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The vagaries of South Asian summer monsoon rainfall on short and long timescales impact the lives of more than a 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 future monsoon rainfall projections.

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-August 2010[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 South Asian 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 give thermodynamic conditions favouring the occurrence of convection poleward of the equator, allowing the monsoon to be viewed as a seasonal migration of the ITCZ[5]. The north-northwest migration of boreal winter convection from the equatorial region[6,7] (see Figure 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 Figure 1?

Since 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 Figure 1, why does the monsoon not extend further 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 further north[14,15]. Alternatively, the northward extent of the poleward branch of the monsoon overturning circulation – and precipitation – has been linked theoretically with the maximum in sub-cloud MSE[5,13-15] (in the boundary layer beneath cloud base), which is neatly shown as a reasonable limit for South Asian precipitation in Figure 1. Finally, idealised studies[14] have shown that convection-Rossby wave interactions[16] in conjunction with warmer SST over the Bay of Bengal[17] help set up an east/west asymmetry of wet/dry precipitation in the South Asia monsoon region. Additionally, 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, while mesoscale convective systems embedded into the monsoon trough contribute a large proportion of rainfall over north-eastern 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 explored fully in comprehensive non-linear general circulation models (GCMs) or indeed in observations.

The familiar pattern of seasonally-reversing winds (Figure 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. 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 particularly affecting 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 observed changes to monsoon rainfall over the second half of the 20th century, a period of unprecedented increase in greenhouse gas (GHG) and aerosol concentration, and attempt to marry these changes with modelled monsoon responses to anthropogenic warming at the end of the 21st 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 current monsoon precipitation climate as well as its spectrum of variability. Additionally, we highlight discrepancies in results obtained from various observations and stress the need for re-processing the data for quality. Finally, we address evolving work in one further major 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 last fifty 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, Figure 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 multi-decadal variability, leading to epochs of 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 timeseries 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 Figure 2 shows AIR in comparison with India Meteorological Department (IMD)[31] and Climatic Research Unit (CRU)[32] gauge-based datasets when measured over a common period. Together these show robust weakening in monsoon rainfall since around 1950 in addition to phase agreement on decadal timescales, although there are discrepancies between CRU and the other datasets in more recent years. Data and modelling work has suggested that over the same period, rainfall has intensified over the Western North Pacific, shifting eastward the centre of action of the broader Asian monsoon[33].

Despite agreement on a weakening trend when measured over a common period as in Figure 2, when other data periods or different regions are considered, there is greater uncertainty. A study focused on central India[34] in the IMD 1-degree gridded dataset[31] suggests little change to the JJAS 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[35]. Examined over 30 individual rainfall subdivisions, the reported decline is evident over only a handful[36] or over the larger northwest and central India homogenous rainfall regions[37]. A recent comparison[38] of four gridded rainfall datasets for South Asia over 1950-1999 shows area-mean reductions in all, but substantial spatial variations. Three of those datasets show common negative trends in central India – statistically significant over a large region in only the CRU data however. There are also consistent negative trends over northwest India and coastal Myanmar with common positive trends over southeast India. The main region of disagreement is in far northeast India. Thus we suggest there is uncertainty among observations, both spatially and due to edge effects, requiring further analysis.

We next examine how coupled GCMs have been able to simulate monsoon rainfall and its variability over the last century or so. For clarity, in Figure 2 we show only the smoothed summer monsoon rainfall of four CMIP3[39] coupled GCMs – judged to reasonably simulate[40] 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 aerosol. The first point to note is that even among the models we judged “reasonable”, there are substantial discrepancies in mean and standard deviation compared to AIR observations (which itself differs from the other observational data shown), suggesting that model improvements and further understanding are necessary. Secondly, all the models exhibit substantial decadal variability. This variability shows no obvious phase relationships between different models or between models and observations, suggesting that 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 aerosol 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. In addition, historic land-use change due to irrigation practices may feed back on the monsoon system[41].

The future projections of monsoon rainfall shown in Figure 2 will be described later in the following section.

Projected mean changes

At the global scale, we have very high confidence that recent warming has anthropogenic causes[42]. In addition, we know that precipitable water and near surface specific humidity over the oceans scale rapidly with Clausius-Clapeyron[43] at around 6.5% K^{-1}, while global mean precipitation is projected to increase more slowly according to energy balance arguments[43,44], at a rate which turns out to be roughly 2% K^{-1} in models[44]. 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[44]. Thus 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[45,46]. But what happens at 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[47]?

