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Climate change and the South Asian summer monsoon

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The vagaries of South Asian summer monsoon rainfall on short and long timescales impact the lives of more than one billion people. Understanding how the monsoon will change in the face of global warming is a challenge for climate science, not least because our state-of-the-art general circulation models still have difficulty simulating the regional distribution of monsoon rainfall. However, we are beginning to understand more about processes driving the monsoon, its seasonal cycle and modes of variability. This gives us the hope that we can build better models and ultimately reduce the uncertainty in our projections of future monsoon rainfall.

The large populations across South Asia are dependent on monsoon rainfall for agriculture, hydroelectric generation and industrial development, as well as basic human needs, and require strategies to cope with variations in the timing, intensity and duration of the monsoon. The flooding in Pakistan in July to August 2010 (ref. 1) has brought the South Asian monsoon to the world's attention — with projected increases in population and pressure on food security, understanding how the monsoon will change in the future is a fundamental challenge for climate science.

The mean monsoon

At the most basic level, the seasonal cycle of solar heating through boreal spring warms the land regions surrounding South and Southeast Asia faster than the adjoining oceans, owing to differences in heat capacity, and develops a large-scale meridional surface temperature gradient[2]. This results in the formation of a surface heat low over northern India in late spring; the north–south pressure gradient then induces a cross-equatorial surface flow and return flow aloft. However, the dynamics and thermodynamics of the South Asian monsoon go beyond this simple land–sea breeze argument that originated as long ago as Halley in 1686. The Himalaya and Tibetan Plateau ensure that sensible heating during boreal spring occurs aloft, meaning that the large-scale meridional temperature gradient exists not just at the surface but over significant depth in the troposphere, anchoring the monsoon onset[2,3] and intensity[4]. The intense solar heating in late spring and summer gives thermodynamic conditions favouring the occurrence of convection poleward of the Equator, allowing the monsoon to be viewed as a seasonal migration of the Intertropical Convergence Zone[5]. The north–northwest migration of boreal winter convection from the equatorial region[6,7] (Fig. 1) and its interaction with circulation leads to a positive feedback and deeper monsoon trough, enhancing the cross-equatorial flow in the lower troposphere that feeds moisture to the monsoon[8], as well as the Tibetan anticyclone and easterly jet with a return cross-equatorial flow at upper levels. The north–south-oriented East African Highlands anchor the low-level cross-equatorial flow[9,10] and the Earth's rotation aids in the formation of the low-level westerly jet[11] as it approaches South Asia from across the Arabian Sea. The rapid intensification of rainfall and circulation during the onset can be attributed to wind–evaporation feedback[12] as well as feedbacks between extratropical eddies and the tropical circulation[13]. Yet, what processes set the poleward extent and east–west asymmetry in the seasonal mean monsoon precipitation seen in Fig. 1?

As the maximum in solar insolation and the positive net flux of energy into the atmospheric column[14] that is expected to lead to rising motion are strong well north of the precipitation extent shown in Fig. 1, why does the monsoon not extend farther north? Viewing the land–sea contrast in terms of moist static energy (MSE), ventilation mechanisms (large-scale dynamical processes) that import low-MSE air to continental regions act to impede convection farther north[14,15]. Alternatively, the northward extent of the poleward branch of the monsoon overturning circulation — and precipitation — has been linked theoretically to the maximum in subcloud MSE[5,13–15] (in the boundary layer beneath the cloud base), which is neatly shown as a reasonable limit for South Asian precipitation in Fig. 1. Finally, idealized studies[14] have shown that convection–Rossby-wave interactions[16] in conjunction with a warmer sea surface temperature (SST) over the Bay of Bengal[17] help to set up an east/west asymmetry of wet/dry precipitation in the South Asia monsoon region. Furthermore, the Himalaya act as a mechanical barrier in preventing the advection of dry air to South Asia[18], touching on theoretical ideas raised earlier[5]. Further local details of the precipitation distribution are fixed by the Western Ghats mountains on the west coast of India and the Arakan Range in Burma, whereas mesoscale convective systems embedded into the monsoon trough contribute a large proportion of rainfall over northeastern peninsular India[19]. The Indian Ocean also plays a regulatory role in the monsoon owing to the seasonality of meridional oceanic heat transports, themselves related to the seasonal monsoon winds[20]. We thus identify the South Asian monsoon as a fully coupled ocean–land–atmosphere system that is also influenced by fixed orography. However, many of the above mechanisms, including all the coupled feedbacks involved, are yet to be fully explored in comprehensive non-linear general circulation models (GCMs) or indeed in observations.

The familiar pattern of seasonally reversing winds (Fig. 1) transports moisture from over the warm Indian Ocean and ultimately contributes 80% of annual rainfall to South Asia between June and September. Once the monsoon is underway, its variations on timescales from intraseasonal to interannual provoke the most concern.

