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Monsoon Responses to Climate Changes–Connecting Past, Present and Future.

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Abstract *Purpose of Review:* Knowledge of how monsoons will respond to external forcings through the 21st century has been confounded by incomplete theories of tropical climate and insufficient representation in climate models. This review highlights recent insights from past warm climates and historical trends that can inform our understanding of monsoon evolution in the context of an emerging energetic framework. *Recent Findings:* Projections consistent with paleoclimate evidence and theory indicate expanded/wetter monsoons in Africa and Asia, with continued uncertainty in the Americas. Twentieth century observations are not congruent with expectations of monsoon responses to radiative forcing from greenhouse gases, due to the confounding effect of aerosols. Lines of evidence from warm climate analogues indicate that while monsoons respond in globally coherent and predictable ways to orbital forcing and inter-hemispheric thermal gradients, there are differences in response to these forcings and also between land and ocean. *Summary:* Further understanding of monsoon responses to climate change will require refinement of the energetic framework to incorporate zonal asymmetries and the use of model hierarchies.

Keywords Monsoons · Global Warming · Climate Changes · Paleo-Monsoons

Introduction

In the nearly two decades since its introduction, the concept of a global monsoon, the tropical overturning circulation and its associated rainfall that responds coherently to the annual cycle of solar forcing [1], has provided a foundation for inquiry

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that has led to substantial gains in understanding of past, present and future monsoons [2,3]. Yet our understanding remains incomplete. Observational trends in regional monsoons since the 1950s have been inconsistent with theory, evidence from paleo-climate, and climate model projections, and model biases have limited the confidence in projections [4]. How global and regional monsoons evolve in the coming decades will most certainly be influenced by anthropogenic drivers, which include greenhouse gases, aerosols and land use change. Untangling the effects of these external forcings as well as the climate system's internal drivers is of critical importance to our understanding. Here we digest the recent literature on the response of monsoons to external forcing during past warm periods, and contrast with the forcing and response seen in historical trends in order to better inform monsoon projections.

An emerging theoretical framework interprets monsoons as an integral part of the global atmospheric overturning circulation, and associated energy, angular momentum and moisture budgets [5], rather than regional land-sea breeze circulations. In this view, monsoons, like the global Hadley cells, are understood as convectively coupled, energetically direct circulations that export the net energy entering the atmospheric column (through surface energy and top-of-atmosphere radiative fluxes) away from their ascending branches and peak precipitation, which nearly coincide with maxima in the near-surface moist static energy [6,7]. This view is consistent with the projected weakening of monsoon circulations with global warming [8, e.g.], despite an increase in land-sea temperature contrast, and the finding that on interannual timescales monsoon strength is correlated with low-level moist static energy gradients, but anticorrelated with low-level temperature gradients [9,10].

The energetic framework has proved particularly powerful in providing theoretical constraints on the position and shifts of the intertropical convergence zone (ITCZ) even in response to forcing at remote latitudes on timescales from seasonal to geologic [11–13]. For an anomalous energy source in one hemisphere, the Hadley circulation can restore energy balance by shifting its ascending branch and ITCZ into the hemisphere with net energy gain and by transporting energy across the equator into the hemisphere with net energy loss, as on average the Hadley cell transports energy across the equator in the direction of its upper-level flow. As discussed by [5], inter-hemispheric energy pertubations usually manifest as inter-hemispheric temperature gradients, primarily at latitudes outside of the tropics, because of the weak temperature gradient constraint in the tropics, with the ITCZ hence shifting into (away from) the relatively warmed (cooled) hemisphere [14, 15]. For example, the late 20th century Sahel drought has been attributed to the climate impacts of anthropogenic aerosols through cooling of the northern hemisphere and a southward shift in the tropical rain belt [16]. Since 1980 this inter-hemispheric temperature asymmetry (annual-mean north minus south) has reversed to show a significant positive trend, which is expected to continue to increase throughout the 21st century in the Coupled Model Intercomparison Project version 5 (CMIP5 [17]) projections [18].

The energetic framework has emphasized how zonal mean ITCZ shifts are anticorrelated with anomalies in cross-equatorial energy transport, with roughly a 3 degree latitude northward shift for every Petawatt of southward cross-equatorial energy transport [19]. More recent work has, however, shown how changes in the efficiency with which the Hadley cell transports energy can lead to changes in cross-equatorial energy transport even without corresponding shifts in the ITCZ

[20,21]. Perhaps more importantly, the emphasis on zonal mean energy budget metrics does not capture changes in monsoons [22], which are zonally asymmetric, and yet responsible for much of the energy transport across the equator during the summer season [23]. Recently [24] and [25] expanded this framework to include zonal and meridional energy fluxes towards the development of a theory based on energetic constraints for regional tropical rainfall shifts.

This emerging theoretical framework based on global energetic constraints might be the path forward to identify the causes of disagreements between paleo and modern observations, theories and numerical simulations [4]. Substantial work will be needed to include the complexities of monsoon dynamics (see schematic representation in Figure 1) in this energetic framework. Meanwhile comprehensive discussions of monsoons on timescales from tectonic to intraseasonal [3] have yielded new paleoclimatic insights [2] and mechanisms across timescales [26].

The overall question posed in this review is - in what ways can recent literature on paleo monsoons and historical observed changes inform our understanding of future monsoon responses to anthropogenic forcing? We examine evidence from past warm climates and discuss examples from regional monsoons. It is important to note that most monsoon research to date has yet to consider the implications of the emerging energetic framework at a regional scale, and we include relevant discussions where appropriate. We focus in particular on the implications on rainbelt shifts in response to increased inter-hemispheric temperature contrasts, with the understanding that regional circulation changes, which to date remain poorly understood and constrained, might impact the tropical precipitation response in ways that remain not fully understood. The structure is as follows: We begin with paleomonsoon responses to external forcing during past warm periods. While there are no perfect analogues to the present climate drivers, *are there useful insights these warm periods can offer toward understanding present and future changes?* We then examine historical and recent changes in monsoons and ask - *can new knowledge about the drivers of change (external and internal) in recent monsoon observations help to place observed changes within the context of expected changes based on theory and evidence from past climates?* This is followed by a discussion of *monsoon projections, with insight gained from past and historical changes.* The summary provides a recap of these three main questions regarding the future of monsoons and the potential role of the energetic framework in future monsoon research.