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[48] or that the convergence zone shifts northwards, attributed to increased land-sea temperature contrast, in a transient experiment[49]. The strengthened monsoon rainfall is generally attributed to increasing atmospheric moisture content over the warmer Indian Ocean[50], resulting in increased vertically integrated moisture fluxes towards India[51] – such thermodynamic forcing has been consistently shown to lead to precipitation increases for South Asia[52,53].

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[54]. Although this has been termed a paradox[52,54,55] and attributed to an increase in tropospheric heating over the equator[54], it may simply form part of the larger global spinning-down of the circulation with warming[44].

The model 20th century precipitation timeseries shown earlier in Figure 2 are continued with the SRES-A1B future scenario. The four models suggest a range of trends in monsoon rainfall out to 2100, on a background of often strong continuing decadal variability. We also note considerable uncertainty between the models, particularly whether they exhibit strong upward trends (e.g., 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, Figure 3 illustrates the time-mean equilibrium response to increasing GHG concentrations only in the 1pctto2x experiment for twenty CMIP3 models. The multi-model mean suggests enhanced rainfall over parts of South Asia, particularly towards the equator: over south India, Sri Lanka and the Maldives; and over the Himalaya, Bangladesh, the Bay of Bengal and in Burma (Figure 3a). The same mean change computed for the four "reasonable" models shows a similar result, providing more confidence in such a projection (Figure 3b). However, examined individually there is considerable uncertainty in CMIP3 projections for the South Asian monsoon[56] (see also Figure 2) with a large range and spatial diversity[25]. The SST response of a given model to anthropogenic forcing will affect available moisture, undoubtedly contributing to the diversity in model responses; however coupled ocean-atmosphere feedbacks complicate this matter somewhat. In addition the projected mean state change further 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[57,58]. The "reasonable" model with the strongest land-sea thermal contrast also suggests a somewhat earlier monsoon onset[40], although note that we have not sought to account for changes in the length of the rainy season in our total monsoon precipitation projections 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[59], although results from a different regional model study[60] 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 Figure 1, we can see multiple 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[60]? 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[33]? This possibility that South Asia may face a double-whammy due to aerosol (see 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[61,62] as well as partially predisposing the total number of active and break days in a year[63]. The monsoon onset and active-break periods are also related to the phase and frequency of the Madden-Julian Oscillation (MJO)[64]. The July 2002 monsoon break is particularly interesting since it relates to the rapid growth of El Niño warming in the central Pacific, itself following sustained MJO activity[65]. This intimate connection between temporal and spatial scales suggests that accurate projections of future monsoon variability requires the simulation of both the ENSO-monsoon association[40] and the complex space-time evolution of intraseasonal variations[66].

Synoptic scale activity

The majority of monsoon depressions, which represent almost all extreme events (rainfall > 100mm/day) over central India[67], form over the warm waters of the northern Bay of Bengal and move west-northwest along the monsoon trough. Trend analysis of observed SLP suggests that monsoon depressions, the main rain-bearing synoptic systems, have decreased[68,69] while the number of weak low-pressure systems has increased[37,68]. On the other hand, analysing daily gridded rainfall observations[31], reveals a decrease in moderate rainfall events (of between 5 and 100mm/day) but an increase in extreme events over central India[34] since the 1950s. In a warmer world, moisture availability increases, leading to stronger extreme events, yet mean precipitation increases more slowly due to energy constraints. Thus the frequency of convection must decrease, or the strength of more moderate rainfall events must decline[70,71]. Consistent with this picture, model projections suggest increased intensity of South Asian monsoon rainfall (total precipitation summed over the number of wet days)[72-74] 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[75]. Furthermore, projections of the heaviest monsoon rainfall suggest generally large positive increases potentially beyond those predicted by thermodynamic arguments alone[25,73]. However it is unknown whether the extreme rainfall events in GCMs are due to monsoon depressions since even in the "reasonable" models monsoon depressions do not penetrate far enough inland from their genesis over the Bay of Bengal[60]. Due to the relatively coarse resolutions employed in global models (typically 100km; larger than the scales involved in genesis), a clear change in depression characteristics is not yet detectable.

