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Palaeoclimatic insights into forcing and response of monsoon rainfall

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Monsoons are the dominant seasonal mode of climate variability in the tropics and are critically important conveyors of atmospheric moisture and energy at a global scale. Predicting monsoons, which have profound impacts on regions that are collectively home to more than 70 per cent of Earth's population, is a challenge that is difficult to overcome by relying on instrumental data from only the past few decades. Palaeoclimatic evidence of monsoon rainfall dynamics across different regions and timescales could help us to understand and predict the sensitivity and response of monsoons to various forcing mechanisms. This evidence suggests that monsoon systems exhibit substantial regional character.

Reliable prediction of summer monsoons is critical to mitigating the often catastrophic consequences of monsoon rainfall anomalies, such as floods and droughts, famine, and economic losses. Yet, despite its pivotal role in the livelihood of billions of people, summer monsoon rainfall remains difficult to predict[1–3]. It is expected 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[4]. Regional differences are expected to be large, and some monsoon regions are predicted to receive more rainfall despite a projected weakening of the monsoon circulation[1]. Even though the latest generation of climate models show substantial overall improvements compared to their predecessors[2,5], the extent and intensity of monsoons are still often under-simulated[2], with most models showing systematic errors in the seasonal cycle and in intra-seasonal-to-interannual variability[5,6]. Moreover, there is low confidence in projections of future changes in the amount of rainfall for several monsoon domains[1]. For instance, projection of the South Asian (Indian) summer monsoon rainfall is a key challenge for global and regional circulation models[7]. Poor simulations of monsoon dynamics arise mainly from the complexity of these land–ocean–atmosphere coupled systems that interact with nearly all other tropical and extratropical climate phenomena, such as the El Niño–Southern Oscillation (ENSO)[3] and the Hadley and Walker circulations[8] (Box 1).

The monsoon concept has recently changed from a regional to a global one. The new idea of a "global monsoon"[8,9] takes into account a coherent response of all monsoon systems, regardless of regional differences, to changes in global-scale atmospheric circulation patterns forced by the annual cycle of solar radiation and land–air–sea interactions[8]. Modern climatology of monsoon domains (Fig. 1) is well depicted by the concept of a global monsoon[9], and models are substantially better at representing the global monsoon than the regional monsoons[1]. However, several reconstructions and transient simulations of past monsoon variability emphasize that it has a substantial regional character, rather than being characterized by the common, global dynamics of the monsoon systems at different timescales[10,11]. Study of monsoon evolution beyond the instrumental record is thus essential to improve our understanding of natural and anthropogenic forcing mechanisms of monsoon rainfall and its interactions and teleconnections on various timescales, which will enable us to test and enhance climate models in their ability to represent and predict monsoon dynamics, and to contribute to the climate change discussion.

Within the past decade, palaeoclimate studies have provided new insight into past monsoon variability with unprecedented temporal and spatial coverage. Here we evaluate the forcing mechanisms of variability in summer monsoon rainfall as evidenced by palaeoclimate research (Fig. 2), and identify several aspects of monsoon dynamics that will improve our understanding of future monsoon response to specific forcing. The scope of this Review is constrained by the available monsoon reconstructions and the timeliness of climate model simulations, and excludes oceanic monsoon domains, highly uncertain forcing mechanisms and tectonic forcing.

The palaeoclimatic evidence shows that monsoon dynamics are strongly shaped by large-scale meridional temperature gradients and the related position of the intertropical convergence zone[12] (ITCZ; Box 1). However, study of past monsoons also reveals that these temperature gradients are sensitive to many types of forcing, the influence of which seems to vary in time and space. Until climate models converge on the simulation of monsoon forcings, a robust projection of future monsoons will remain elusive[13]. In this Review, we discuss the main forcings of monsoon variability and their uncertainties, and argue that a coordinated effort to quantify past variations in meridional temperature gradients, including site-specific monsoon reconstructions, will provide a crucial test bed for model improvement.

Orbital forcing

Changes in the tilt of Earth's axis (obliquity) as well as axial and apsidal precession (wobble of Earth's axis and rotation of Earth's elliptical orbit over time, respectively) modulate the temporal and spatial distribution of insolation. Precession, with periods of about 19 kyr and 23 kyr, affects the seasonal cycle of incoming solar radiation and its hemispheric distribution, and is therefore considered a major control on changes in monsoon intensity[14]. A prominent example of this control was during the early-to-mid Holocene, when higher-than-today Northern Hemisphere summer insolation rendered the North African monsoon strong enough to turn the Sahara desert into a steppe or savannah landscape[15,16].

Generally, monsoon rainfall and seasonality (that is, the amplitude of the annual rainfall cycle) are enhanced in the Northern Hemisphere and reduced in the Southern Hemisphere during a precession minimum (when the Northern Hemisphere summer solstice occurs at perihelion—the point in the orbit of the Earth at which it is nearest to the Sun) and vice versa during a precession maximum (when the Northern Hemisphere summer solstice occurs at aphelion—the point in the orbit of the Earth at which it is farthest from the Sun); see Fig. 3. Substantial support for this view is provided by more than a decade of research on stable oxygen isotope ($\delta^{18}O$) records of high-resolution and absolute-dated cave

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BOX 1

Key characteristics of monsoon systems and related climate phenomena

Intertropical convergence zone (ITCZ). The ITCZ is a tropical belt of maximum precipitation that results from deep convection that migrates seasonally towards the warming hemisphere[37]. Over land, it moves back and forth across the equator following the zenith point of the Sun. The zonal-mean position of the ITCZ is associated with the rising branch of the global Hadley cell.

Tropical and subtropical monsoons. In tropical monsoons, precipitation occurs almost entirely within an ITCZ that is seasonally displaced in the presence of cross-equatorial pressure gradients. The onset of tropical monsoons correlates with a distinct change in the wind shear, such as in the South Asian monsoon[28,43,99]. In subtropical monsoons, precipitation is mainly controlled by the position and migration of the subtropical highs and frontal systems. For the East Asian monsoon, the jet stream and large-scale topography are also crucial to the seasonal evolution of rainfall[28].