This brief review does not provide a comprehensive summary of recent literature, but rather a selection of recent research, curated to highlight the state of science in response to the questions above. For this reason not all monsoon regions are equally discussed. Figure 2 presents the monsoons regions (South Asia, East Asia, West Africa, North and South America) discussed in this review, although details of the region boundaries vary among studies. The South Asian monsoon is part of the larger coupled Asian monsoon system and results from the interaction between the seasonally migrating ITCZ and the Himalayan mountain range [27], while in East Asia monsoon rainfall occurs over East China and along a band across Korea and Japan and into the western North Pacific [28]. The West African/African summer monsoon extends to the Sahel region at its poleward margin. [29]. In the Americas, the North American monsoon region is located in central and northern Mexico and the southwestern United States [30,31], and the South American Monsoon extends from the Amazon basin southward to Bolivia, Argentina, and Paraguay [32,33].

Paleo monsoon responses to external forcing

Primary external drivers of past climates include variations in insolation resulting from changes in Earth's orbit, and atmospheric carbon dioxide which affects long-wave cooling. Evidence suggests that the long-term CO_2 decline over the past tens of millions of years has acted as a driver of global temperature, cooling Earth's climate [34]. These long timescale carbon cycle processes reduced atmospheric CO_2 from $\approx$ 400ppm in the Pliocene through the Quaternary to pre-industrial levels of 280ppm [35]. There is evidence that the South Asian and East Asian monsoons have responded to the resulting cooling and ice sheet growth over the past 3.6M years [26]. At orbital timescales ($\approx$20–100K years), as seen during the ice advances and retreats of the past 800k years, CO_2 amplifies changes in temperature initiated by orbital variations. It is well established that the cyclic pacing of solar forcing affects the global monsoon system in coherent and largely predictable ways. Earth's precession produces hemispheric antiphased insolation variations in the subtropics and leads to an antiphase response between the northern and southern hemisphere monsoons, albeit with regional differences [3,2,36]. In this section we pose the question: despite the lack of exact analogues, in what ways can the climates of recent warm paleoclimate epochs inform monsoon projections? The relevant literature is summarized in Table 1.

Anthropogenic warming is the consequence of a radiation imbalance at the top of the atmosphere driven by an increase in greenhouse gas concentrations. The main greenhouse gases are well mixed in the troposphere, so that concentration is essentially uniform in the free atmosphere (away from point sources), with CO_2 having surpassed 400 ppm in recent years. One could expect that warming would be the same everywhere, but recent studies have pointed to the role of the oceans in breaking the symmetry between northern and southern hemispheres even in present day climate [37]. Under continued greenhouse warming, northern hemisphere polar amplification and southern hemisphere cooling in the circumpolar current might suggest northward ocean heat transport, a shift in the ITCZ toward the warmer northern hemisphere and southward energy transport in the atmosphere via the cross-equatorial Hadley cell and monsoons. A positive trend has already been observed in the resulting inter-hemispheric temperature asymmetry since the 1980's, and is expected to continue to increase through the 21st century in the CMIP5 projections [18]. It is important to note that more pronounced warming over land is not just a transient feature, but rather a robust response at equilibrium [38]. Despite the increasing temperature asymmetry, a narrowing rather than a clear shift of the ITCZ has been observed [39], and although individual models link simulated ITCZ location to changes in cross-equatorial heat transport, they neither agree on heat transport nor ITCZ shifts [13, 19]. Thus, the response of tropical precipitation to any given forcing is complex and not always in line with expectations.

With this in mind, we consider Earth's recent warm climates and what conditions might qualify as appropriate analogues for anthropogenic greenhouse warming.

Pliocene

During the early Pliocene (3-5 Mya), CO_2 was roughly equivalent to present day while global average temperatures and sea levels were substantially higher, prior to the development of a large Greenland ice sheet. Thus, proxy data and model simulations emphasize an equilibrated climate, while the present climate is transient and in the early stage of response to CO_2 forcing. Paleoclimatic records suggest that monsoons across Asia were wetter during the Pliocene. For example, reconstructions using biogenic and lithogenic indices indicate a more intense South Asian summer monsoon prior to the development of northern hemisphere ice sheets around 3.5 Mya [40]. Land and marine-based proxies suggest more rainfall in the East Asian summer monsoon prior to 2.7 Mya, small-amplitude monsoon oscillations between 2.7 and 1.2 Mya, and large-amplitude fluctuations after 1.2 Mya [41,42,26]. Proxy data from the Pliocene (both early and mid-Pliocene, 3.2-3 Mya) also indicate a weakened zonal and meridional sea surface temperature (SST) gradient in the Pacific Ocean, which has been labelled a permanent El Niño-like state [43–45]. Pliocene proxy data for southern hemisphere monsoons has not been discussed in the literature to date.

Model experiments carried out for the mid-Pliocene warm period (3.3-2.95 Mya) under the Pliocene Model Intercomparison Project (PlioMIP, [46]) use pre-industrial orbital parameters with two primary experiments: one with prescribed estimated SST, and a coupled model simulation. The external forcing is comprised of greenhouse gas concentrations, decreased albedo due to the disappearance of the West Antarctic ice sheet and smaller Greenland ice sheet, and resulting sea level rise. PlioMIP results from both experiments show polar amplification leading to warming in both northern and southern high latitudes with reduced meridional temperature gradient [46]. The reduced equator-to-pole temperature gradient results in a robust weakening of the Hadley circulation [47]. However, the coupled simulations show a less robust weakening of the Walker circulation than those with prescribed SST, which depends on the amount of warming in the tropical Indian ocean [48]. Tropical precipitation shows an expansion in both hemispheres with a decrease near the equator in the prescribed SST experiment, while the coupled experiment indicates a northward shift in the tropical rainbelt. Stronger East and South Asian monsoons are robust in both types of experiments [48–51]. It should be noted that the coupled model experiments using the PlioMIP forcing have difficulty in reproducing SST values and meridional temperature gradients in agreement with paleo proxies.