Intraseasonal variability

At intraseasonal timescales (typically defined as on 30-60 day timescales), even less is known. In the observed record, there is some suggestion of a declining (increasing) number of days defined as an active (break) monsoon[76] as well as a significant increase in the number of short rains and dry spells, while periods of long duration rain have declined[77]. 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[73], however 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[66] shows that while all the models simulate the eastward propagating equatorial component of convection represented by OLR (with various levels of skill), difficulty remains in simulating poleward migration at Indian longitudes. An alternative study[78] showed that northward propagation was better simulated, however the much shorter range of years used may have introduced sampling problems.

Interannual variability

At 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[79,80] one emerging result from modelling studies is that the ENSO-monsoon association remains intact in a warmer world[40,81]. 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[55] due to increased ENSO amplitude[49,81], although there is also a suggestion that ENSO amplitude could decline[82]. However even in forced future climate simulations where ENSO variability remains fixed[83], 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[40,84]. The CMIP3 models have a large diversity in the amplitude of simulated ENSO[85,86], perhaps related to the representation of competing atmospheric feedbacks[87], and in future climate projections, changes to the tropical Pacific mean state and ENSO amplitude and frequency are highly uncertain[88]. Figure 4 shows the probability distribution of drought and flood years in current and future climates as simulated by a suite of models that display robust

ENSO-monsoon relationships. In all models, while 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 only in one of the four "reasonable" models that has the lowest interannual monsoon variability under control conditions (Fig 4.) Further, there is clear inter-model disagreement or uncertainty regarding changes in the tails.

Scale interactions

Observational, theoretical and modelling studies confirm that the mean monsoon precipitation and circulation exert influence on monsoon variability at all timescales[40,84,89] and specifically that monsoon variability cannot be correctly simulated without accurate representation of the mean state[40,84]. Since extended breaks such as July 2002 occur as a superposition of intraseasonal variability and boundary forcing such as ENSO[65,90], any projected change to the low-frequency forcing may also affect future projections of extended breaks. Further, evidence suggests the phase of intraseasonal variability may modulate the frequency and tracking of monsoon depressions[91]: active monsoon conditions aid the formation of synoptic systems[19] that in turn can influence the incidence of heavy rainfall events. While large-scale teleconnections are reasonably represented in only a few CMIP3 models[40], simulation of subseasonal variability[66] 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, since the mean state, intraseasonal and interannual variability are linked one must be able to model all of these aspects in order 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 current physical understanding. At 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, i.e., 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 severe monsoons remain somewhat predictable.

At 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[66].

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[60]. Our confidence in future projections of heavy rainfall events will likely 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 multi-model 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 datasets (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 aerosol and the ability to model their impact on the monsoon, making much further work necessary. The inconsistencies between the forcing datasets 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 aerosol, if any, will be a step forward in understanding. Further, one of the major untapped resources in narrowing uncertainty may lie in better understanding the role of the land surface, since evidence suggests that land cover change may have already played a role in a complex pattern of precipitation changes over South Asia[41].

As heard at the recent WCRP Open Science Conference (Denver, USA, October 2011), there is an established need for actionable science from which decision formers and policy makers 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 surrounding future projections of the South Asian monsoon outlined here can be properly addressed through understanding the physics involved; these uncertainties must then be better communicated to those who need to use the information.

References

1 Lau, K. M. & Kim, K.-M. The 2010 Pakistan flood and Russian heatwave: Teleconnection of Hydrometeorologic Extremes. *Journal of Hydrometeorology* **in press**, doi:10.1175/JHM-D-11-016.1 (2011).

2 Li, C. F. & Yanai, M. The onset and interannual variability of the Asian summer monsoon in relation to land sea thermal contrast. *Journal of Climate* **9**, 358-375 (1996). Useful discussions on the reversal of the meridional temperature gradient essential for monsoon onset and the contribution of sensible and latent heating to warming over the Tibetan plateau and Indian Ocean respectively.

3 Fasullo, J. & Webster, P. J. A hydrological definition of Indian monsoon onset and withdrawal. *Journal of Climate* **16**, 3200-3211, doi:10.1175/1520-0442(2003)016<3200a:AHDOIM>2.0.CO;2 (2003).

4 Chou, C. Land-sea heating contrast in an idealized Asian summer monsoon. *Climate Dynamics* **21**, 11-25, doi:10.1007/s00382-003-0315-7 (2003).

5 Prive, N. C. & Plumb, R. A. Monsoon dynamics with interactive forcing. Part I: Axisymmetric studies. *Journal of the Atmospheric Sciences* **64**, 1417-1430, doi:10.1175/jas3916.1 (2007).

