple line) in percentage (right ordinate). Contours represent climatology. Left two panels **c** and **d** are the same as **a** and **b**, except for ALL. White dots indicate grid points where 12 or more out of the 19 models agree in the sign of the anomaly

association with the changing MMC. Specifically, we will focus on changes in precipitation efficiency and rainfall types. Here, the change in precipitation efficiency will be examined via a scale analysis, based on the water balance requirements (Sugiyama et al. 2010; Lu et al. 2014). In ASM regions, where the climatological mean vertical motion is upward, the area mean precipitation, P, can be expressed as:

$$P = \alpha M q, \tag{1}$$

where M is the upward mass flux at cloud base, q is the specific humidity at cloud base, and α is a scale factor representing the bulk precipitation efficiency, defined as rainfall per unit moisture flux at cloud base. As defined, α is dependent on the cloud properties and types, entrainment rate, and relative humidity of the environment (Li et al. 2002; Sui et al. 2007). Differentiating Eq. (1) yields

$$\frac{\mathrm{d}P}{P} = \frac{\mathrm{d}w}{w} + \frac{\mathrm{d}q}{q} + \frac{\mathrm{d}\alpha}{\alpha}, \tag{2}$$

where we have assumed that $\frac{\mathrm{d}M}{M} \sim \frac{\mathrm{d}w}{w}$, with w representing the vertical motion at the 500 hPa level, which signifies the strength of the MMC. Since cloud base information for each CMIP5 model is not available, the approximation of cloud mass flux by vertical moisture flux at the mid- and lower troposphere has been used in many previous climate-scale rainfall scale analysis (Held and Soden 2006; Sugiyama et al. 2010; Lu et al. 2014). The fractional change of area mean values of P, w, q for each simulated year from 1870 to 2005 (Fig. 4a) is computed relative to the pre-industrial climatology. Under GHG, the trend in increasing q is very pronounced, since the 1930s to 2005 (Fig. 4a). During the same period, the trend in increased rainfall is also obvious, but relatively muted relative to q, while the