Dynamic and thermodynamic mechanisms. Monsoon rainfall is affected by dynamic and thermodynamic mechanisms. Dynamic mechanisms refer to changes in winds with unchanged water-vapour concentration in the air. Thermodynamic mechanisms refer to changes in water-vapour concentration with unchanged winds. Thermodynamic mechanisms dominate the hemispherically antisymmetric, annual-mean precipitation response to precession in the absence of land–sea contrasts[24].

Atlantic Multidecadal Oscillation (AMO). The AMO is a mode of natural climate variability characterized by a coherent pattern of variability in basin-wide North Atlantic sea surface temperature (SST) with a period of 60–80 years, and is associated with multidecadal variations in the strength of the Atlantic overturning circulation[100].

Pacific Decadal Oscillation (PDO). The PDO is the leading empirical orthogonal function of monthly SST anomalies over the North Pacific, and is closely related to the strength of the wintertime Aleutian low-pressure system. It is characterized by SST anomalies with a period of 20–30 years and opposite signs in the western extratropical and eastern Pacific.

El Niño–Southern Oscillation (ENSO). The ENSO is a naturally occurring, interannual fluctuation in equatorial Pacific SST, with a warm (El Niño) and a cool (La Niña) phase. Its atmospheric component, the Southern Oscillation, is measured by the sea-level pressure difference between Darwin, Australia and Tahiti, French Polynesia. The central-Pacific El Niño is characterized by positive SST anomalies in the central, rather than the eastern, equatorial Pacific.

Walker circulation. Walker circulation describes thermally direct, equatorial, zonal overturning circulation that converts available potential energy to kinetic energy of atmospheric motion. Over the Pacific Ocean, a zonal sea-level pressure gradient causes surface air to move from high pressure (caused by sinking motion) in the eastern Pacific to low pressure (caused by rising motion) in the western Pacific. Walker circulation is intrinsically connected to the ENSO, with a stronger flow during La Niña and a weaker flow during El Niño.

Hadley circulation. Hadley circulation describes tropical, meridional overturning circulation and is quantified by a mass-flux stream function. Strong diabatic heating near the thermal equator results in ascending air that spreads poleward, descends at subtropical high-pressure zones of both hemispheres, and flows towards the equator near the ocean or land surface. During the summer monsoon season, the Hadley circulation changes to a distinctly asymmetric flow, with ascent in the summer hemisphere and substantial cross-equatorial transport of energy and moisture[28,98].

stalagmites that vary with 19-kyr or 23-kyr periodicity, similarly to precession, with an anti-phased interhemispheric relationship[17,18]. Recently, climatic interpretations of the stalagmite δ^{18}O variability, particularly in the East Asian monsoon domain, have become controversial, with an overwhelming and growing number of observational and palaeoclimate data and model studies suggesting that the intensity of the local summer monsoon rainfall is not the only control on this proxy[19–23].

Despite this ongoing controversy surrounding the interpretation of stalagmite δ^{18}O from the East Asian monsoon domain, model simulations support the notion that precession is a strong control on rainfall in all monsoon domains (Fig. 3). During a precession minimum, the Northern Hemisphere summer is characterized by higher insolation and a stronger land–sea thermal gradient, which increase the atmospheric humidity (the thermodynamic component of monsoon rainfall) and wind circulation intensity (the dynamic component) (Box 1), whereas the Southern Hemisphere summer experiences the opposite scenario[24]. Simulations of changes in the spatial distribution of rainfall due to precession do not support a simple meridional shift in the seasonal position of the ITCZ, but do indicate a shift in the rainfall between land and ocean (Fig. 3a, b). Here, higher insolation causes the early-summer surface temperature to increase much faster over land than it does over the ocean, so that the maximum near-surface equivalent potential temperature (a quantity related to the stability of a column of air: if the equivalent potential temperature at the surface is greater than aloft, then the column is unstable and convection can occur) is shifted over land before the onset of the summer monsoon, resulting in enhanced land precipitation at the expense of rainfall over the adjacent sea[20]. By contrast, the maximum near-surface equivalent potential temperature and the precipitation centroid tend to stay over the ocean when insolation is low[20].

Changes in obliquity with a period of 41 kyr affect the seasonality of incoming solar radiation equally in both hemispheres, with stronger variation in incoming radiation at high latitudes. Despite weak changes in incoming solar radiation at low latitudes, palaeoclimate data and model studies suggest that obliquity has a substantial effect on the strength of monsoon systems[11,19,25,26], with increased summer monsoon rainfall when obliquity is maximal (Fig. 3c, d). A key factor in the traditional view of the (indirect) effect of obliquity on monsoons is high-latitude remote climate forcing associated with Northern Hemisphere ice sheets and sea-ice[27]. Obliquity-induced changes in cryosphere extent have been suggested to affect the monsoon domains by changing the oceanic and atmospheric circulations and the trajectories of moisture advection on glacial–interglacial timescales. Recent modelling results suggest that these changes are small for the South Asian monsoon, which becomes drier during glacial periods owing to lower temperatures[23] (a thermodynamic mechanism). However, for the East Asian monsoon domain, circulation changes are critically large and result in moisture convergence from the Pacific Ocean and increased precipitation, partly due to redistribution of air mass from the continents to the oceans as ice sheets grow, thereby enhancing the subtropical high-pressure system over the Pacific Ocean[23] (Fig. 4). In addition, the waxing and waning of ice affect the subtropical monsoons (Box 1) by changing the latitudinal temperature gradient and the position of the jet stream—a critical component of the East Asian monsoon[22,28]—and by inducing stationary planetary waves that strengthen the East Asian summer monsoon when ice grows[29]. The release of meltwater into the North Atlantic by waning ice sheets suppresses the North American monsoon more than any other monsoon domain[30].

Recent studies suggest that obliquity also has a direct effect on monsoon rainfall by changing the meridional insolation gradient in the summer hemisphere and the interhemispheric insolation gradient[26,31]. The direct insolation-gradient forcing by obliquity can thus greatly contribute to changes in monsoon intensity at many locations without involving the (indirect) high-latitude remote climate forcing associated with Northern Hemisphere ice sheets[25,26] (Fig. 3). The presence of 41-kyr periodicity in West African monsoon records during the warm Pliocene[27], that is, before the onset of strong Quaternary ice-sheet feedbacks in the Northern Hemisphere, supports the model-derived finding of a direct insolation-gradient forcing.