6 Webster, P. J. *et al.* Monsoons: Processes, predictability, and the prospects for prediction. *Journal of Geophysical Research-Oceans* **103**, 14451-14510 (1998). A comprehensive and authoritative review on monsoon processes and predictability.

7 Meehl, G. A. THE ANNUAL CYCLE AND INTERANNUAL VARIABILITY IN THE TROPICAL PACIFIC AND INDIAN-OCEAN REGIONS. *Monthly Weather Review* **115**, 27-50, doi:10.1175/1520-0493(1987)115<0027:tacaiv>2.0.co;2 (1987).

8 Pearce, R. P. & Mohanty, U. C. ONSETS OF THE ASIAN SUMMER MONSOON 1979-82. *Journal of the Atmospheric Sciences* **41**, 1620-1639, doi:10.1175/1520-0469(1984)041<1620:ootasm>2.0.co;2 (1984).

9 Hoskins, B. J. & Rodwell, M. J. A MODEL OF THE ASIAN SUMMER MONSOON .1. THE GLOBAL-SCALE. *Journal of the Atmospheric Sciences* **52**, 1329-1340 (1995).

10 Slingo, J., Spencer, H., Hoskins, B., Berrisford, P. & Black, E. The meteorology of the Western Indian Ocean, and the influence of the east African highlands. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **363**, 25-42 (2005).

11 Findlater, J. *et al.* A MAJOR LOW-LEVEL AIR CURRENT NEAR INDIAN OCEAN DURING NORTHERN SUMMER - INTERHEMISPHERIC TRANSPORT OF AIR IN LOWER TROPOSPHERE OVER WESTERN INDIAN OCEAN. *Quarterly Journal of the Royal Meteorological Society* **96**, 551-&, doi:10.1002/qj.49709640919 (1970).

12 Boos, W. R. & Emanuel, K. A. Annual intensification of the Somali jet in a quasi-equilibrium framework: Observational composites. *Quarterly Journal of the Royal Meteorological Society* **135**, 319-335, doi:10.1002/qj.388 (2009).

13 Bordoni, S. & Schneider, T. Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience* **1**, 515-519, doi:10.1038/ngeo248 (2008).

14 Chou, C. & Neelin, J. D. Mechanisms limiting the northward extent of the northern summer monsoons over North America, Asia, and Africa. *Journal of Climate* **16**, 406-425, doi:10.1175/1520-0442(2003)016<0406:mltneo>2.0.co;2 (2003).
15 Chou, C., Neelin, J. D. & Su, H. Ocean-atmosphere-land feedbacks in an idealized monsoon. *Quarterly Journal of the Royal Meteorological Society* **127**, 1869-1891, doi:10.1002/qj.49712757602 (2001).
16 Rodwell, M. J. & Hoskins, B. J. Monsoons and the dynamics of deserts. *Quarterly Journal of the Royal Meteorological Society* **122**, 1385-1404, doi:10.1002/qj.49712253408 (1996).
17 Shenoi, S. S. C., Shankar, D. & Shetye, S. R. Differences in heat budgets of the near-surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon. *Journal of Geophysical Research-Oceans* **107**, doi:10.1029/2000jc000679 (2002).
18 Boos, W. R. & Kuang, Z. Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. *Nature* **463**, 218-U102, doi:10.1038/nature08707 (2010).
19 Choudhury, A. D. & Krishnan, R. Dynamical Response of the South Asian Monsoon Trough to Latent Heating from Stratiform and Convective Precipitation. *Journal of the Atmospheric Sciences* **68**, 1347-1363, doi:10.1175/2011jas3705.1 (2011).
20 Loschnigg, J. & Webster, P. J. A coupled ocean-atmosphere system of SST modulation for the Indian Ocean. *Journal of Climate* **13**, 3342-3360, doi:10.1175/1520-0442(2000)013<3342:acoaso>2.0.co;2 (2000).
21 Charney, J. G. & Shukla, J. in *Monsoon Dynamics* (eds J. Lighthill & R. P. Pearce) 99-109 (Cambridge University Press, 1981).
22 Bhat, G. S. The Indian drought of 2002 - a sub-seasonal phenomenon? *Quarterly Journal of the Royal Meteorological Society* **132**, 2583-2602, doi:10.1256/qj.05.13 (2006).
23 Subbiah, A. Initial Report on the Indian Monsoon Drought of 2002. (Asian Disaster Preparedness Center, 2002).
24 Gadgil, S. & Gadgil, S. in *Economic and Political Weekly* Vol. 41 4887-4895 (Mumbai, 2006).
25 Turner, A. G. & Slingo, J. M. Uncertainties in future projections of extreme precipitation in the Indian monsoon region. *Atmospheric Science Letters* **10**, 152-158, doi:10.1002/asl.223 (2009).
26 Sutton, R. T., Dong, B. W. & Gregory, J. M. Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. *Geophysical Research Letters* **34**, doi:10.1029/2006gl028164 (2007).
27 Knutson, T. R. *et al.* Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. *Journal of Climate* **19**, 1624-1651 (2006).
28 Parthasarathy, B., Munot, A. A. & Kothawale, D. R. ALL-INDIA MONTHLY AND SEASONAL RAINFALL SERIES - 1871-1993. *Theoretical and Applied Climatology* **49**, 217-224 (1994).
29 Krishnamurthy, V. & Goswami, B. N. Indian monsoon-ENSO relationship on interdecadal timescale. *Journal of Climate* **13**, 579-595 (2000).
30 Ramanathan, V. *et al.* Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proceedings of the National Academy of Sciences of the United States of America* **102**, 5326-5333, doi:10.1073/pnas.0500656102 (2005).
31 Rajeevan, M., Bhate, I., Kale, J. D. & Lal, B. High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells. *Current Science* **91**, 296-306 (2006).