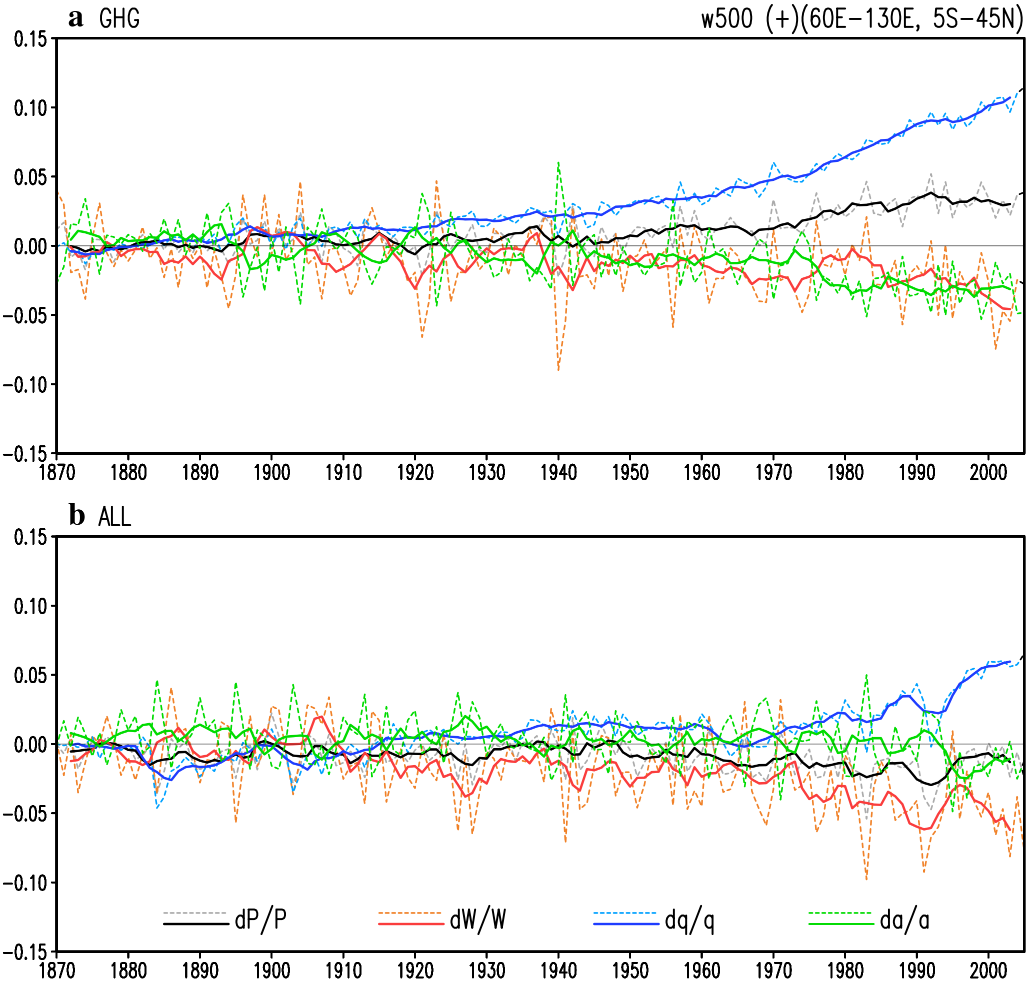

Fig. 4 Time series (1870–2005) showing fractional change of precipitation (d*P*/*P*), 500 hPa vertical motion (d*w*/*w*), moisture (d*q*/*q*), and precipitation efficiency (d*α*/*α*) over the ASM domain for (**a**) GHG and (**b**) ALL. Dotted and solid lines indicate JJA mean and 5-year mean respectively

MMC shows a weakening (negative) trend, with magnitude comparable to but opposed to the rainfall. As a result, α shows a strong decreasing trend, signaling a large reduction in precipitation efficiency. Under ALL, the increasing trend in q is strong from 1960s to 2005, although weaker compared to GHG. Here, both rainfall and MMC show negative trends, with a much faster rate in the latter, indicating a substantially weakened MMC with reduced overall ASM rainfall (see Fig. 3d). Interestingly, the bulk precipitation efficiency shows no noticeable trend during the last three decades, compared to GHG.

To investigate changes in precipitation types under GHG and ALL, following previous work (Lau and Wu 2006, 2011), we have computed the model rainfall probability distribution functions (pdf) over the ASM land region and compared with observations from APHRODITE (Yatagai et al. 2012). Rainfall pdf, binned by ranked rain rates, were first constructed, over the ASM domain for the climatology. Twenty percentiles, with a bin width of 5%, were chosen, with the top 95% representing the most extreme rain events, and the bottom 5%, the extreme light events, i.e., drizzles. Quantile regression analysis (Koenker 2005; Lau et al. 2013) was then carried out to extract the linear trend for each percentile for the period 1950–2005. Under GHG (Fig. 5a), the probability of heavy rain event (top 80%) is strongly increased, with the highest rate for the more extreme events. However, moderate and light rain events are generally suppressed. In contrast under ALL (Fig. 5b), the frequency of heavy rain (top 70%) is reduced, but moderate rain event occurs more often, in good agreement with observations (Fig. 5c). The physical reasons for changing rainfall types under GHG and ALL are not obvious. Here, we offer a plausible explanation, inferred from information currently available. Under GHG, over the ASM domain, a given moist parcel rising from cloud base will lose cloud liquid mass by dry detrainment as it encounters drier air in the MCB, and thus yield less precipitation per unit moisture flux at cloud base, i.e., reduction in bulk precipitation efficiency, consistent with the reduction in moderate and light rain events. However, the steady increase in MSE due to strong WOWL effect under GHG allows the build-up of excessive convective available potential energy (CAPE) in the lower troposphere. Eventually, delayed deep convection breaks out locally under conditions of locally forced strong upward motion, releasing the excessive CAPE in the form of extreme heavy precipitation (Wang and Zhou 2005; O' Gorman and Schneider 2009). Under ALL, the "WOWL" effect is strongly "masked," resulting in a much slower rate of CAPE increase. In addition, the increased stability in the lower troposphere by aerosols sustains and strengthens the MCB, allowing only increased moderate rain, while suppressing extreme heavy rain (Fan et al. 2008; Yang et al. 2013). Note that this applies for large domain mean only, and does not preclude the outbreak of extreme heavy rainfall event locally under ALL. The aforementioned scenario needs to be verified by further studies using high-resolution regional climate models with detailed aerosol–cloud microphysics.