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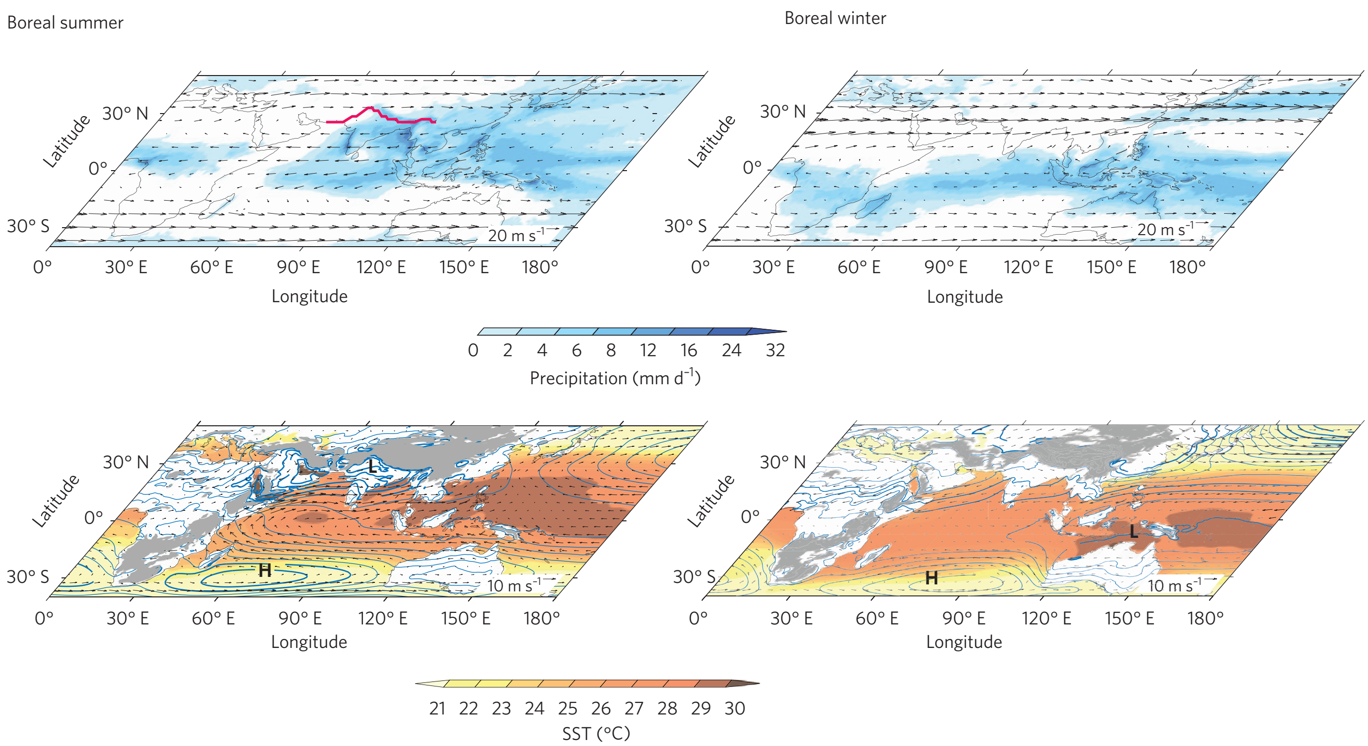

Figure 1 | Schematic of summer and winter climate in the South Asian monsoon region. Schematic of boreal summer (June–September) and winter (December–February) atmospheric conditions in the South Asian monsoon region. The summer and winter panels depict the Asian and Australian monsoons, respectively. In each case, the lower panels show: orography (>1,000 m, shaded grey); SSTs from the Hadley Centre Sea Ice and Sea Surface Temperature[91] data set for 1979–2010 (shaded yellow/orange); sea-level pressure for 1979–2010 (blue contours, interval 2 hPa) and lower tropospheric (850 hPa) winds from the European Centre for Medium Range Weather Forecasts Interim Reanalysis[92]. 'H' and 'L' refer to the monsoon highs and lows, respectively, in the both summer and winter. In summer, the high reaches around 1,024 hPa, whereas the low is approximately 1,000 hPa. The upper panels show upper tropospheric (200 hPa) wind vectors and Tropical Rainfall Measuring Mission 3B43 monthly rainfall[93] for 1998–2010 (shaded blue). The seasonal cycle of solar insolation leads to temperature gradients at the surface. In summer, this leads to a cross-equatorial pressure gradient from the Mascarene High in the southern Indian Ocean to the monsoon trough over northern India. Orography helps to both steer the cross-equatorial flow back towards India and isolate South Asia from dry air to the north: the summer diagram shows a line (in red) representing the location of maximum vertically integrated MSE, bounding the northward extent of the monsoon Hadley-type circulation. Over the ocean, rainfall locates over the warmest SST, whereas maxima over India occur near the Western Ghats and Himalaya, and near the Burmese mountains. During summer, the upper-level jet structure moves north, yielding the South Asia High over the Tibetan Plateau. This leads to upper-level easterly flow over South Asia, indeed the strength of the vertical shear at Indian latitudes has been shown to relate to the intensity of the Asian summer monsoon[94].

The monsoon undergoes seasonal changes in response to slow variations at the lower boundary of the atmosphere[21], including the El Niño/Southern Oscillation (ENSO) or snow cover. However, these interannual variations in rainfall are relatively low, the interannual standard deviation being around 10% of the summer rainfall total. It is the active or break events on short (intraseasonal) timescales of a few days to weeks that often have large impacts that particularly affect agriculture or water supply[6]. These include the famous break of July 2002, where less than 50% of the usual rainfall fell[22], contributing to substantially reduced agricultural output and growth of gross domestic product[23,24]. Understanding how variability in the South Asian monsoon on daily to interannual timescales will change against a background of anthropogenic warming is a demanding task.

Scope of the Review

In this Review we describe the observed changes to monsoon rainfall over the second half of the twentieth century — a period of unprecedented increase in greenhouse gas and aerosol concentration — and attempt to link these changes with modelled monsoon responses to anthropogenic warming at the end of the twenty-first century or in equilibrium experiments, which tend to suggest increases in monsoon rainfall. Despite this, model uncertainty for projections of monsoon rainfall is high[25] and so a weighty question for climate scientists is how can this uncertainty be reduced? Building on ideas that show variability on different temporal and spatial scales to be linked, one possible approach that we discuss is to choose models capable of simulating the present monsoon precipitation climate as well as its spectrum of variability. Furthermore, we highlight discrepancies in results obtained from various observations and stress the need for reprocessing the data for quality. Finally, we address evolving work in one further important uncertainty: the role aerosols may play in modulating any response to anthropogenic warming.