In a modeling study unrelated to PlioMIP, a climate similar to the Pliocene is simulated by modifying cloud radiative properties. In this simulation a weakened overturning, or negative dynamical change, translates into drying in the tropical cores of convection, and wetting at the poleward margins of monsoons in both hemispheres [52]. Because the primary forcing applied in these experiments (reduction of meridional cloud albedo) is quite different from those employed in the coordinated PlioMIP experiments, it is difficult to identify precisely the cause of the agreement or disagreement in the details of regional monsoon responses (e.g., expansion of tropical rainfall versus northward shift).

It has been suggested that present and future greenhouse warming could lead to permanent El Niño, Pliocene-like climate, as seen in the experiments described above [52]. Despite the uncertainties in tropical Pacific variability under global warming, projected changes in the mean state reduce the zonal asymmetry with a robust weakening of the Walker Circulation [53]. In addition, models have been shown to lack processes and feedbacks [54] that might make permanent El Niño conditions more relevant in the future.

Quaternary

Cooling from the Pliocene led to the Quaternary (which includes the Pleistocene and Holocene epochs) and was marked by the growth of the Greenland ice sheet and orbitally paced glacial-interglacial cycles. During the last interglacial (LIG) prior to Holocene, the Eemian (129-116Kyr), atmospheric CO_2 was similar to the pre-industrial value ($\approx$300 ppm) and the orbital configuration (large obliquity, large eccentricity and perihelion in July) resulted in peak northern hemisphere summer (June-August) insolation $\approx$125Kya. The summer radiative forcing was stronger than seen in the Mid-Holocene, but annual mean insolation was slightly lower than pre-industrial values [55]. This asymmetry in forcing yielded strong northern hemisphere polar amplification with high latitude temperature increases estimated $\approx 3^{\circ}$C warmer than present day. [56].

Modeling studies of the Eemian simulate a global mean annual warming similar to projections in a low emissions scenario, with greater warming at high latitudes than at low latitudes [56]. However, the external forcing for the Eemian is the insolation change due to orbital forcing which has a different seasonal response (more warming in boreal summer) than the greenhouse gas forcing of the present and future (more warming in the winters of the two hemispheres). While the LIG is not an exact analog for future warming, proxy reconstructions reveal wetter summer monsoons in East Asia and South Asia [57], West Africa [58] and a drier South American monsoon [59, 60]. Various modeling studies support the hypothesis that insolation-driven latitudinal temperature gradients drive monsoon intensity, simulating increased West African, South Asian and East Asian precipitation during the LIG [61, 62]. In West Africa the particular mechanism involved in strengthening the monsoon is related to a low pressure anomaly over northern Africa which increases the winds and moisture transport from the tropical Atlantic [63], although recently it has been shown, at least on interannual time scales, the heat low and associated shallow circulation might in fact weaken the monsoon through advection of lower level moist static energy air [64].

During the time since the Eemian, paleo-records for the past 100 Kyr indicate a strong correlation between the marine ITCZ position and monsoons [65, 63, 59]. The West African monsoon response suggests that hemispheric asymmetry in forcing may have been important even in the early Pliocene, and may have increased in importance as northern hemisphere glaciations proceeded [66].

Recent model integrations that span the period since the last interglacial suggest a more complex response of tropical rainbelts to, on the one hand, insolation driven asymmetry, which can result in an expansion/contraction of the rainbelt, versus northern hemisphere cooling (due to the presence of ice sheets or meltwater hosing), which drives a southward shift [22]. Further, the responses differ over land and ocean. Over land the rain belt appears to be influenced by local insolation and thermodynamic processes, while the response to northern hemisphere extratropical forcing, such as the Dansgaard-Oeschger and Heinrich events that are simulated via freshwater hosing experiments produce a meridional rainbelt shift mainly over oceans [22, 67, 68].

To the extent that projections show that the future warming will not be meridionally uniform [69, 70] due to polar/Arctic amplification and the presence of an inter-hemispheric gradient with warmer northern than southern hemisphere, it makes sense to consider paleoclimate analogues that display an inter-hemispheric difference, specifically, analogues that are warmer in the northern hemisphere such as the Eemian (above), and this is also the case for the mid-Holocene: increased obliquity, and, most importantly, precession phased such that the perihelion occurs near the time of northern hemisphere summer solstice (June).

Lines of evidence from paleoclimatic proxies and modeling studies of the Mid-Holocene concur that the African and South Asian monsoons are generally strengthened and southern hemisphere monsoons are weakened [15, 71]. The expansion of the northern hemisphere monsoon is generally captured by models but underestimated especially over Africa [72–74]. [14, 72] summarize oceanic feedbacks as positive in the case of the African monsoon, but negative in the case of the South Asian monsoon.

Evidence suggests that the North American monsoon system with its peak rainfall occurring in the northern hemisphere summer reached its greatest geographical extent in 6Kya [75]. CMIP5 models indicate both an expansion and increase in rainfall during this period [74]. After 4Kya, as autumn insolation declined and the ITCZ tracked south, the modern antiphase pattern between northern (Mexico, Baja Peninsula and Southwest U.S.) and southern (Central America and Yucatan Peninsula) regions of the North American monsoon emerged, with summer rain continuing to dominate in the south, but with winter rain becoming more important in the north [75]. In South America, evidence from proxy data indicates drier conditions in monsoon regions of southern and southeastern Brazil, while Northeast Brazil appears wetter during the mid-Holocene, suggesting a weaker (than present day) South American monsoon system [76, 59].