32 Mitchell, T. D. & Jones, P. D. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* **25**, 693-712, doi:10.1002/joc.1181 (2005).

33 Annamalai, H., Hafner, J., Sooraj, K. P. & Pillai, P. Global Warming Shifts The Monsoon Circulation, Drying South Asia. *Nature Geosciences* **submitted** (2011).

34 Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S. & Xavier, P. K. Increasing trend of extreme rain events over India in a warming environment. *Science* **314**, 1442-1445, doi:10.1126/science.1132027 (2006). This article describes some of the competing trends in monsoon rainfall characteristics over recent decades.

35 Gautam, R., Hsu, N. C., Lau, K. M. & Kafatos, M. Aerosol and rainfall variability over the Indian monsoon region: distributions, trends and coupling. *Annales Geophysicae* **27**, 3691-3703 (2009).

36 Naidu, C. V. *et al.* Is summer monsoon rainfall decreasing over India in the global warming era? *Journal of Geophysical Research-Atmospheres* **114**, doi:10.1029/2008jd011288 (2009).

37 Pattanaik, D. R. Analysis of rainfall over different homogeneous regions of India in relation to variability in westward movement frequency of monsoon depressions. *Natural Hazards* **40**, 635-646, doi:10.1007/s11069-006-9014-0 (2007).

38 Bollasina, M. A., Ming, Y. & Ramaswamy, V. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *Science (New York, N.Y.)* **334**, 502-505 (2011).

39 Meehl, G. A. *et al.* The WCRP CMIP3 multimodel dataset - A new era in climate change research. *Bulletin of the American Meteorological Society* **88**, 1383-+, doi:10.1175/bams-88-9-1383 (2007).

40 Annamalai, H., Hamilton, K. & Sperber, K. R. The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. *Journal of Climate* **20**, 1071-1092, doi:10.1175/jcli4035.1 (2007). The effect of increased anthropogenic emissions on the mean monsoon, its interannual variability and teleconnection with ENSO in the CMIP3 models that are judged to reasonably simulate these aspects.

41 Niyogi, D., Kishtawal, C., Tripathi, S. & Govindaraju, R. S. Observational evidence that agricultural intensification and land use change may be reducing the Indian summer monsoon rainfall. *Water Resources Research* **46**, doi:10.1029/2008wr007082 (2010).

42 IPCC 2007: Summary for Policymakers in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon *et al.*) (Cambridge University Press, 2007).

43 Allen, M. R. & Ingram, W. J. Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224-+, doi:10.1038/nature01092 (2002). Useful discussion on the constraints to change in global mean and extremes of precipitation.

44 Held, I. M. & Soden, B. J. Robust responses of the hydrological cycle to global warming. *Journal of Climate* **19**, 5686-5699 (2006).

45 Knutson, T. R. & Manabe, S. TIME-MEAN RESPONSE OVER THE TROPICAL PACIFIC TO INCREASED CO2 IN A COUPLED OCEAN-ATMOSPHERE MODEL. *Journal of Climate* **8**, 2181-2199, doi:10.1175/1520-0442(1995)008<2181:tmrott>2.0.co;2 (1995).