Trends in present-day mean monsoon rainfall

Under increasing greenhouse-gas forcing, we know that the land–sea temperature contrast, shown to relate to monsoon strength in simple models[4], will increase[26]. Also, the warm pool of the Indo-Pacific oceans has already warmed in the past 50 years[27], potentially allowing for an increased supply of moisture to the monsoon regions. In the face of these potential drivers of increased monsoon rainfall, the evidence for such trends in observations is unpersuasive.

To illustrate the complexity of monsoon rainfall variability over the recent observed record, Fig. 2 shows smoothed summer rainfall from the all-India rainfall (AIR) data[28] based on a weighted mean of 306 stations. Century-long trend identification is difficult owing to the presence of multidecadal variability, leading to epochs of

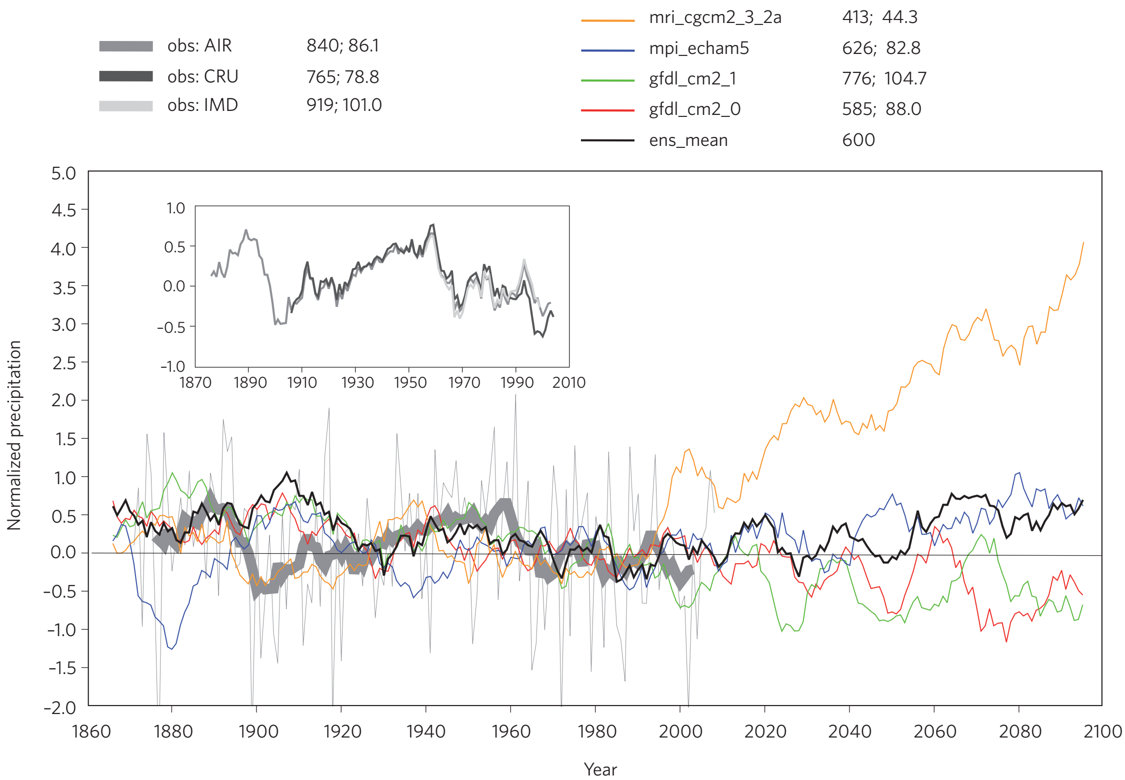

Figure 2 | Historical and SRES A1B projection of South Asian monsoon rainfall. Time series of mean summer (June–September) precipitation averaged over land points within 60–90° E, 7–27° N in the historical (20c3m; 1861–1999) and SRES A1B (2000–2100) future projection CMIP3 experiments. Only four models, shown[39] to have a reasonable simulation of the spatial pattern, seasonal cycle and interannual variability of monsoon rainfall, are depicted; the black curve shows their ensemble mean. Observations from the AIR index[28] based on gauge information are also shown for the 1871–2008 period as a proxy for South Asia rainfall. All curves are first normalized by their mean and standard deviation measured over 1961–1999 and are passed through an 11-year moving window. The faint black curve shows the observations without this smoothing. The inset compares the AIR with area-mean averages over the same domain as above from 1951–2004 IMD daily gridded data[31] and 1901–2009 monthly gridded CRU data[32]. The values listed in the legend are for June–September mean rainfall and interannual standard deviation, in mm. Obs, observations.

strong and weak monsoon rainfall[29]. The observed data suggest a negative trend since 1950, although the addition of more recent data to the AIR time series as in our analysis suggests a slightly weaker decline since 1950 than in an earlier study[30], where summer rainfall declined up to 2000. The inset panel in Fig. 2 shows AIR in comparison with the India Meteorological Department (IMD)[31] and Climatic Research Unit (CRU)[32] gauge-based data sets. Together these show robust weakening in monsoon rainfall since around 1950 as well as phase agreement on decadal timescales, although there are discrepancies between the CRU and the other data sets in more recent years. Data and modelling work have suggested that over the same period, rainfall has intensified over the western North Pacific, shifting the centre of action of the broader Asian monsoon eastwards (H. Annamalai, J. Hafner, K. P. Sooraj and P. Pillai, unpublished observation).