Summary: paleo-monsoons

Overall the development of coordinated modelling exercises (e.g., PlioMIP, LIG, LGM, midHolocene) is useful to test and investigate hypotheses about the role of external forcings (greenhouse gases and orbital parameters, as well as their influence on ice sheets) on monsoons. To date, most of these exercises have been limited to time-slice experiments. Nevertheless, the development and consistent use of forcing datasets across models has yielded results that are comparable and provide some reliability in the evaluation of monsoon responses to past climates.

The mid-Pliocene is not the most appropriate analog for anthropogenic climate change in the near term, as this warm period was equilibrated with no West Antarctic ice Sheet and relatively little ice in Greenland. Still, it is useful to examine the potential for a climate future wherein substantial ice loss occurs. For the mid-Pliocene, there is good model agreement with existing proxy reconstructions of a stronger summer monsoon across West Africa and South Asia compared to pre-industrial conditions [48], although it remains unclear whether the response is a symmetric expansion of tropical rainfall versus a northward shift. Furthermore, experiments that include changes in orbital configuration indicate that these variations modulate the monsoon response as expected from the mechanistic understanding of orbital pacing of monsoon variability (stronger northern monsoons for orbital configurations that enhance northern summer insolation and vice-versa) [50].

The asymmetric insolation forcing of the orbital cycles since the LIG and inclusive of the mid-Holocene provides more instructive, though not exact, analogues for future climate. There is model agreement with paleo-records for intensified African, South Asian and East Asian monsoons in response to peak northern summer insolation during the last interglacial [57, 58, 61, 62]. However, experiments that span the period since the LIG reveal differences in tropical rainbelt response to asymmetric solar insolation versus northern hemisphere cooling, and the response of land versus ocean that complicate expectations based on the zonal mean energetic framework.

Role of external forcing in observed trends

To understand historical and recent trends in monsoons, we must consider external as well as internal drivers. Because climate models are the primary means for separating their influence, the categorization of drivers depends on how they are incorporated in the models. In general, we refer to external drivers as those prescribed in models and include natural (insolation changes and volcanic aerosols) and anthropogenic (greenhouse gases, aerosols from fossil fuel combustion, and landuse change). Internal drivers are variations generated by interaction within the climate system (air, sea, sea-ice, and land).

Let's first set present day insolation within the context of orbital forcing. The current phase of precession, with perihelion in January, suggests wetter southern hemisphere monsoons, but a small eccentricity will limit the effect of precession through the next precession cycle ($\approx$next 20K years). Obliquity is in the middle of its range, yielding moderate seasonality at high latitudes. Because this present orbital forcing is and will continue to be relatively weak for the next several thousand years, greenhouse gas and related anthropogenic forcings are the primary drivers of change. The temperature response to present greenhouse gas forcing shows an inter-hemispheric asymmetry with relatively more warming in the north [18].

Monsoons can also be sensitive to variations internal to the coupled ocean-atmosphere system (see for example, Figure 3, which shows the variability generated by internal dynamics (grey lines) in a large ensemble of realizations with a single climate model). Modes of internal variability that have unique large-scale influences on the individual regional monsoons include the Madden-Julian Oscillation on intraseasonal timescales, the El Niño-Southern Oscillation (ENSO) on interannual timescales, and multi-decadal variations in the extratropical oceans known as the Inter-decadal Pacific Oscillation and the Atlantic Multidecadal Oscillation (AMO). However, the extent to which the 20th century evolution of the AMO itself is internal or externally forced is hotly contested [77,78].

Mechanisms discussed in the literature have, in many cases, focused on near-surface thermal gradients (see below). We note in advance of this discussion that the nascent view of monsoons as energetically direct circulations emphasizes near-surface moist static energy and associated meridional gradients as more directly linked to the spatial extent and strength of monsoonal circulations than the near surface temperature gradient [9,10]. An intention of this review is to support a shift to this new framework for how we view and understand monsoons. With this background, the recent literature on observed trends is discussed and summarized in Table 2.

Precipitation metrics associated with the "global monsoon" (large-scale seasonal tropical overturning circulation) have been developed and used to quantify the global monsoon, hemispheric monsoons, and their changes [79]. Global monsoon indices computed from observations including land and ocean regions from

1979-2008 show increasing trends in total precipitation and total area covered, and because the area has increased more than the total rainfall, a decrease in precipitation intensity [80]. The increasing trend in precipitation is corroborated by [81] for the global and (both) hemispheric monsoon indices from 1979-2011 across five reanalysis products.

In contrast, when considering the global monsoons over land only, changes in area and rainfall accumulation from 1949-2002 showed an overall weakening trend during the past 54 years, due mostly to changes in the West African and South Asian monsoons [82]. Since the 1950's anthropogenic aerosols and greenhouse gases have been dominant forcings in Earth's top of the atmosphere energy imbalance (see for example, Figure 3, which shows the mean externally forced response (black line) in a single climate model and estimates from two commonly used observational products, GPCP and CMAP, which highlight uncertainties in the observations). The observed precipitation decreases in the monsoon regions of the northern hemisphere (Africa and Asia) through the 1980's have been attributed to increased anthropogenic aerosol emissions [83, 84]. The cooling and stabilizing effects of aerosol forcing countered the greenhouse gas warming in the northern extratropics, creating an inter-hemispheric thermal gradient anomaly that shifted the tropical rainbelt and monsoon precipitation equatorward [13, 85, 86]. As aerosol emissions decrease as a result of policy interventions, the expected polar amplification has resumed with an inter-hemispheric gradient showing enhanced warming and reduced stability in the northern hemisphere. The observed annual-mean inter-hemispheric temperature asymmetry has varied within a 0.8^{o}C range and features a significant positive trend since 1980 [18]. This appears to have led to a revival of regional monsoons in the recent few decades, which we explore in more detail next.

Several studies have suggested that, since the 1950s, rainfall associated with the South Asian summer monsoon has decreased [87,88]. The reduction has been associated with a weakening of the land-ocean thermal contrast driven by relatively enhanced warming of the Indian Ocean in response to greenhouse gases [89,90], and the effect of anthropogenic aerosols [91–93], and land-cover changes [94]. A recent study reported a reversal of the rainfall trends concurrently with the land-ocean thermal gradient since the early 2000s, which also coincided with suppressed Indian Ocean warming [95]. As discussed by Walker et al. (2015) [10], however, this declining trend is not robust across regions and datasets and might be more indicative of local changes than changes in the large-scale monsoon.