The timing of the response of different monsoon systems to precession and obliquity forcing and the degree to which they respond are matters of debate. Reconstructions of rainfall from the South American[32] and eastern North African[11] monsoons point to precession as the main forcing, whereas other reconstructions consider obliquity forcing to be at least of comparable importance for the West African[11] and South Asian[11,19] monsoons. On the other hand, model studies consistently suggest that, when ice sheet feedbacks are disabled, precession has a more severe

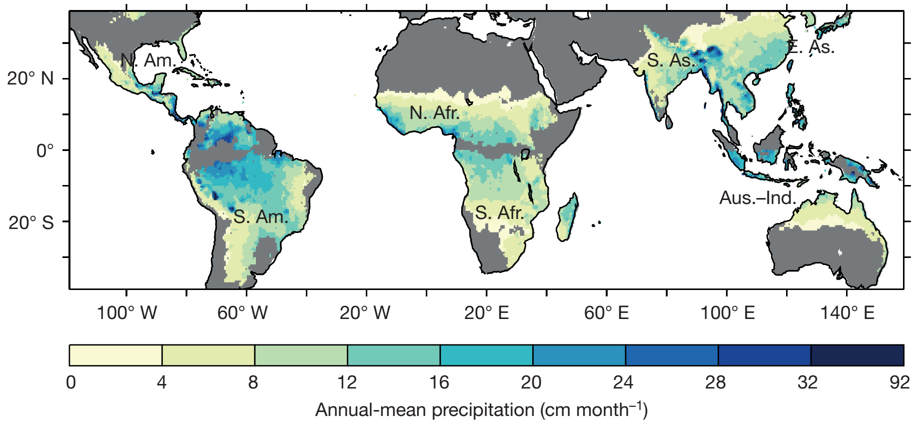

Figure 1 | Global monsoon domain (coloured regions) as defined by the seasonality (summer–winter difference) in rainfall. For the calculation of the monsoon domain, we applied the criteria of ref. 9—which require that the annual precipitation range (local summer-minus-winter precipitation) is larger than 6 cm month^{-1} and exceeds 50% of the annual-mean precipitation—except that the boreal summer was defined as June–August and the austral summer as December–February. Colours denote annual-mean precipitation. Monthly global gridded, high-resolution (0.5°) precipitation data from 1901–2010 from the University of Delaware were used. Regional monsoon areas are: North America (N. Am.), South America (S. Am.), North Africa (N. Afr.), southern Africa (S. Afr.), South Asia (S. As.) or India, East Asia (E. As.) and Australia–Indonesia (Aus.–Ind.).

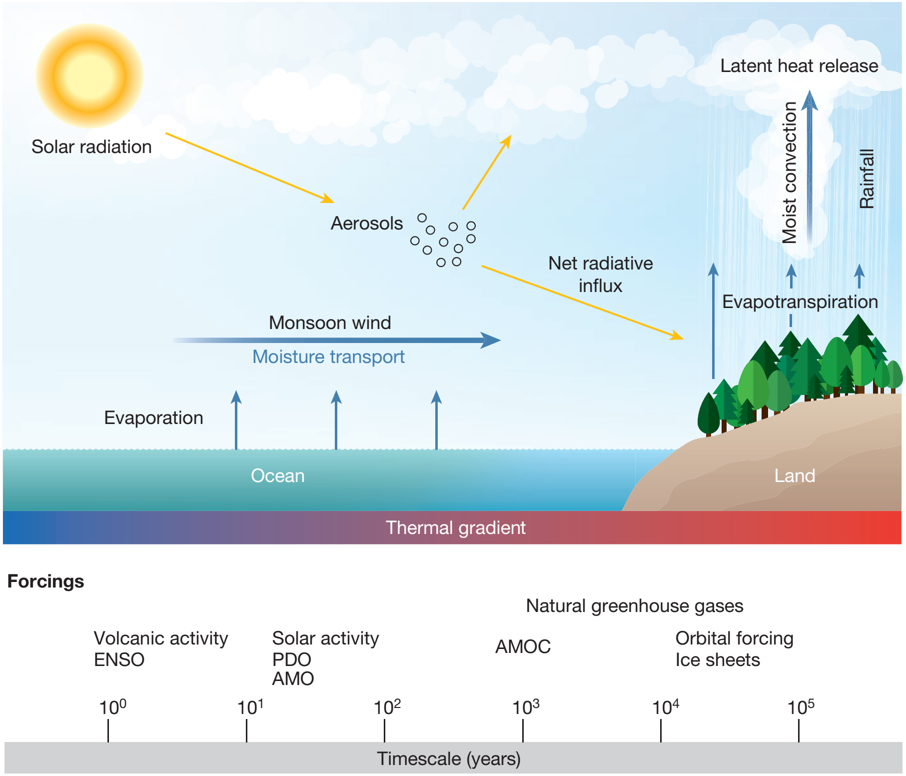

Figure 2 | Basic components of a summer monsoon and its driving forces. Summer solar radiation heats the surface. A land–ocean thermal contrast, resulting from a lower surface heat capacity of the land compared to the ocean, causes the low-level inflow of moist air from ocean to land during summer and the rising of air over the landmass. Recent studies of monsoon dynamics have de-emphasized the relevance of land–ocean surface contrasts and suggested that interactions between extratropical eddies and the tropical circulation are essential for the development of monsoons[98]. Condensation of water vapour in the rising air leads to the release of latent heat and rainfall. The latent-heat release in the troposphere reinforces the circulation and helps to pull in additional moisture from ocean to land. Depending on the vegetation cover, evapotranspiration on land may further feed the monsoon rain via local water recycling. Evapotranspiration may also affect the dynamics of the monsoon system via evaporative cooling of the land surface. Aerosols can affect the land–sea thermal contrast and, hence, the monsoon by modifying the transfer of solar radiation through the atmosphere by scattering and absorption processes. Aerosols may also have an effect on cloud microphysics, including changes in the radiative properties, frequency and lifetime of clouds. Because the various components of the monsoon system are closely coupled through feedback mechanisms, perturbation of any component may cause a chain reaction that affects the monsoon system as a whole. Different forcings perturb different components of the monsoon system, which then affect the entire system via feedback mechanisms, and act on different timescales. AMO, Atlantic Multidecadal Oscillation; AMOC, Atlantic meridional overturning circulation; ENSO, El Niño–Southern Oscillation; PDO, Pacific Decadal Oscillation.