Despite agreement on a weakening trend when measured over a common period as in Fig. 2, when other data periods or different regions are considered, there is greater uncertainty. A study focused on central India[33] in the IMD 1° gridded data set[31] suggests little change to the June–September seasonal mean monsoon rainfall since the mid-twentieth century. However, within that region compensating trends of either sign are present. In AIR data the strongest trend up to 2000 was noted in July[30], the month that dominates seasonal rainfall. Looking at the trends in AIR data up to 2004 suggests that except for June, the other three months (July to September) all show declining trends[34]. Examined over 30 individual rainfall subdivisions, the reported decline is evident over only a handful[35] or over the larger northwest and central India homogenous rainfall regions[36]. A recent comparison[37] of four gridded rainfall data sets for South Asia from 1950 to 1999 shows area-mean reductions in all, but substantial spatial variations. Three of those data sets show common negative trends in central India — however, these are statistically significant over a large region in only the CRU data. There are also consistent negative trends over northwest India and coastal Burma with common positive trends over southeast India. The main region of disagreement is in far northeast India. Thus we suggest that there is uncertainty among observations, both spatially and owing to edge effects, requiring further analysis.

We next examine how coupled GCMs have been able to simulate monsoon rainfall and its variability over the past century or so. For clarity, in Fig. 2 we show only the smoothed summer monsoon rainfall of four Coupled Model Intercomparison Project phase 3 (CMIP3)[38] GCMs — judged to reasonably simulate[39] the seasonal cycle of monsoon rainfall and interannual variability — in 20c3m historical control simulations. The 20c3m experiments use the time-varying historical record or estimates of greenhouse gases, but are implemented in different ways by the modelling groups owing to the diversity in attempts to model additional factors such as volcanism or natural and anthropogenic aerosols. The first point to note is that even among the models that we judged 'reasonable', there are substantial discrepancies in the mean and standard deviation compared with AIR observations (which also differ from the other observational data shown), suggesting that model improvements and further understanding are necessary. Second, all the models exhibit substantial decadal variability. This variability shows no obvious phase relationships between different models or between models and observations, suggesting that

Box 1 | The role of aerosols.

Carbon dioxide and other greenhouse gases are not the only atmospheric constituents known to affect monsoon climate. South Asia's increasing industrialization in the second half of the twentieth century and the widespread biomass burning and use of cooking fires mean there are large and increasing local emissions of scattering and absorbing aerosols (predominantly sulphate and black carbon, respectively). Their trends may even explain the inconsistency noted earlier (Fig. 2) as to why seasonal mean rainfall over India has not shown increases in the recent observed record despite increasing carbon dioxide.

On the simplest level, the direct radiative effect limits the solar radiation reaching the Earth's surface, reducing the surface meridional thermal contrast and partially countering the impact of increasing carbon dioxide. Indeed, scattering and absorbing aerosols may have masked up to 50% of the potential surface warming owing to greenhouse gases[30]. Such a mechanism may also cool the northern Indian Ocean, reducing monsoon rainfall[30]. In future projections, the inclusion of sulphate aerosols in addition to increasing carbon dioxide leads to a more restrained increase in monsoon rainfall[55]. Recently, attempts have been made to attribute historical negative trends in regional rainfall over India to the increasing aerosol burden[37], yet one questions what may have caused apparent rising trends in monsoon rainfall in the first half of the twentieth century, as shown in Fig. 2. Furthermore, there is considerable work to be done to establish the species and effects involved and to carefully evaluate the impacts of non-standardized forcings used in different models. The suggestion at present is that the indirect effects on cloud lifetime or albedo could dominate[37]. The role of absorbing aerosols such as black carbon is more uncertain. Although it reduces insolation at the surface, the aerosol layer itself is warmed, heating the troposphere. This intensifies the thermally driven circulation and results in increased monsoon rainfall[96], contradicting other results[30]. The combination of locally emitted black carbon with local and remotely sourced mineral dust that accumulates during spring at the southern slopes of the Tibetan Plateau has led to the elevated heat pump hypothesis[97,98]. This involves dry convection heating the mid-troposphere and enhancing the large-scale meridional temperature gradient, upper-level anticyclone and monsoon rainfall during June and July. This is supported by other observations[34], but modelling results suggest a more complex picture once the monsoon begins. The raining-out of black carbon reduces the anomalous tropospheric heating, leaving behind a signature of surface cooling in the northern Indian Ocean that was formed as a result of reduced incident solar radiation before the monsoon onset, causing both monsoon circulation and rainfall to weaken slightly[99]. There is considerable ongoing debate over the ability of black carbon to enhance the monsoon[100,101].

A further consideration is the semidirect effect, whereby the presence of absorbing aerosol may lead to evaporation in cloud layers, burning off the cloud. Model results have suggested this possibility[102]; however, observations of cloud cover over the northern Indian Ocean actually show increases[103], suggesting that this process is not dominant.

With increasing industry and population in South Asia, concentrations of aerosol species and their vertical distribution will need to be carefully monitored and properly modelled to quantify their overall contribution to monsoon variability and change. Aerosols clearly represent a major uncertainty for our future climate projections.

it is internal to the coupled ocean–atmosphere system. We emphasize that we have shown only one realization of the 20c3m experiment for each model — others may match the phase changes in observations but we do not yet understand why.

The possible role of aerosols in monsoon rainfall trends and mitigating the effects of increased greenhouse gases on monsoon rainfall is discussed in Box 1, although discrepancies in the forcing terms used and aerosol physics accommodated by the different models is problematic. Furthermore, historic land-use change owing to irrigation practices may feed back on the monsoon system[40].

The future projections of monsoon rainfall shown in Fig. 2 are described later in the following section.