The East Asian monsoon has exhibited a significant weakening trend in precipitation and circulation [96] from 1954-2010. However, instrumental records since 1901 indicate decadal variations but the long term trend is absent [97,98]. A number of mechanisms have been proposed to explain the declining trend in rainfall since the 1950's, including variations in snow cover over the Tibetan Plateau [99], variability in both tropical and mid-latitude circulations [96]), and variations in tropical Indian and Pacific Ocean SSTs [100]. Analysis of CMIP5 individual forcing experiments indicate a large contribution from aerosol forcing in the second half of the 20th century [101] for which additional evidence has recently been provided [102].

In Africa, Sahel rainfall over the 20th century was characterized by marked multi-decadal variability. The 1950s and 60s were wetter than the century-scale mean, and were followed by the decades of persistent drought of the 1970s and 80s.

Since then, rainfall has partially “recovered” [103]. Spatial and temporal features of this observed recovery resemble patterns of long-term change in model projections [104, 105]: an increase in precipitation in the interior of the Sahel, east of 5°W, and a shift in seasonality, with a decrease in rainfall in the early season, and an increase in the late season.

As much as past wet and dry periods were characterized by year-to-year persistence, conditions during the current recovery are characterized by year-to-year variability. The recovery is consistent with a reduction in North Atlantic aerosol loadings, which by cooling local SSTs relative to the global tropical mean were responsible for drought [77, 106, 107]. CMIP5 simulations are in better agreement than prior assessments that greenhouse gas-induced warming may result in a wetter monsoon, broadly consistent with the current recovery. This can be interpreted to occur when the “upped ante” in increased vertical stability that results from the global ocean-mediated warming is met by increased moisture supply from the local, North Atlantic Ocean. A positive oceanic feedback is consistent with paleoclimate modeling [14]. The extent to which the significant year-to-year variability that has characterized Sahel rainfall since the mid-1990s is a manifestation of internal variability superimposed on an emergent wetting trend remains to be ascertained.

Observations to date show weak or nonexistent trends [82] over the North American Monsoon region due to the presence of large amplitude decadal variations [108]. Despite increases in the land-sea contrast from 1979-2004, [109] found small negative trends in summer precipitation (June-August) over the region in reanalysis datasets, but no such trends in land-based observations over the period 1979-2004. Similarly, Petrie et al. (2014) [110] show no change in precipitation over the northern Chihuahuan Desert over the past century. There is some spatial variability in trends, with precipitation increases over June through September in northwest Mexico and the southwestern United States from 1948-2010, with decreases occurring in central and southern Mexico over the same time period [111]. The reduced precipitation could be linked to antecedent wildfire aerosols [112].

Our understanding of South American monsoon trends is limited by intermittent and sparse observations, particularly in the Amazon. Analysis of available data since 1950 suggest an increasing precipitation trend in the southeast [113], with increasing drought in the region of the South Atlantic convergence zone (SACZ), which implies a poleward shift [114]. There is more confidence in observed trends of increasing precipitation extremes in southern and southeastern Brazil and La Plata River Basin, which lends support for the intensification of the monsoon poleward of 20°S [113,115]. The increasing trend in this region of southeastern South America has been attributed to Antarctic ozone loss and greenhouse warming, both acting to shift the Hadley cell and southern hemisphere jets poleward [116]. Further, there is evidence for a longer monsoon season, with early onsets and late demises for 1979-2010 [115].

The South American monsoon response to ENSO and decadal Pacific and Atlantic SST variations involves a north-south shift in the SACZ that results in a dipole in precipitation [114]. Arias et al. (2012) [117] and Fernandes et al. (2015) [118] found evidence for decadal variability with dry (1948-1970 and 1991-2005) and wet regimes (1971-1990 and 2005-2009). These modes of internal variability can, for a time, mask the regional response to external forcings. This can be seen, for example, in Figure 3 wherein the model ensemble mean shows precipitation decreases in past decades in response to aerosol forcing before exhibiting precipitation increases as the greenhouse gas forcing begins to dominate the signal.

Let's summarize this discussion of recent trends as they relate to paleo-monsoon responses. First, while cooling in the northern hemisphere due to aerosols was a dominant factor from the 1950's to 80's, asymmetric warming in the northern hemisphere is emerging in the recent period as a result of greenhouse gas forcing[18]. Given this context, observations of precipitation declines in the earlier period followed by recent increases, particularly in the northern hemisphere African and Asian monsoon systems are consistent with expectations [103, 96, 98]. The weak signals seen in the American monsoons are likely due to the dominant influence of internal decadal variations over external forcing [108, 114].

Future of monsoons in a warming world

Anthropogenic greenhouse gases emissions are expected to be the dominant external forcings on climate through the next 100 years. In addition to the competing thermodynamic (increasing atmospheric humidity) and dynamic (slowing of the tropical overturning) responses, as anthropogenic aerosol loadings continue to decrease the asymmetric warming of the northern hemisphere is likely to continue. Uncertainties in this evolution include internal variations on interannual and decadal timescales (Figure 3), and regional cooling in response to a slowing of the oceanic Atlantic meridional overturning circulation. Although there is some correspondence between inter-hemispheric temperature gradients and shifts in tropical rainfall, a stronger anti-correlation has been shown between ITCZ shifts and cross-equatorial energy fluxes which can respond to remote factors.

Climate projections of the global monsoon precipitation indices point to future increases in global monsoon area (i.e., monsoon expansion), precipitation and intensity, largely in response to higher atmospheric humidity (thermodynamic) rather than circulation (dynamic) changes [119, 120]. It is surprising that northern monsoons' future response is shown to be weaker than in simulations of the mid-Holocene given that the future warming is larger [74]. This result is attributed to differing mechanisms: during the mid-Holocene both thermodynamic and dynamic responses act in concert and cross-equatorial energy fluxes shift the ITCZ towards the warmer northern hemisphere; in the future the dynamic response (weakened tropical circulation) acts against the thermodynamic response with a small net energy flux.