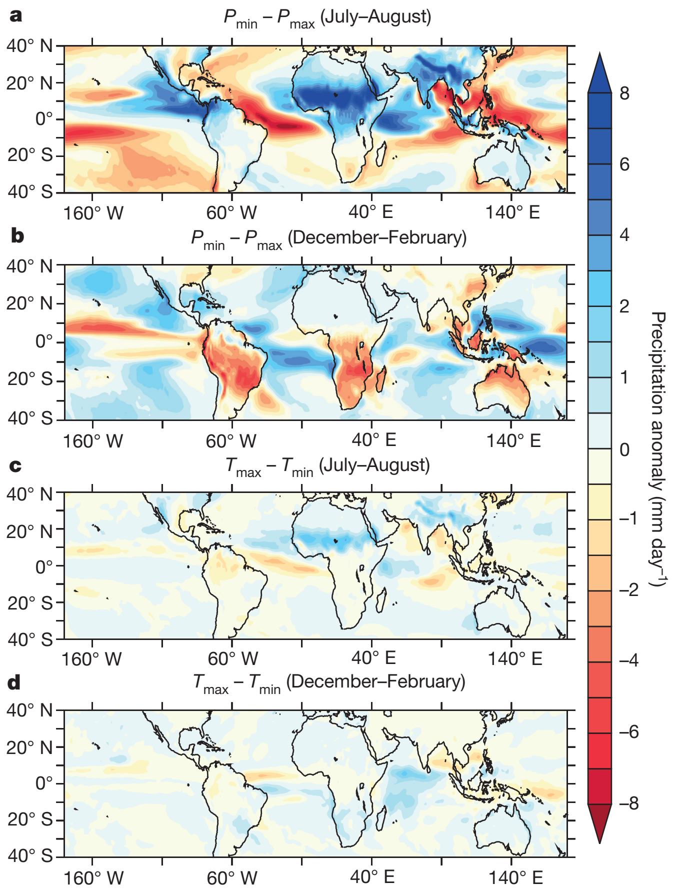

Figure 3 | Effects of obliquity and precession on tropical rainfall. **a**–**d**, Precipitation anomalies (in millimetres per day; colour scale) as simulated by the high-resolution (1.125° horizontal resolution with 62 levels in the atmosphere), fully coupled, atmosphere–ocean general circulation model EC-Earth[25]. $P_{min} - P_{max}$ (**a**, **b**) refers to the difference between the minimum and maximum climatic precession; $T_{max} - T_{min}$ (**c**, **d**) refers to the difference between the maximum and minimum obliquity (axial tilt). Results are shown for boreal summer (June–August; **a**, **c**) and austral summer (December–February; **b**, **d**) mean precipitation. Applied minimum and maximum values for obliquity and climatic precession correspond to extreme values of the orbital parameters during the last one million years. Obliquity was set to a minimum value in **a** and **b**. In **c** and **d**, a circular orbit was assumed; that is, climatic precession was set to zero. During precession minimum (P_{min}), summer solstice occurs at perihelion such that seasonality is enhanced in the Northern Hemisphere and reduced in the Southern Hemisphere. During precession maximum (P_{max}), summer solstice occurs at aphelion. All other boundary conditions, such as the solar constant, greenhouse gas concentrations, sea level, ice sheets and vegetation, were kept fixed at pre-industrial levels during the model experiments. Details of the experimental set-up are described in ref. 25. Figure courtesy of J. H. C. Bosmans, University of Utrecht.

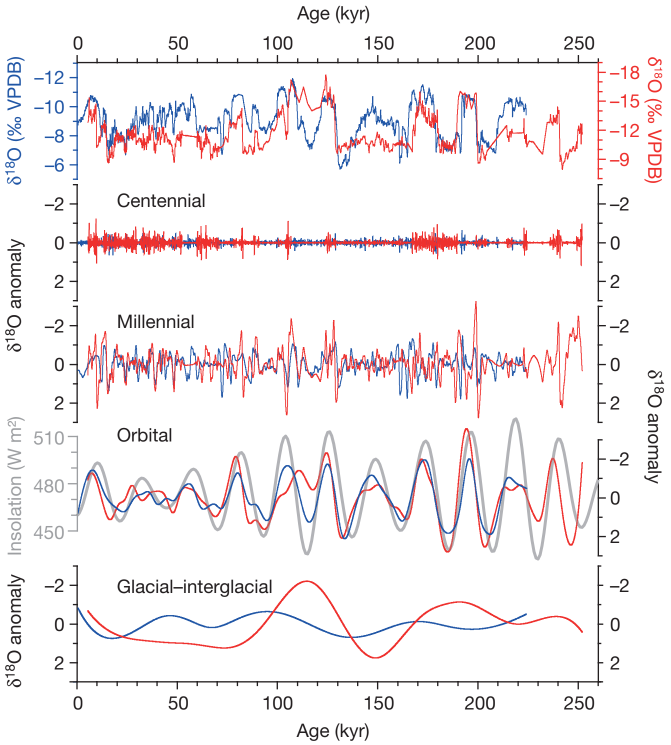

Figure 4 | Monsoon variability at different timescales as evidenced by δ^{18}O of cave stalagmites. Ensemble empirical mode decomposition of cave speleothem δ^{18}O records from the South Asian (red) and East Asian (blue) monsoon domains. Values are relative to Vienna Pee Dee Belemnite (VPDB). The bottom four panels show the intrinsic components decomposed from the speleothem δ^{18}O records (top panel) ordered by timescales, as indicated, illustrating the stalagmite δ^{18}O variance at each specific timescale. Summer (July–August) insolation at 30° N is shown in grey in the fourth panel. The lack of glacial–interglacial variability in the East Asian (blue) record in the bottom panel can be explained by the cancelling effect of increased precipitation (decrease in δ^{18}O) and a greater contribution of the Pacific moisture source (increase in δ^{18}O). Image adapted from ref. 23, National Academy of Sciences.