Projected mean changes

On the global scale, we have very high confidence that recent warming has anthropogenic causes[41]. Furthermore, we know that precipitable water and near-surface specific humidity over the oceans scale rapidly with Clausius–Clapeyron[42] at around 6.5% K^{-1}, whereas global mean precipitation is projected to increase more slowly according to energy-balance arguments[42,43], at a rate that turns out to be roughly 2% K^{-1} in models[43]. A consequence of this is that globally, as well as in the tropics, the mass flux from the boundary layer to the free troposphere involved in deep convection must decrease[43]. Therefore, as the climate warms and precipitation increases, the global-scale circulation weakens. This has been noted in the zonal overturning Walker circulations in the CMIP3 models[44,45]. But what happens on the relatively smaller scale of the South Asian monsoon, whereby increases in diabatic heating north of the Equator may be expected to lead to increased circulation from the west[46]?

Early coupled model studies have generally suggested increases in South Asian monsoon rainfall, with the suggestion in an equilibrium experiment that the Somali jet shifts northwards as it flows across the Arabian Sea[47] or that the convergence zone shifts northwards, attributed to increased land–sea temperature contrast, in a transient experiment[48]. The strengthened monsoon rainfall is generally attributed to increasing atmospheric moisture content over the warmer Indian Ocean[49], resulting in increased vertically integrated moisture fluxes towards India[50] — such thermodynamic forcing has been consistently shown to lead to precipitation increases for South Asia[51,52].

CMIP3 models are consistent with earlier results, both in transient and equilibrium experiments. A comparison of a subset of the CMIP3 models showed increases in South Asian monsoon rainfall, despite weakening of the monsoon circulation[53]. Although this has been termed a paradox[51,53,54] and attributed to an increase in tropospheric heating over the Equator[53], it may simply form part of the larger global spinning-down of the circulation with warming[43].

The model twentieth-century precipitation time series shown in Fig. 2 are continued with the Intergovernmental Panel on Climate Change *Special Report on Emissions Scenarios* A1B (SRES A1B) future scenario. The four models suggest a range of trends in monsoon rainfall to 2100, on a background of often strong continuing decadal variability. We also note considerable uncertainty between the models, particularly in whether they exhibit strong upward trends (for example, mri_cgcm2_3_2a) or are roughly flat (as in gfdl_cm2_0 and gfdl_cm2_1). When measured over this small domain, the decadal variability seems particularly large in these two latter models. To examine the spatial pattern of the monsoon rainfall response to anthropogenic warming, Fig. 3 illustrates the time-mean equilibrium response to increasing greenhouse-gas concentrations in only the 1pctto2x experiment for 20 CMIP3 models. The multimodel mean suggests enhanced rainfall over parts of South Asia,

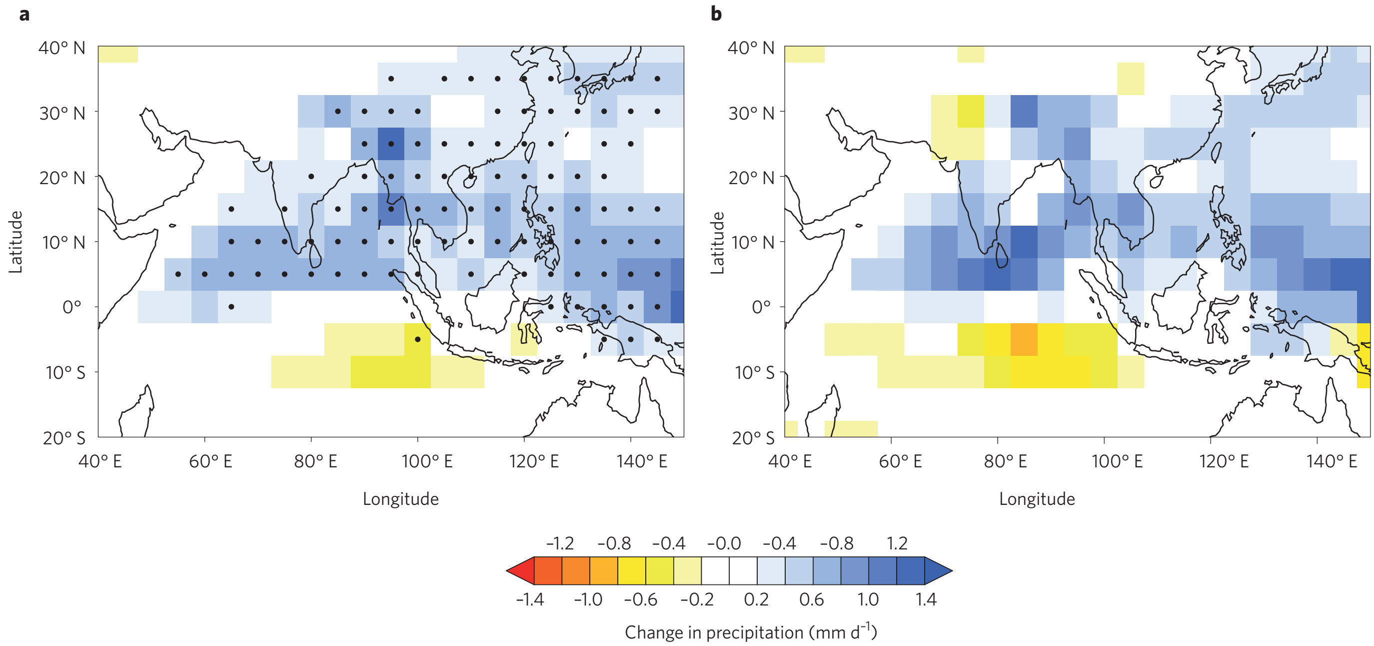

Figure 3 | Precipitation response to doubling of carbon dioxide concentrations. Mean summer (June–September) precipitation projections in the 1% per year increasing carbon dioxide experiment (1pctto2x) of the CMIP3 multimodel database after doubling of carbon dioxide concentrations relative to control conditions. **a**, Mean across 20 models. **b**, A subset of four of these models judged[39] to reasonably simulate the monsoon seasonal cycle, interannual variability and the teleconnection between monsoon rainfall and ENSO. Models were first bilinearly interpolated onto a common 5° grid to compute ensemble means. Stippling in **a** indicates where more than two-thirds of the models agree on the sign of change.