Conclusions

In this work, using model outputs from CMIP5 historical (1870–2005) simulations we have investigated the roles of GHG warming and aerosols on changes in the large-scale circulation structure and rainfall characteristics in Asian monsoon regions. The GHG experiments, which included anthropogenic GHG emissions only, are used to establish the baseline for assessing ASM climate change. The ALL experiments, which included additional anthropogenic aerosol emissions, are used to evaluate aerosol impacts. Results show that under GHG warming a stronger land–sea thermal contrast associated with the WOWL effect leads to increased anomalous low-level moist static energy (MSE). However, the expansion of the anomalous subsidence zones of the Walker and Hadley circulations associated with the deep tropical squeeze (DTS) results in extensive regions of anomalous mid-tropospheric dryness over subtropical and mid-latitude land and the maritime continent forming a midtropospheric convective barrier (MCB), which suppresses ASM convection. Deep convection, strong ascent, and heavy rain can only break out in regions where the stronger MSE, facilitated by local processes such as orographic forcing and dynamical feedback, can overcome the MCB. Anthropogenic aerosol emission induces cooling over monsoon land and ocean, masking up to 50% or more of the WOWL effect. As a result, MSE only increases moderately over land, compared to GHG only. The MCB over the ASM land region is increased by absorbing aerosols via the semi-direct effect, which increases atmospheric stability in the lower troposphere favoring suppressed convection (Fan et al. 2008; Lau et al. 2008, 2016; Wang et al. 2013). Under the combined effects of GHG and aerosols, the overall Asian monsoon circulation is weakened and ASM rainfall reduced. Changes of the monsoon circulation structure, rainfall characteristics, and key remote and regional drivers are shown schematically in Fig. 6. A rainfall scale analysis shows a strong reduction in precipitation efficiency under GHG, reflected in widespread suppressed moderate precipitation, but enhanced extreme heavy precipitation. Under ALL, extreme heavy rain is suppressed, but moderate rain is enhanced over the ASM domain due to the increased lapse-rate stability by absorbing aerosol, in good agreement with rainfall observations from APHRODITE.