Given the recent findings, rainfall increases are projected for northern hemisphere monsoons due to atmospheric moistening, and in part to asymmetry in warming, which more than compensate for the stabilization of the tropical troposphere as warming proceeds [121], while smaller increases are seen in the southern monsoons. Projections of the length of the monsoon season appear to be mixed, but model sensitivity studies corroborate a remarkable model agreement regarding increased amplitude of the annual cycle of precipitation in the tropics, as well as a phase delay (later start and later end) to warm season rains [122]. In addition to these globally coherent responses, regional differences occur in projections, as are summarized in Table 2 and discussed in the following for the Asian, African, and American monsoons.

CMIP5 projections of the Asian monsoon indicate increased precipitation during summer in South Asia and East Asia as well as Australia [123]. The increasing inter-hemispheric gradient (warmer in the north) leads to larger increases in precipitation in South and East Asia compared to the Australian monsoon [123]. For South Asia, further analysis suggests a poleward shift in the moisture-bearing monsoon low level jet [124]. High resolution model projections point to weakening and poleward shift in the genesis distribution of monsoon low pressure systems which implies an increased frequency of extreme precipitation events over northern India [125]. Uncertainty in the CMIP5 model projection of South Asian monsoon rainfall has been related to the pattern of SST changes across the western Pacific and Indian Ocean [126].

For the African monsoon, [105] shows greater agreement among CMIP5 models (than was seen in the previous model intercomparison [127]) in the projection of a wetter monsoon overall, and this is reaffirmed by [74]. Despite the particular sensitivity to choice of convection parameterization seen in Sahel rainfall changes [128] (e.g. the Community Earth System Model (CESM) large ensemble in Fig 3 shows little change in precipitation at the end of the 21st century), a wetter future outcome is consistent with understanding the role of external forcing explored in this review. Specifically, it is consistent with the hypothesis that while greenhouse gas-induced warming contributed to the recent drought, it was not warming per se that dried the Sahel. Rather, it was the absence of warming of the North Atlantic relative to the global tropical oceans that caused the drought [106]. Since the absence of North Atlantic warming is largely attributable to anthropogenic aerosols, the reduction in their loading [129] is consistent with the recovery of the rains, and with projections for wetter conditions.

Over the North American monsoon region, the model projections agree that early season monsoon precipitation will decrease while late rainy season precipitation in September and October will increase, with little change in total warm season precipitation [130, 131] despite increases in land-sea contrasts in the models and warming overall [109]. These model projections are at odds with the monsoon expansion during paleoclimatic periods such as the mid-Holocene maximum when radiative forcing intensified. The difference between paleo periods and future projections may be even larger, as model biases in sea surface temperatures, particularly over the Atlantic Ocean, appear to have long-ranging effects on the future projections [8]. When these SST biases are corrected in high resolution simulations performed with double CO_2, decreases in monsoon precipitation occur from July to October (i.e., even in the late season), with the largest decreases in July and August [8]. These decreases in precipitation are linked to overall increases in atmospheric stability arising from increases in SSTs (the "remote" mechanism discussed by [132–134]).

In contrast with northern hemisphere, during the mid-Holocene the monsoons were weaker in the southern hemisphere in response to decreased summer insolation [76]. In the 21st century, however, radiative forcing increases in both hemispheres. Consequently, projections show a wetter and longer (both early onset and late withdrawal) South American Monsoon [135], consistent with the idea that the monsoon precipitation should increase in a warmer world. The trends are consistent with the longer monsoon season shown in observations [135]. The monsoon is also projected to expand poleward with diminished early season precipitation and enhanced late season precipitation [115], similar to the North American monsoon without the SST correction applied by [8], however the ozone recovery will act in opposition to warming and could lessen the response in this region [116].

Summary

Although there is no perfect analog to the seasonality and hemispheric asymmetry in the warming response expected in the coming decades, the mid-Holocene and Eemian provide estimates of monsoon response to changes in the inter-hemispheric gradients and cross-equatorial energy fluxes set by orbital variations. Lines of evidence from paleoclimatic proxies and from modeling concur that the African and Asian monsoons are generally wetter and southern hemisphere monsoons are drier [15, 71, 59]. Rainfall in northern monsoons increased during strong precession maxima (Mid-Holocene and early Eemian). While this would suggest a similar response of northern hemsiphere monsoons with increased greenohuse warming, the different patterns of anomalous net energy input especially over land and differing impacts on stability might make these climates not precise analogues of future warming [74, e.g.]. Estimates of reduced rainfall in southern monsoons during mid-Holocene may be less appropriate for the future because greenhouse gas forcing is warming the southern hemisphere and its oceans, even if not at the same rate as north of the equator. CO_2 also causes a direct increase in dry static stability, with corresponding circulation changes in both hemispheres [136]. It is also worth restating the difference in the regional ocean feedbacks to the monsoon response in Africa and South Asia [72].

The 20th century declines in Asian (South and East) and African monsoon rainfall are inconsistent with theory and evidence from paleoclimatic proxies which indicate increasing monsoon precipitation in a warmer climate. Although an array of potential drivers of the observed declines have been proposed for each monsoon region, there is strong evidence that anthropogenic aerosols were a dominant factor in the persistent Sahel drought [83, 84, 77, 106]. There is mounting evidence that aerosols have been a significant driver in South and East Asia as well [83, 84, 102, 101, 91–93]. The compensating influence of aerosol forcing has diminished, with rainfall recoveries occurring in Africa and South Asia, and this forcing is expected to decline in the coming decades due to policy interventions. Thus, the radiative forcing from greenhouse gases is expected to be dominant through much of the 21st century.