particularly towards the Equator: over south India, Sri Lanka and the Maldives; and over the Himalaya, Bangladesh, the Bay of Bengal and in Burma (Fig. 3a). The same mean change computed for the four 'reasonable' models shows a similar result, providing more confidence in such a projection (Fig. 3b). However, examined individually there is considerable uncertainty in CMIP3 projections for the South Asian monsoon[55] (see also Fig. 2) with a large range and spatial diversity[25]. The SST response of a given model to anthropogenic forcing will affect the available moisture, undoubtedly contributing to the diversity in model responses; however, coupled ocean–atmosphere feedbacks complicate this matter. Furthermore, the projected change in mean state farther afield may affect the monsoon: weakening of the mean zonal temperature gradient in equatorial Pacific SST in a given model may lead to less notable increases in monsoon rainfall in response to warming[56,57]. The 'reasonable' model with the strongest land–sea thermal contrast also suggests an earlier monsoon onset[39], although note that we have not sought to account for changes in the length of the rainy season in our projections of total monsoon precipitation here.

CMIP3 models that show generally drier conditions over South Asia in the future are rare. A nested regional model has suggested declining rainfall in response to a weaker dynamical monsoon and a reduction in the contribution from active phases of intraseasonal variability[58], although results from a different regional model study[59] are consistent with projections by CMIP3 models. However, the ability of regional models to properly assess such variations must be questioned, given the likelihood of coupled interactions in the region. Emerging evidence also suggests that we must pay more attention to dynamical interactions within the broader Asian monsoon domain, rather than only the thermodynamic arguments outlined earlier. In Fig. 1, we can see many sources of diabatic heating (rainfall) over the Western Ghats/Bay of Bengal, equatorial Indian Ocean and South China Sea/Philippine Sea region. Can changes in these regions feed back on each other? Could a negative rainfall tendency around the Equator (Fig. 3) weaken the cross-equatorial flow[59]? If rainfall increases over the western North Pacific continue to outpace those over South Asia, could Rossby-forced advection of low-MSE air over South Asia act to further inhibit the monsoon rainfall there (H. Annamalai, J. Hafner, K. P. Sooraj and P. Pillai, unpublished observation ? This possibility that South Asia may face a double whammy owing to aerosols (Box 1) or other anthropogenic factors and dynamical feedbacks from elsewhere in the Asian monsoon domain needs to be further investigated.

Subseasonal to interannual variability

Rainfall during the summer monsoon is not steady but consists of sequences of active and break periods as well as synoptic-scale variability. Society can plan and adapt to changes in time-mean rainfall but may face dire consequences, for example in agriculture, if subseasonal characteristics change. Both observations and model simulations suggest that many monsoon drought and flood years are associated with ENSO. However, in a given year the seasonal mean rainfall is also related to the total number of active or break days and these subseasonal variations are largely determined by internal dynamics[6]. Promisingly enough, slowly varying boundary conditions such as ENSO can lead to a large-scale predictable component[60,61] as well as partially predisposing the total number of active and break days in a year[62]. The monsoon onset and active–break periods are also related to the phase and frequency of the Madden–Julian Oscillation[63]. The July 2002 monsoon break is particularly interesting as it relates to the rapid growth of El Niño warming in the central Pacific, itself following sustained Madden–Julian Oscillation activity[64]. This intimate connection between temporal and spatial scales suggests that accurate projections of future monsoon variability require the simulation of both the ENSO–monsoon association[40] and the complex space–time evolution of intraseasonal variations[65].

Synoptic-scale activity. Most monsoon depressions, which represent almost all extreme events (rainfall >100 mm d^{-1}) over central India[66], form over the warm waters of the northern Bay