impact on monsoon rainfall than does obliquity[25,33] (Fig. 3), but without a consistent response of the specific monsoon systems to orbitally forced insolation changes. This is in part due to the varying influence of the internal feedback mechanisms such as ocean–atmosphere interaction. For instance, the sign and magnitude of sea surface temperature (SST) feedbacks on monsoon rainfall are equivocal in model simulations, with some implying a very limited effect on the South American[34] and East Asian[35] monsoons and others suggesting a large impact on the East Asian monsoon[21]. The influence of SST has been shown to amplify the insolation-induced strengthening of the African[36] and South Asian[35] monsoons, and to reduce the intensification of the South Asian monsoon[36]. Mechanistically, in some models, SST increases promote inland advection of moist air from the tropical Atlantic into the North African monsoon domain[36], but shift the rainfall centroid towards the ocean in the South Asian monsoon domain[20,36]. By contrast, other models suggest that more divergent upper-tropospheric flow above the Arabian Sea and greater atmospheric water availability act as a positive feedback on the South Asian monsoon rainfall[35].

The inconsistent and, in part, out-of-phase behaviour of the monsoon domains in response to insolation forcing is also due to their resonant response to insolation changes[36]. Transient simulations suggest that the subtropical monsoon systems are less sensitive to insolation forcing than are the tropical monsoons in terms of total rainfall, because the insolation-induced changes in summer rainfall are partly counter-balanced by precipitation changes in other seasons[10]. The sensitivity of the tropical monsoons is also not uniform: the North African monsoon is most sensitive to summer insolation, whereas the South Asian monsoon is most sensitive to spring-to-early-summer insolation[33]. It has been suggested that the reason for this non-uniformity is a resonant response of the South Asian monsoon to insolation forcing when maximum insolation anomalies occur near the summer solstice (for example, during the early Holocene) and a resonant response of the African monsoon—which has its rainfall maximum one month later in the annual cycle than the South Asian monsoon—when the maximum insolation change is delayed after the summer solstice (for example, during the middle Holocene)[36].

In summary, it appears that the different responses of the individual monsoons to orbital forcing arise from their differing seasonal cycles that are influenced by regionally distinctive internal feedbacks. However, orbital forcing affects all the monsoon domains by changing

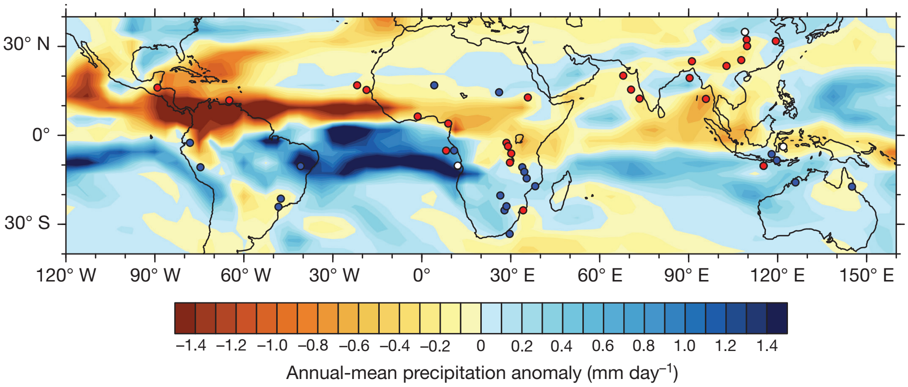

Figure 5 | Monsoon rainfall anomalies during Heinrich stadial 1. Changes in rainfall during HS1 (15–17 kyr before present) relative to the Last Glacial Maximum (LGM, 19–21 kyr before present) as indicated by monsoon proxy records (filled circles) and simulated by the TraCE-21k climate model[45] (annual-mean precipitation anomalies, colour shading). The TraCE-21k simulation was performed with the coupled atmosphere–ocean general circulation model CCSM3 (Community Climate System Model, version 3). The resolution of the atmospheric component is 3.75° in the horizontal direction with 26 layers in the vertical direction. Starting from the LGM, the model was integrated to the present-day, subject to realistically varying forcings by orbital insolation, atmospheric greenhouse gas concentrations, continental ice sheets, and meltwater fluxes. Filled red and blue circles indicate negative and positive monsoon rainfall anomalies, respectively. Filled white circles indicate no change or uncertain changes during HS1 compared to the LGM. Only records from monsoon domains as indicated in Fig. 1 are shown. For references, see main text.

the meridional gradient in insolation and, hence, heating; considering the recent differential hemispheric warming that will probably increase in the future[4], exploring this aspect in palaeo-monsoon studies may help to better assess and predict future changes in monsoon rainfall. In addition, it has been suggested that obliquity-induced changes have some qualitative similarities with global-warming-induced changes, with respect to the summer-hemisphere Hadley cell driven by baroclinic eddies[31]. Therefore, a deeper understanding of obliquity-induced changes in tropical circulation is crucial for more reliable predictions of climate change.

North Atlantic forcing

Today, a northward cross-equatorial, ocean heat transport of about 0.5 PW, which is mainly due to the Atlantic meridional overturning circulation (AMOC), results in relatively warm surface waters in the northern North Atlantic and renders the Northern Hemisphere warmer than the Southern Hemisphere. In response, there is a cross-equatorial, southward transport of energy via the mean Hadley circulation, as a result of the ascending branch of the Hadley circulation and the mean position of its ITCZ being located north of the Equator[37]. Any physical mechanism that induces anomalous warming or cooling of one hemisphere relative to the other will cause a shift in the mean position of the ITCZ towards the warming hemisphere[38,39], which will affect tropical monsoon systems.