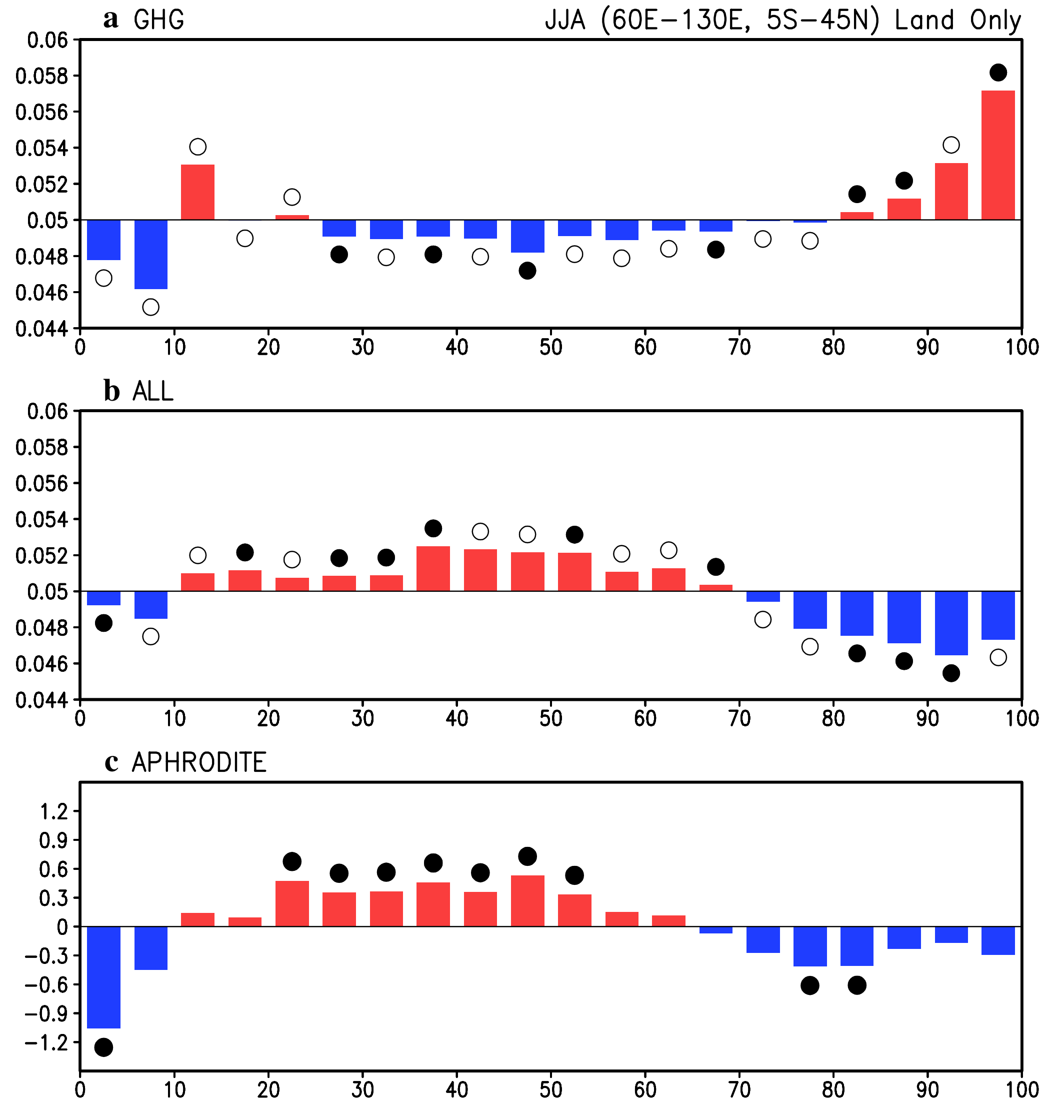

Fig. 5 Quantile regression showing trends in fractional change in frequency of rainfall as a function of ranked rain rate for (**a**) GHG only, (**b**) ALL, and (**c**) APHRODITE rainfall observation, for the period 1950–2005. In **a** and **b**, open (solid) circle annotating each quantile represents 10 (12) out of 19 models having the same sign. In **c** solid circle represents 95% statistical significance

As a caveat, we should point out that the CMIP5 multi-model mean quantities we examined are only moderately robust, with only approximately 60% of model consistency over the ASM domain. Further work will be needed using "observational constraints" to reduce diversity of model results and to improve understanding of the underlying physical feedback processes, and skills of ensemble model climate projections (Allen et al. 2002). Most importantly, our results suggest that the recent debate on whether the ASM is "weakened" or "strengthened" by greenhouse warming or aerosol is not very meaningful. Such a debate is based on the assumption that the underlying circulation structure and rainfall characteristics are unchanged. As demonstrated by our results, this is not the case. Under global warming, competing influences of increased MSE and large-scale mid-tropospheric MCB are already set up as a result of planetary-scale thermodynamic and dynamical adjustment processes, resulting in changing structure of the ASM meridional circulation and rainfall characteristics. Including anthropogenic aerosol emissions can further upset the ASM energy and water balance, leading