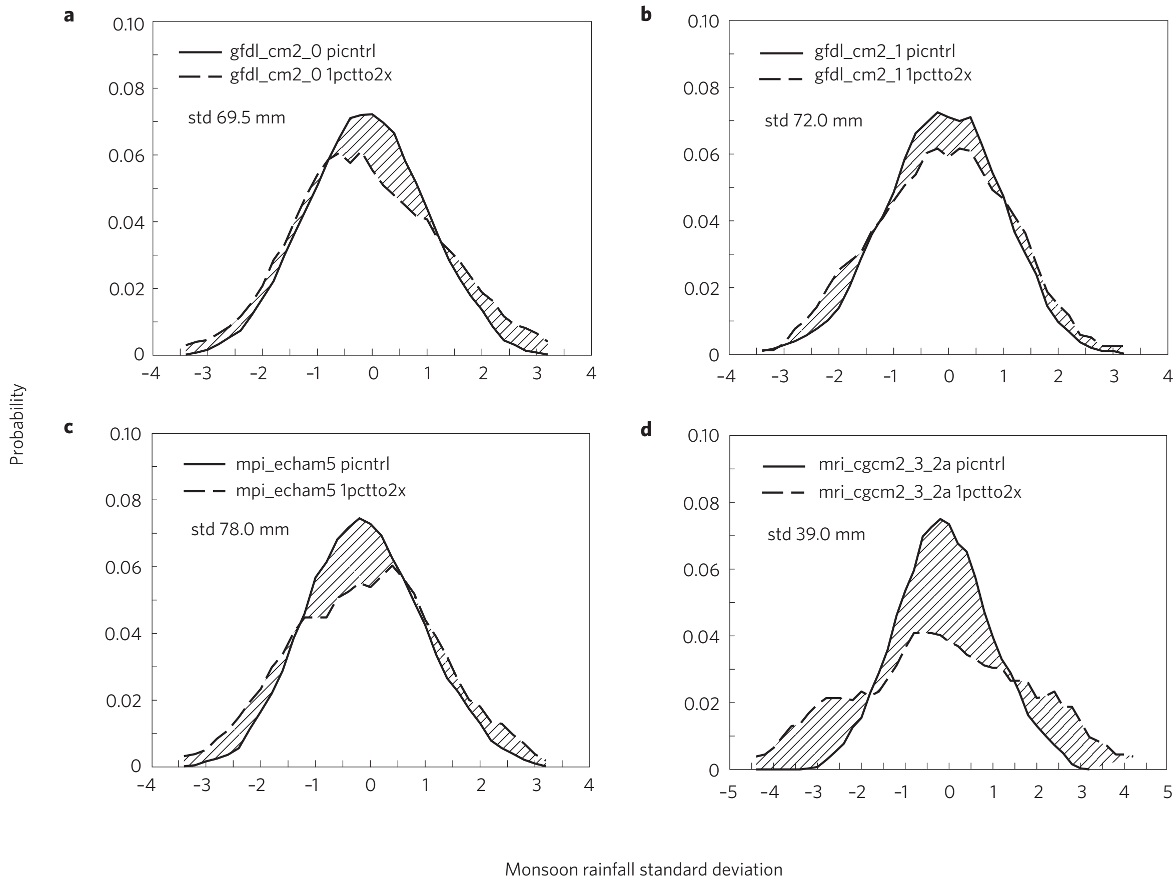

Figure 4 | Probability density functions of interannual variability in monsoon rainfall in control and future climate scenarios. Normalized probability of occurrences (number of occurrences divided by the total number of years) of interannual variability of South Asian monsoon rainfall from four CMIP3 models that depict realistic mean monsoon precipitation and ENSO–monsoon association[39]. **a**, gfdl_cm2_0. **b**, gfdl_cm2_1. **c**, mpi_echam5. **d**, mri_cgcm2_3_2a. Region of averaging is as in Fig. 2. Pre-industrial control probability density function (PDF; solid line) and future climate (1% per year increase in carbon dioxide experiments, 1pctto2x) PDF (dashed line) are shown. The future variations are scaled by the pre-industrial control interannual standard deviations (std) whose values (in mm) are also shown. The differences in the shape of the PDFs have been tested for significance based on a Kolmogorov–Smirnov test[95]. Although all models suggest a reduction in the occurrence of normal monsoon years (± one standard deviation in monsoon rainfall) the changes in the tails of the distribution are significant in only one model, mri_cgcm2_3_21 (**d**). The caveat is that this particular model has the least agreement in terms of mean and interannual standard deviation with observed rainfall (see legend in Fig. 2 as well as in Fig. 4). In the model that has the best agreement with observations, gfdl_cm2_1 (**b**), changes in the tails are not significant.

of Bengal and move west–northwest along the monsoon trough. Trend analysis of observed sea-level pressure suggests that monsoon depressions, the main rain-bearing synoptic systems, have decreased[67,68], whereas the number of weak low-pressure systems has increased[36,67]. However, analysing daily gridded rainfall observations[31] reveals a decrease in moderate rainfall events (of 5–100 mm d^{-1}), but an increase in extreme events over central India[34] since the 1950s. Moisture availability increases in a warmer world, leading to stronger extreme events, yet mean precipitation increases more slowly owing to energy constraints. Thus the frequency of convection must decrease, or the strength of more moderate rainfall events must decline[69,70]. Consistent with this picture, model projections suggest increased intensity of South Asian monsoon rainfall (total precipitation summed over the number of wet days)[71–73] as the number of wet days decreases. The caveat, however, is that smearing of convection over the coarse grid scale of GCMs biases the intensity of rainfall downwards and increases its frequency[74]. Furthermore, projections of the heaviest monsoon rainfall suggest generally large positive increases potentially beyond those predicted by thermodynamic arguments alone[25,72]. However, it is unknown whether the extreme rainfall events in GCMs are caused by monsoon depressions, because even in the 'reasonable' models these depressions do not penetrate far enough inland from their genesis over the Bay of Bengal[59]. Owing to the relatively coarse resolutions employed in global models (typically 100 km; larger than the scales involved in genesis), a clear change in depression characteristics is not yet detectable.

Intraseasonal variability. On intraseasonal timescales (typically defined as 30–60-day timescales), even less is known. In the observed record, there is some suggestion of a declining or increasing number of days defined, respectively, as an active or break monsoon[75], as well as a significant increase in the number of short rains and dry spells, whereas periods of long-duration rain have declined[76]. But in other studies no significant trends are detected[31]. Such a discrepancy may relate to different definitions of these events. Some coupled modelling studies suggest that in future, both active and break events will become wetter and drier respectively relative to the seasonal cycle[72], yet others have shown inconsistencies even between different scenarios for a given model[31]. This suggests that attention must be paid to the level of skill at which a model can simulate monsoon intraseasonal variability. Examination of the CMIP3 models[65] shows that whereas all the models simulate the eastward-propagating equatorial component of convection represented by outgoing longwave radiation (with various levels of skill), difficulty remains in simulating poleward migration at Indian longitudes. An alternative study[77] showed that northward propagation was better simulated, but the much shorter range of years used may have introduced sampling problems.