Heinrich and Dansgaard–Oeschger events of the last glacial period serve as paradigms of oscillations in interhemispheric temperature asymmetry[40]. During these millennial-scale climate fluctuations, changes in the interhemispheric thermal gradient were probably caused by variations in the AMOC[41] and its associated heat transport, and amplified by sea-ice feedbacks[42]. As a result, the largest temperature anomalies appeared in the North Atlantic realm[40,42]; nevertheless, millennial-scale glacial climate variability is well expressed in numerous palaeo-monsoon records from all over the globe[17,18,43] (Fig. 4).

The largest body of data exists for the last Heinrich stadial (HS1, about 18–15 kyr before present) when the AMOC was nearly shut off and surface temperatures in the North Atlantic realm were at a minimum[44]. A compilation of available palaeo-hydrological records for HS1 suggests a general pattern of a global-scale, southward ITCZ shift associated with changing interhemispheric thermal asymmetry (Fig. 5). Specifically, substantial drying in the North African and South Asian monsoon regions is found, whereas the Australian–Indonesian and South American monsoon systems become wetter. Speleothem isotope records from the East Asian monsoon system also indicate dry conditions during HS1, although model studies cast doubt on the local-rainfall interpretation of these records (see above). The pattern of HS1 precipitation response for the southern African monsoon region appears to be more complex. While the northern portion of the southern African monsoon region becomes drier, the southern portion witnesses anomalously wet conditions during HS1 (Fig. 5).

Owing to the global distribution of HS1 monsoon records, model–data comparison for this climate event offers a unique possibility for testing the reliability of climate model simulations with respect to AMOC slowdown. The TraCE-21k transient simulation of the last deglaciation supports the notion that AMOC intensity is a dominant control on tropical rainfall patterns on millennial timescales[45,46]. A comparison of the HS1 hydroclimatic records with the TraCE-21k-simulated HS1 precipitation response shows agreement in terms of the sign of the rainfall anomalies over most monsoon regions (Fig. 5). However, discrepancies between the model and the data stand out in southeastern Brazil, close to the South Atlantic convergence zone. Furthermore, reconstructed dry conditions in the South Asian monsoon region appear to be greatly underestimated by TraCE-21k. The reason for this weak rainfall response in the model is still uncertain, but we are beginning to understand the teleconnections between North Atlantic SST forcing and the South Asian summer monsoon. Several studies have examined possible teleconnections, and different mechanisms have been proposed, including a tropospheric temperature anomaly over Eurasia related to the North Atlantic Oscillation[47], a pathway over the Pacific Walker circulation[48], a southward shift of the subtropical westerly jet over Africa and Asia[49], and a wave-like atmospheric teleconnection between the northern North Atlantic and India[50].

As well as abrupt climate events during the last glacial period and deglaciation, several palaeo-monsoon records also witness centennial-to-millennial-scale climate variability during the Holocene associated with North Atlantic cold phases, such as the effect of the North Atlantic cold event that took place 8.2 kyr ago and is akin to the HS1 rainfall anomaly pattern[17,18,43]. Operating on a much shorter timescale, the Atlantic Multidecadal Oscillation (AMO; Box 1) is a mode of natural climate variability characterized by a coherent pattern of variability in basin-wide North Atlantic SST with a period of 60–80 years. Observational data suggest that North Atlantic SST associated with the AMO has an influence on multidecadal global monsoon variability[51], with the overall pattern of changes in global monsoon rainfall during the cold phase of the AMO resembling the HS1 anomaly pattern (Fig. 5). However, owing to the shortness of the instrumental record, the robustness of these links is difficult to assess. High-resolution proxy records enable us to extend the instrumental monsoon records to the past few thousand years[30,52–54].

In view of a potential slowdown of the AMOC in the coming decades[55], understanding the connection between oceanic heat transport and monsoon systems is of paramount importance for predicting the fate of the monsoons. Meanwhile, a growing body of palaeo-monsoon records allows us to paint a global picture of changes in monsoon rainfall in response to large-scale oceanic redistribution of heat.

CO_2 forcing

Models predict an increase in total monsoon rainfall during the twenty-first century in response to rising atmospheric greenhouse gas (GHG) forcing, increasing atmospheric moisture content, and an expansion of the area affected by monsoons[1]. Isolating the effects of atmospheric GHG forcing on monsoon dynamics from palaeoclimatic records is difficult because changes in GHG concentrations and other forcings usually occurred contemporaneously. Not only did GHG concentrations oscillate in concert with Quaternary glacial–interglacial cycles, but so did the size of ice sheets, the area of sea-ice, and the orbital forcing. Traditionally, dry conditions in North Africa during Quaternary glacial stages have been attributed to expansion of the boreal cryosphere and North Atlantic cooling[27]. However, recently published results from the TraCE-21k transient simulation of the last glacial termination suggest that the GHG forcing plays an important role in developing wet interglacial conditions in the African monsoon regions[46]. Conversely, the lack of glacial–interglacial variability in rainfall proxy records from deep tropical monsoon systems that reach beyond the last glacial termination indicates that GHG forcing plays a limited role and that the boreal cryosphere has a stronger influence[56].

The Pliocene warm period with a relatively high atmospheric CO_2 concentration is often considered as a potential analogue of future climate. Palaeoclimatic evidence suggests wet Pliocene conditions in the West African monsoon region, including the presence of Saharan palaeo-rivers, while forests, woodland and savannah extended further north compared to the Pleistocene[57]. For the East Asian monsoon region, proxy data and climate models suggest stronger-than-modern summer winds associated with wetter conditions during the mid-Pliocene warm period[58]. To what extent the wetter Pliocene conditions can be attributed to direct GHG forcing of the monsoons remains uncertain, because other potential forcing factors (for example, ice sheets, topography and global ocean circulation) were also different from today. Yet additional Pliocene records of rainfall from other monsoon regions will help identifying the sign of change in a warmer-than-today Earth. Isolating the effects of atmospheric GHG forcing on monsoon dynamics remains a critical task for palaeo-monsoon studies, to narrow down uncertainties in projections of future monsoon rainfall.