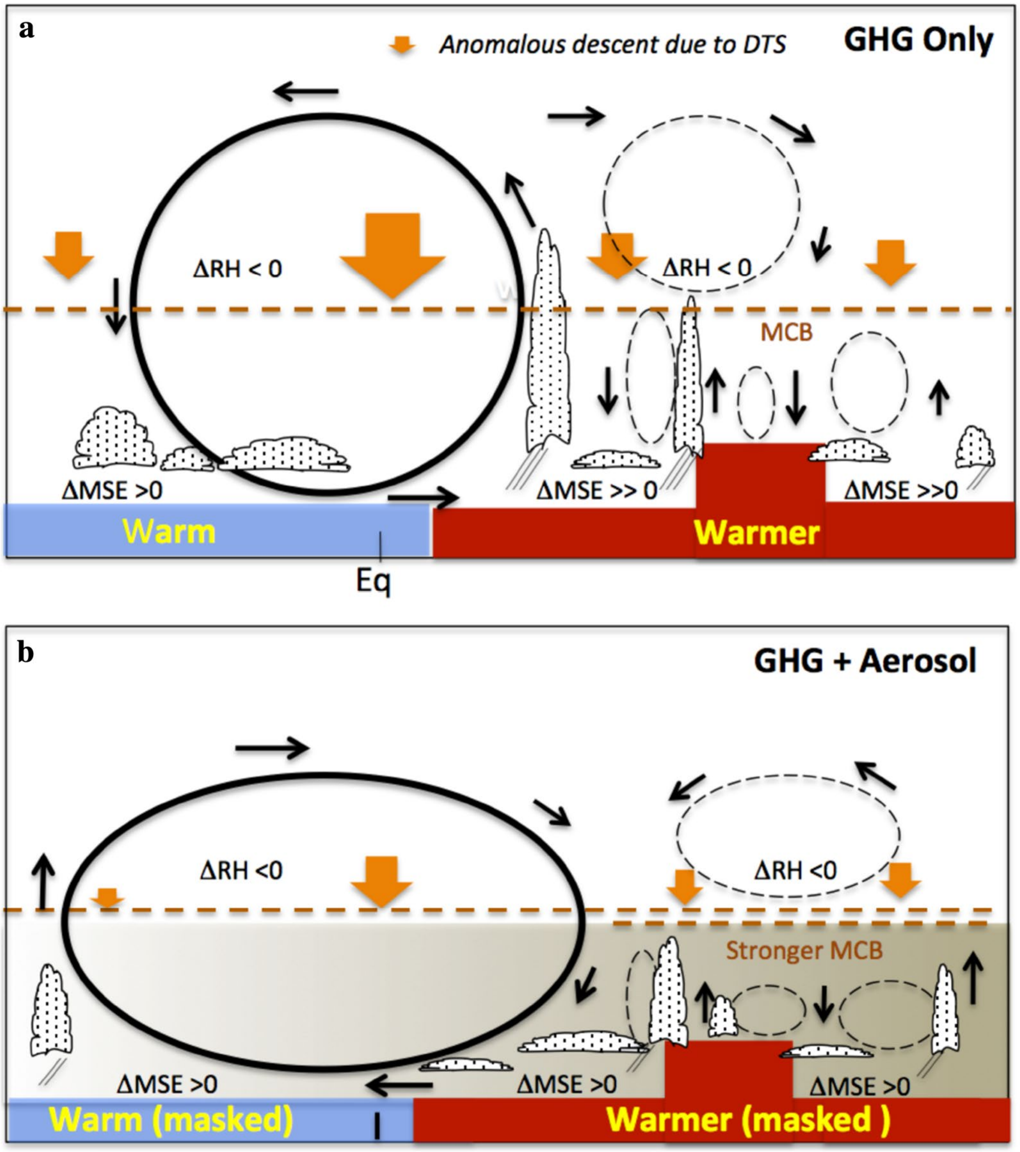

Fig. 6 Schematics showing structural changes in the Asian summer monsoon meridional circulation (MMC), rainfall and cloud processes, as a result of competing influences of enhanced low-level moisture static energy (MSE) and the mid-tropospheric convective barrier (MCB, denoted by dashed brown line) due to tropospheric drying (ΔRH < 0), stemming from adjustment of the large-scale circulation to the Deep Tropical Squeeze (DTS), and regional precipitation–cloud–radiation dynamical feedback processes under (**a**) GHG warming and (**b**) combined GHG and aerosol effects. Solid circles denote major changes in the oceanic and adjacent land portion of the MMC. Dashed circles represent anomalous multi-cellular structure over the ASM land regions

to further changes in circulation and rainfall properties. Indeed, many recent studies have indicated that absorbing aerosols such as desert dusts, black carbon, and organic carbon, which are plentiful in the ASM regions, could strengthen the early phase of the ASM via radiation dynamical feedback processes (Lau et al. 2006, 2008; and others), and that aerosol-cloud microphysics may strongly impact the development of monsoon convection and rainfall (Rosenfeld et al. 2014; Li et al. 2016). These aspects of aerosol–monsoon interactions involving both natural and anthropogenic aerosols are not considered here. Future work along these lines of investigation will yield further new insights into the fundamental physical processes driving climate change in ASM regions.

Abbreviations
ALL: all forcing including anthropogenic GHG and aerosol emissions; APHRODITE: Asian Precipitation Highly-Resolved Observational Data Integration Towards Evaluation; ASM: Asian summer monsoon; CAPE: convective available potential energy; CMIP5: Coupled Model Intercomparison Project-5; DTS: deep tropical squeeze; GHG: greenhouse gases; HC: Hadley circulation; ITCZ: Inter-Tropical Convergence Zone; MCB: mid-tropospheric convective barrier; MMC: monsoon meridional circulation; MMM: multi-model mean; MSE: moist static energy; WC: Walker circulation; WOWL: Warm-Ocean-Warmer-Land.