[2] conclude that total monsoon precipitation in the northern and southern hemispheres will change in opposite directions in the coming decades, owing to differences in hemispheric warming. Given the vertically integrated moist static energy framework that describe shifts in tropical rainbelts, the increasing inter-hemispheric temperature gradient has been associated with a northward ITCZ shift in the zonal mean. How this ITCZ response will manifest in precipitation shifts in different monsoon regions remains an open question in the literature. Climate model projections indicate overall expansion of, but weakened monsoon circulations and increased precipitation in both hemispheres. While more work is need to incorporate the complexities of different monsoon systems, the atmospheric energy budget might provide a basis for a consistent understanding of the role of each of these changes (e.g., stability, lateral import of moist static energy, inter-hemispheric temperature gradients).

As with many other open questions in climate science, our understanding of monsoon circulations remains limited (note for example, significant model biases in Figure 3) because of the complexity of these systems, which involve interplays between the large-scale tropical circulation and convection, the influence of both local and remote forcing, interactions between land, atmosphere and ocean, and other components of the climate system [137]. The framework as currently defined (Figure 2) appears to represent reasonably well the monsoons of Asia and Africa, but will require refinement for monsoons that do not include cross-equatorial circulations such as North America. Forward progress requires the use of model hierarchies, which allow for the development and testing of physically-driven hypotheses by introducing complexity in a progressive way [138, 139]. For a problem as complex as that of the monsoon, this needs to include model setups spanning from zonally symmetric aquaplanets with idealized physics [140] to idealized representations of land masses or other zonal asymmetric in both idealized and full physics global climate models [141, 64, 142] or of the interaction with the ocean circulation [143–145]. The physical constraints and testable ideas emerging from this approach can hence be used to interpret paleo records, to evaluate comprehensive Earth system models, and to better constrain their past reconstructions and future projections.

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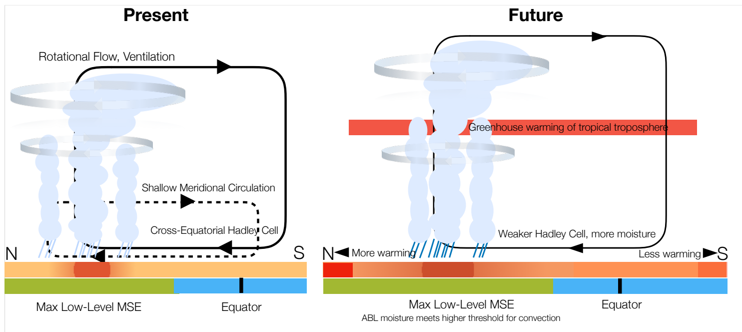

Fig. 1 Mechanistic view of monsoons. Emerging theories interpret monsoons as energetically direct cross-equatorial circulations, integrally linked to the marine ITCZ, and N-S (Hadley) and E-W (Walker) overturning circulations, through global energy budget constraints. The green and blue bar shows land and ocean, respectively. The red and yellow bar shows near-surface moist static energy, where red and orange colors indicate higher moist static energy, and yellow indicates lower values of moist static energy. In the future, the blocks of red at each end of the bar represent the inter-hemispheric gradient (more warming in the Northern Hemisphere). The shallow meridional circulation is not shown in the future diagram because changes to it are uncertain. Not all monsoons show a clear cross-equatorial flow, and more work is needed to understand how theories applicable for large-scale systems can be modified to other monsoon systems. Adapted from [4].

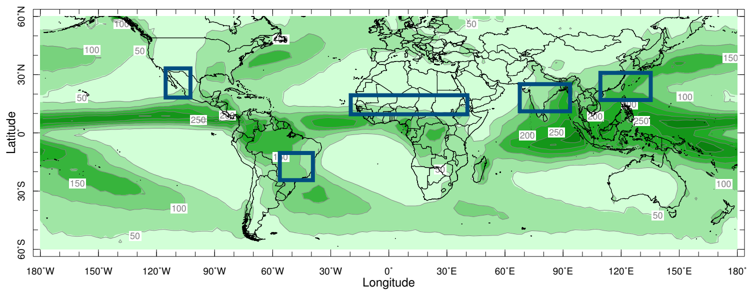

Fig. 2 Observed climatological annual mean precipitation from Climate Prediction Center Merged Analysis of Precipitation version 2 (CMAP) [146, 147], 1981-2010. Boxes indicate monsoon region boundaries analyzed in this review. Note that reviewed studies consider differing boundaries for these regions.

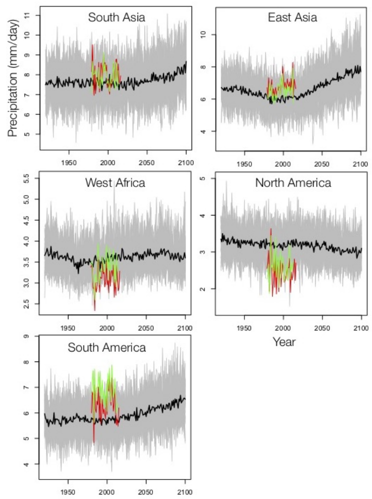

Fig. 3 Time series of regional-average monsoon season precipitation from observations - CMAP [146,147], (red) and Global Precipitation Climatology Project (GPCP) [148,149] (green) – for the historical period (1979-present) and the National Center for Atmospheric Research CESM Large Ensemble Project (1920-2100) with all historical forcings from 1920-2005 and the RCP 8.5 scenario from 2006-2100 [150]. Grey lines indicate the individual ensemble members and the black line is the 40-member ensemble average. The monsoon domains include South Asia (65-100°E, 10-25°N), East Asia (110-135°E, 20-35°N), West Africa (20W-40°E, 10-20°N), North America (115-102.5°W, 17-33°N), and South America (60-40°W, 10-25°S). The monsoon seasons are defined as June-August for the Northern Hemisphere and December-February for the Southern Hemisphere.