Interannual variability. On interannual timescales, SST anomalies related to ENSO are the dominant forcing of monsoon variability and, despite recent uncertainty over the stability of the monsoon–ENSO teleconnection[78,79], one emerging result from modelling studies is that this association remains intact in a warmer world[39,80]. An understanding of what will happen to ENSO in the future may help predict how monsoon interannual variability, particularly severe weak and strong monsoons, will change. Previous studies have suggested increased interannual variability in the future[54] owing to increased ENSO amplitude[48,80], although there is also a suggestion that amplitude could decline[81]. However, even in forced future climate simulations where ENSO variability remains fixed[82], enhanced evaporation variability resulting from the warmer mean state could enhance monsoon interannual variability. To have confidence in their future projections, models must be able to realistically simulate the mean state of the tropical Pacific and the monsoon–ENSO teleconnection[39,83]. The CMIP3 models have a large diversity in the amplitude of simulated ENSO[84,85], perhaps related to the representation of competing atmospheric feedbacks[86], and in future climate projections, changes to the tropical Pacific mean state and ENSO amplitude and frequency are highly uncertain[87]. Figure 4 shows the probability distribution of drought and flood years in present and future climates as simulated by a suite of models that display robust ENSO–monsoon relationships. In all models, although there is a suggestion that normal monsoon years will become less frequent in a warmer planet, changes to the occurrence of severe weak and strong monsoons (the tails of the distribution) are significant in only one of the four 'reasonable' models that has the lowest interannual monsoon variability under control conditions (Fig. 4.). Furthermore, there is clear intermodel disagreement or uncertainty regarding changes in the tails.

Scale interactions. Observational, theoretical and modelling studies confirm that the mean monsoon precipitation and circulation influence monsoon variability on all timescales[39,83,88] and specifically that such variability cannot be correctly simulated without accurate representation of the mean state[39,83]. As extended breaks such as July 2002 occur as a superposition of intraseasonal variability and boundary forcing such as ENSO[64,89], any projected change to the low-frequency forcing may also affect future projections of extended breaks. Moreover, evidence suggests that the phase of intraseasonal variability may modulate the frequency and tracking of monsoon depressions[90]: active monsoon conditions aid the formation of synoptic systems[19] that, in turn, can influence the incidence of heavy rainfall events. Although large-scale teleconnections are reasonably represented in only a few CMIP3 models[39], simulation of subseasonal variability[65] and our understanding of its connections with other modes of variability are in their infancy. This represents a major opportunity for more detailed research.

Outlook and key issues

As we have described in this Review, even among the best models there is still considerable difficulty in simulating the South Asian monsoon and its variability on a range of timescales.

Projections of future monsoon rainfall for South Asia are generally positive resulting from thermodynamic forcing. But we must pay attention to emerging ideas about complex dynamical feedbacks from within the tropical Indo-Pacific region to be sure that the South Asian monsoon will remain stable in the future.

Model systematic biases in monsoon simulation still cause great concern for climate modellers, but we recognize that climate projections are inherently uncertain because a model can never fully describe the system that it attempts to specify. As we argue, because the mean state, intraseasonal and interannual variability are linked, one must be able to model all of these aspects to make reliable projections of monsoon variability for the future.

When we begin to select models in this way, the mean future projections remain generally positive in agreement with our present physical understanding. On interannual timescales, future changes are measured by changes in the probability distribution and we have suggested that interannual variability will increase even though the future of drivers such as ENSO is uncertain. However, the significance of such signals, that is, changes to severe weak and strong monsoons, is low. Fortunately the suggestion is that teleconnections that lend predictability to seasonal mean monsoon rainfall will still function in the same way, implying that severe monsoons remain predictable.

On intraseasonal timescales, however, we still don't understand enough about the physical mechanisms involved or the relationship with longer timescale variability. This makes the impact of intraseasonal variability, particularly of prolonged breaks and extreme rainfall events, hugely uncertain in the future. At present, the ability of even state-of-the-art coupled GCMs to simulate the intricate distribution of heating and northward and eastward propagation associated with boreal summer intraseasonal variability is questionable[65].

To assess any future changes in the expected number of flood days, climate models must be able to capture the genesis and intensification of depressions and their track[59]. Our confidence in future projections of heavy rainfall events is likely to remain low until resolution is improved. This makes further study of the impact of anthropogenic warming on monsoon intraseasonal variability and synoptic systems difficult.

It remains to be seen what robust results can be accomplished from the new multimodel data in the CMIP5 database, but ultimately the development of better models will improve our confidence in future projections. One way to achieve this will be to evaluate key monsoon processes such as those outlined in our introduction — often established theoretically or in idealized models — in state-of-the-art GCMs.

Observational constraints also present an obstacle. We have shown large decadal variability in observations and model simulations, but really need to better quantify the effect of decadal variability in the past to find its causes, ultimately helping us to determine how it will act in consort with anthropogenic factors in the future. Such efforts are hampered by the apparent discrepancies between land-rainfall data sets (at least spatially), which warrant careful techniques to identify and remove observed uncertainties and reprocess the data for consistency, using improved interpolation methods and employing independent verifications such as agricultural yields.

As we have suggested, the large increasing trend of aerosol concentrations over South Asia may be part of the reason that we have not yet seen the emergence of increasing seasonal monsoon rainfall. However, there is considerable uncertainty over the level of aerosols and the ability to model their impact on the monsoon, making much further work necessary. The inconsistencies between the forcing data sets used for detection and attribution studies in different models are also problematic. Establishing the point at which greenhouse-gas forcing of the monsoon takes over from the inhibiting effects of aerosols, if any, will be a step forward in our understanding. Furthermore, one of the main untapped resources in narrowing uncertainty may lie in better understanding the impact of the land surface, as evidence suggests that land-cover change may have already played a role in a complex pattern of precipitation changes over South Asia[40].

As heard at the recent World Climate Research Programme Open Science Conference (Denver, USA, October 2011), there is an established need for actionable science from which decision formers and policymakers can make the right choices for the future. For South Asia, which is undergoing rapid economic development as well as supporting vast subsistence agriculture, this need is even more important. But we must be careful to ensure that the uncertainties outlined here surrounding future projections of the South Asian monsoon can be properly addressed through understanding the physics involved; these uncertainties must then be better communicated to those who need to use the information.

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Additional information
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