Authors' contributions
WKML conceived the research, interpreted the results, and wrote the paper. K-MK conducted the data processing and analyses, and plotted the figures. RL provided useful advice and insights on interpretation of the results, proofread, and suggested valuable revisions on the final draft of the paper. All authors read and approved the final manuscript.

Authors' information
WKM Lau is a senior scientist at the Earth System Science Interdisciplinary Center (ESSIC), an adjunct professor at the Department of Atmospheric and Oceanic Sciences, University of Maryland, and former President, Atmosphere Section, American Geophysical Union. During the opening ceremony of the AOGS (Asian Oceania Geophysical Sciences) Meeting, 2017, Singapore, he delivered the Axford Lecture, "*Competing Influences of Greenhouse Warming and Aerosols on Asian Monsoon Climate Change*," which included, among other materials, new findings described in this paper.

Author details
[1] Earth System Science Interdisciplinary Center, University of Maryland, College Park, USA. [2] Department of Atmospheric and Oceanic Sciences, University of Maryland, College Park, MD 20740, USA. [3] Climate and Radiation Laboratory, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA. [4] Pacific Northwest National Laboratory, Richland, WA 99352, USA.

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Not applicable.

Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
CMIP5 model data used for this research are open source data available at data portal http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html. APHRODITE daily precipitation datasets are available from https://climatedataguide.ucar.edu/climate-data. Data for specific analyses and findings are archived in local data repositories at University of Maryland and are available upon request.

Ethical approval and consent to participate
Not applicable.

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