Table 1 Monsoon responses for past climates. Analysis type includes models (M) and proxy data (P). Precession forcing refers to northern summer perihelion, and Obliquity forcing to increased seasonality. PlioMIP forcing employs a pre-industrial orbit, with 400 ppm CO_2, no ice sheet in West Antartica, a small ice sheet in Greenland, and increased sea level. Response to forcing represents overall stronger (+) or weaker (–) monsoons and is given for northern/southern hemispheres. A ◦ represents no information given. Abbreviations include: Northern Hemisphere (NH), Southern Hemisphere (SH), East Asia (EAsia), West Africa (WAF), and North America (NAM).

Period	Paper	Region	Analysis M/P	Response NH/SH	Forcing
Review	Zhishen et al. (2015)	Global	M/P	+/–	orbital
	Mohtadi et al (2016)	Global	M/P	+/◦	Precession/Obliquity
	Wang et al (2017)	Global	M/P	+/–	Precession/Obliquity
Pliocene	Haywood et al. (2013)	Global	M	+/◦	PlioMIP
	Sun et al. (2013)	EAsia	M	+/◦	PlioMIP
	Burls, Federov (2014)	Global	M	+/◦	CO_2, Cloud
	Zhang et al. (2015)	EAsia	M	+/◦	PlioMIP, Precession/Obliquity
	Sun et al. (2016)	EAsia	M	+/◦	PlioMIP
	Corvec et al. (2017)	Africa Asia	M	+/◦	PlioMip
	Keuchler et al. (2018)	WAF	P	+/◦	Precession/Obliquity
Eemian	Otto-Bliesner et al. (2013)	Global	M	+/–	Precession/Obliquity
	Schneider et al. (2014)	Global	M	+/◦	Precession/Obliquity
	Govin et al. (2014)	WAF	P	+/◦	Precession/Obliquity
	Kathayat et al. (2016)	SAsia	P	+/◦	Precession/Obliquity
	Singarayer et al. (2017)	Global	M	+/◦	Precession/Obliquity
	Pedersen et al. (2017)	Global	M	+/–	Precession/Obliquity
	Gierz et al. (2017)	Global	M	+/◦	Precession/Obliquity
Mid-Holocene	Biasutti et al (2018)	Global	M/P	+/–	Precession/Obliquity
	Braconnot et al. (2012)	WAF	M	+/◦	Precession
	Jiang et al. (2015)	Global	M	+/◦	Precession
	Zhao, Harrison (2012)	Global	M	+/◦	Precession
	Metcalfe et al. (2015)	NAM	M/P	+/◦	Precession
	Prado et al (2013)	SAM	M/P	◦/–	Precession
	Baker, Fritz (2015)	SAM	P	◦/–	Precession

Table 2 Monsoon responses for present and future climates. Analysis type includes observations (O) and models (M). The 20th century response (20C) is given as stronger (+) or weaker (–) circulation (C) and wetter(+) or drier (–) for precipitation (P) and likewise for the Present, and late 21st century (21C). A ∘ represents no information given and ? indicate inconclusive results within the C/P pair. The observed mechanism or model forcing is given in a separate column to the right of 20C and Present columns. The scenario employed in experiments for the future is given in the column to the right of 21C. Abbreviations include: Representative Concentration Pathway (RCP), Historical simulation (HIST), no change (nc).

Region	Paper	Analysis O/M	20C C/P	Forcing or Mechanism	Present C/P	Forcing or Mechanism	21C C/P	Scenario
Global	Wang et al. (2012)	O	∘/+		∘/+			
	Hsu et al. (2013)	M					∘/+	RCP4.5
	Kitoh et al. (2013)	M					–/+	RCP4.5,8.5
	Lin et al. (2013)	O			∘/+			
	Lee et al. (2014)	O			∘/+			
	Lee, Wang (2014)	O/M	∘/–		∘/+	HIST	–/+	RCP4.5
	Polson et al. (2014)	O	∘/–	Aerosols	∘/+			
	Hurley, Boos (2015)	O	nc/∘		nc/∘			
South Asia	Singh et al. (2014)	O	∘/–					
	Salzmann et al. (2014)	O/M	–/–	Aerosols				
	Wang et al. (2014)	O/M			nc/nc	HIST	–/+	RCP4.5
	Guo et al. (2015)	M	–/–	Aerosols				
	Roxy et al. (2015)	O	–/–	-Gradient				
	Walker et al. (2015)	O	∘/nc		∘/nc			
	Paul et al. (2016)	O/M	∘/–	Land cover				
	Jin, Wang (2017)	O/M			+/+	+Gradient		
East Asia	Zhu et al. (2012)	O	–/–	Circulation				
	Qian, Zhou (2013)	O	–/–	trop SST				
	Li et al. (2016)	O	–/–	Aerosols				
	Song et al. (2014)	O	–/–	Aerosols				
	Wang et al. (2014)	O/M			nc/nc	HIST	nc/+	RCP4.5
West Africa	Sanogo et al. (2015)	O			∘/+			
	Giannini et al. (2013)	O/M	∘/–	Aerosol, CO_2	∘/+	CO_2		
	Biasutti (2013)	O/M	∘/–		∘/+	CO_2	∘/?	RCP, 4x
	Booth et al. (2012)	M	∘/–	Aerosol				
	Dong, Sutton (2015)	M			+/+	CO_2		
	Wang et al. (2016)	M	–/–	Aerosol				
	Hill et al. (2017)	M					?/?	+2°K
NAM	Arias et al. (2015)	O	?/nc	SSTs	?/nc	CO_2		
	Hoell et al. (2016)	O			?/nc	?	∘/+	RCP
	Petrie et al. (2014)	O	∘/nc		∘/nc	?		
	Cook, Seager (2013)	M					∘/nc	RCP
	Maloney et al. (2013)	M					∘/–	RCP
	Pascale et al. (2017)	O/M					∘/–	2xCO_2
SAM	Arias et al. (2015)	O	?/nc	SSTs	?/nc	CO_2		
	Skansi et al. (2013)	O	?/+		?/+			
	Grimm, Saboia (2014)	O	?/+					
	de Carvalho et al. (2016)	O			?/+	CO_2	∘/?	RCP

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