ENSO and PDO

Similarly to the AMO (see above), instrumental records suggest that SST anomalies in the tropical Pacific associated with the ENSO are a predominant forcing of monsoon variability in modern climate[3]. ENSO-related SST anomalies affect the global atmospheric circulation, particularly the Walker circulation (Box 1). Generally, the east–west displacement of the ascending and descending branches of the Walker circulation during El Niño years results in an increased descent over Australasia and reduced monsoon rainfall[59]. However, this relationship appears unstable in the instrumental records, partly as a result of the different types of the ENSO, which are characterized by spatially varying SST anomalies (between the central and eastern equatorial Pacific; Box 1) and teleconnections[60], and highlights the need for palaeoclimatic evidence beyond the instrumental records.

Proxy records of monsoon rainfall in North America support a leading role of the ENSO and the Pacific Decadal Oscillation (PDO; Box 1) after the Northern Hemisphere summer and autumn insolation declined about 4,000 years ago by changing the Pacific SST[61], the Pacific–Atlantic SST gradient[62], or the position of the ITCZ[63]. Whether the observed changes in monsoon precipitation are caused by a combination of forcings[30], the ENSO only[61,64], or solar forcing[65] remains controversial. This is in part due to the fact that different forcings give rise to similar responses within the same monsoon domain. For example, La Niña, positive AMO and negative PDO cause a wet Mesoamerica and dry southwest USA, whereas El Niño, negative AMO and positive PDO give rise to a dry Mesoamerica and wet southwest USA. More importantly, the suggested links to ENSO, PDO or AMO rely mainly on simple statistical analyses of the rainfall proxy data such as power spectra or correlation coefficients that are not sufficient to infer any causal mechanisms.

Palaeoclimate data from the Australasian monsoon regions imply that the ENSO has a heterogeneous spatiotemporal impact even within the same monsoon domain. A 50-year stalagmite record from northeast India suggests that El Niño and positive PDO have diminished monsoon precipitation in central India and shortened the moisture transport pathways to northeast India during the past decades[66]. Tree-ring data of the last millennium suggest that a simple canonical form of ENSO influence is insufficient to explain Asian monsoon variability, probably owing to the different pathways through which ENSO interacts with the different components of the monsoon[67]. Secular changes in ENSO teleconnections further complicate a general assessment of ENSO-related rainfall variability and make it somewhat regionally dependent[1]. Finally, the lack of indisputable and continuous benchmark records for the ENSO, PDO and AMO is another obstacle in untangling their relationship to monsoons. While many independent reconstructions of the AMOC, atmospheric CO_2 concentration and solar activity are available, data relating to the variability in the ENSO, PDO and AMO, in forcings and responses, and in lead and lag times on scales longer than a few decades do not exist. Therefore, reconstructing past changes in the monsoon–ENSO–PDO relationship remains one of the most critical contributions of palaeoclimate research to the climate change discussion.

Land cover

Land-cover changes alter surface roughness, albedo and water fluxes, thereby affecting the energy and moisture budgets of monsoon systems (Fig. 2). Over the Tibetan plateau, expansion of vegetation has been observed in response to recent warming, leading to enhanced evaporative cooling with potential effects on the South Asian monsoon[68]. On the other hand, deforestation in Mexico has been identified as a drought amplifier[69], and human-induced land-cover changes in China over the past 3,400 years have been suggested to weaken the East Asian summer monsoon[70]. Observational evidence from the period 1981–2003 suggests that the decrease in the South Asian monsoon rainfall may have been caused by agricultural intensification[71], and model simulations indicate that land-use changes and deforestation may cause a locally delayed[72] and reduced monsoon rainfall in the Northern Hemisphere by shifting the ITCZ southward[73].

Although anthropogenic land-cover changes may act as a forcing for shifts in monsoons, a dynamic vegetation cover may also act as a feedback to changes in monsoon rainfall, especially in North Africa. Pioneering work by Charney[74] has suggested a strong positive feedback between vegetation cover and monsoon rainfall in the Sahel region. On the basis of these ideas it has been proposed that the effect of expanded North African vegetation cover on surface albedo would have been crucial in amplifying the orbitally triggered, early-to-mid Holocene, West African monsoon rainfall anomaly—the so-called African humid period, during which the Sahara was much 'greener' than it is today[15]. Provided that the positive vegetation–rainfall feedback is strong enough to introduce nonlinear dynamics into the climate–vegetation system, two equilibria of the regional atmosphere–vegetation state may exist: a humid/green state and a dry/desert state. A transition from the humid state to the dry state by a catastrophic bifurcation was suggested to have abruptly terminated the African humid period around 5.5 kyr ago[16]. Other studies have questioned both the abruptness of the large-scale North African climate transition[75,76] and the existence of a strong local Charney feedback, which operates through changes in surface albedo[77]. Instead, a recent model study has suggested a positive vegetation–rainfall feedback during the Holocene that operated via anomalies in surface latent-heat flux caused by canopy evaporation and transpiration and their effect on the mid-tropospheric African easterly jet[78]. Another study highlighted the role of remote forcing from expanded forest cover in Eurasia in amplifying North African rainfall during the early-to-mid Holocene[79]. Both feedback mechanisms are specific to the North African monsoon and cannot be generalized to the other monsoon regions[35].

In summary, forcing and feedbacks associated with land-cover changes may have important effects on the different regional monsoon systems. Even though quantification of monsoon–vegetation feedbacks by means of proxy data alone will be difficult, reconstructions of past land and vegetation cover are indispensable to test model-derived hypotheses and may aid in the improvement of parameterizations in land surface models.

Solar and volcanic forcing

Solar and volcanic activities are considered major external forcings of climate variability for the last millennium and beyond[80,81]. Several studies suggest that short-term changes in solar activity, such as the 11-year sunspot cycle, may affect monsoon intensity. In some parts of the South Asian monsoon domain, the average precipitation anomalies in the five most-recent peaks in the sunspot cycle reached values as high as 20% above normal, and suggest that solar activity influences monsoon strength[82]. A response to the 11-year solar cycle was also found for the East Asian monsoon[83], with the band of heaviest rain penetrating further north when sunspot numbers were high. However, observations of sun–monsoon relationships are based on relatively short time series and, hence, are inherently uncertain. High-resolution speleothem records from Northern Hemisphere monsoon domains suggest a positive correlation between solar activity and Holocene monsoon rainfall on longer timescales[65,84,85]. Because changes in solar forcing are rather small, any noticeable effect on climate requires nonlinear responses and amplifying feedbacks[80]. 'Top-down' processes, based on solar heating of the stratosphere and changes in stratospheric ozone concentration via modification of photo-dissociation rates, are considered to be crucial to most climatic phenomena associated with solar forcing[80]. Yet 'bottom-up' processes, acting via solar-induced changes in SST, may also be important in the tropics, owing to positive feedbacks associated with surface evaporation, moisture fluxes and latent-heat release in monsoon systems[86,87].

Recent observations, palaeoclimate data and model studies show that volcanic forcing is probably more important than solar forcing on a hemispheric-to-global scale, and drove a large portion of the interannual-to-multidecadal monsoon variability during the late Holocene by affecting the SST, ENSO and AMO[81,88–90]. The primary effect of volcanic sulfate aerosols in the stratosphere is to cool the surface of Earth by reflecting incoming solar radiation. As post-eruption cooling is generally stronger over land than it is over the ocean, a weaker summer monsoon circulation should result from a reduced land–ocean thermal contrast (see Fig. 2). Model results suggest that, after large volcanic eruptions, cooling over east Asia is stronger than that over the tropical ocean, favouring weaker East Asian summer monsoon circulation[91]. However, tree-ring data of the past 750 years contradict model results regarding the sign of the monsoon response in the year of eruption, and suggest an anomalously wet southeast Asia and dry conditions over central Asia[92]. On a global scale, large, explosive volcanic eruptions may cause reorganizations of the Hadley cell and a shift of the ITCZ away from the hemisphere with the greater aerosol concentration[90].

The magnitudes of solar and volcanic forcing and their effects on the hydrologic cycle are sources of large uncertainty in most model simulations, owing to the common model deficiencies in capturing precipitation variability at decadal-to-multi-decadal timescales as well as chemical and physical processes related to aerosol forcing[89]; overcoming these deficiencies in the next generation of climate models is critical. A growing body of evidence from palaeoclimatic data underpins a strong influence of solar and volcanic forcing on monsoon variability, and may help to better identify these model deficiencies.

Outlook

Various forcings acting on different timescales affect the monsoon systems on a global scale (Figs 2, 4); regional monsoon responses differ from global responses in terms of sensitivity and timing, which can be attributed to different feedbacks and teleconnections. Palaeoclimatic records may help to elucidate the regional characteristics of the different monsoon subsystems and to better understand the internal feedback processes within the climate system; these feedback processes are suggested to influence the recent monsoon circulation more severely than the external forcing by increasing GHGs[3]. In addition, palaeoclimatic records provide valuable information that can be used to assess the ability of climate models to simulate monsoon changes for different climates, and are of utmost importance in testing model-derived hypotheses. For instance, a recent model study highlighted the role of differential warming between the Northern Hemisphere extratropics and tropics in determining the future development of the North African monsoon, where strong extratropical warming will induce a substantial increase in Sahel rainfall[93]. A large obliquity signature in the North African palaeo-monsoon records[27] strongly supports this model-derived finding, because obliquity forcing involves a substantial change in the meridional gradients of insolation and heating in the summer hemisphere[31] as well as amplification of extratropical temperature change via cryosphere expansion and retraction[27]. In a more general sense, it has been suggested that obliquity-induced changes have some qualitative similarities with global-warming-induced changes, with respect to the summer-hemisphere Hadley cell and ITCZ shifts related to mid-latitude eddy activity[31]. Therefore, a deeper understanding of obliquity-induced changes in tropical and extratropical circulation may help to better assess and predict future changes in monsoon rainfall.

Climate models predict that the ongoing interhemispheric thermal asymmetry will lead to a northward shift of the mean ITCZ position[4], but accurate projection of monsoon rainfall suffers from uncertainties in SST warming[13]. Because the location of the ITCZ is sensitive to changes in the meridional SST gradient[12], which can be constrained using palaeo-thermometric methods, palaeoclimate reconstructions that involve changes in (inter)hemispheric SST gradients provide unambiguous evidence for such ITCZ migrations and a blueprint of the associated changes in monsoon rainfall patterns.

Changes in monsoon rainfall can be thermodynamic or dynamic[24], and may be related to changes in the length of the rainy season, the rainfall intensity or the monsoon area. The various aspects of changes in monsoon rainfall require a deeper understanding of the mechanisms behind palaeo-monsoon variability, which may be achieved by means of palaeoclimatic monsoon reconstructions that use multiple proxy records, ideally from the same location[94]. Combining proxies for wind and precipitation changes may help to estimate the relative importance of the dynamic and thermodynamic aspects of changes in monsoon rainfall. A promising approach for distinguishing past changes in wet-season intensity from changes in wet-season length has been proposed, which involves combining leaf-wax δD with leaf-wax $\delta^{13}C$ analyses[95].

Palaeoclimatic data might contain further quantitative information on the magnitude of change that could help to better project future climate variations. Climate model experiments suggest that the observed decrease in South Asian monsoon rainfall over the last 70 years is mostly attributable to anthropogenic aerosol emissions[96]. Water-isotope-enabled climate models will be essential for the appropriate interpretation of water-isotope records and a quantitative reconstruction of past monsoon rainfall variability; however, reducing the uncertainty related to atmospheric aerosol loading and to the associated teleconnections, including the ENSO, PDO and AMO, is of equal importance for achieving more trustworthy climate projections. In particular, it has been shown that eastern and central Pacific ENSO events have different effects on the South Asian[59] and East Asian[97] monsoons. Indisputable and continuous records of the different states (El Niño and La Niña) and types (central and eastern Pacific) of the ENSO and of the PDO and AMO are critical to evaluate the stability of monsoon teleconnections. Finally, the middle Pliocene is probably the best available analogue for future warming and, thus, palaeoclimate records of the warm, high-CO_2 Earth of the Pliocene are urgently needed to narrow down uncertainties in future monsoon projections.

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