46 Vecchi, G. A. & Soden, B. J. Global warming and the weakening of the tropical circulation. *Journal of Climate* **20**, 4316-4340, doi:10.1175/jcli4258.1 (2007).

47 Gill, A. E. SOME SIMPLE SOLUTIONS FOR HEAT-INDUCED TROPICAL CIRCULATION. *Quarterly Journal of the Royal Meteorological Society* **106**, 447-462, doi:10.1002/qj.49710644905 (1980).

48 Ashrit, R. G., Douville, H. & Kumar, K. R. Response of the Indian monsoon and ENSO-monsoon teleconnection to enhanced greenhouse effect in the CNRM coupled model. *Journal of the Meteorological Society of Japan* **81**, 779-803 (2003).

49 Hu, Z. Z., Latif, M., Roeckner, E. & Bengtsson, L. Intensified Asian summer monsoon and its variability in a coupled model forced by increasing greenhouse gas concentrations. *Geophysical Research Letters* **27**, 2681-2684 (2000).

50 Douville, H. *et al.* Impact of CO2 doubling on the Asian summer monsoon: Robust versus model-dependent responses. *Journal of the Meteorological Society of Japan* **78**, 421-439 (2000).

51 May, W. Simulated changes of the Indian summer monsoon under enhanced greenhouse gas conditions in a global time-slice experiment. *Geophysical Research Letters* **29**, doi:10.1029/2001gl013808 (2002).

52 Cherchi, A., Alessandri, A., Masina, S. & Navarra, A. Effects of increased CO_2 levels on monsoons. *Climate Dynamics*, 1-19, doi:10.1007/s00382-010-0801-7 (2010).

53 May, W. The sensitivity of the Indian summer monsoon to a global warming of 2°C with respect to pre-industrial times. *Climate Dynamics*, 1-26, doi:10.1007/s00382-010-0942-8 (2010).

54 Ueda, H., Iwai, A., Kuwako, K. & Hori, M. E. Impact of anthropogenic forcing on the Asian summer monsoon as simulated by eight GCMs. *Geophysical Research Letters* **33**, doi:10.1029/2005gl025336 (2006). Discusses the competition between moisture and circulation changes in determining changes to Asian summer monsoon rainfall in the future.

55 Kitoh, A., Yukimoto, S., Noda, A. & Motoi, T. Simulated changes in the Asian summer monsoon at times of increased atmospheric CO2. *Journal of the Meteorological Society of Japan* **75**, 1019-1031 (1997).

56 Meehl, G. A. *et al.* in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon *et al.*) Ch. 10, (Cambridge University Press, 2007).

57 Meehl, G. A. *et al.* Response of the NCAR climate system model to increased CO2 and the role of physical processes. *Journal of Climate* **13**, 1879-1898 (2000).

58 Douville, H. Impact of regional SST anomalies on the Indian monsoon response to global warming in the CNRM climate model. *Journal of Climate* **19**, 2008-2024 (2006).

59 Ashfaq, M. *et al.* Suppression of south Asian summer monsoon precipitation in the 21st century. *Geophysical Research Letters* **36**, 5, doi:10.1029/2008gl036500 (2009).

60 Stowasser, M., Annamalai, H. & Hafner, J. Response of the South Asian Summer Monsoon to Global Warming: Mean and Synoptic Systems. *Journal of Climate* **22**, 1014-1036, doi:10.1175/2008jcli2218.1 (2009).

61 Krishnamurthy, V. & Shukla, J. Intraseasonal and interannual variability of rainfall over India. *Journal of Climate* **13**, 4366-4377 (2000).

62 Krishnamurthy, V. & Shukla, J. Intraseasonal and seasonally persisting patterns of Indian monsoon rainfall. *Journal of Climate* **20**, 3-20, doi:10.1175/jcli3981.1 (2007).

63 Sperber, K. R., Slingo, J. M. & Annamalai, H. Predictability and the relationship between subseasonal and interannual variability during the Asian summer monsoon. *Quarterly Journal of the Royal Meteorological Society* **126**, 2545-2574 (2000).

64 Wheeler, M. C. & Hendon, H. H. An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Monthly Weather Review* **132**, 1917-1932 (2004).
65 Saith, N. & Slingo, J. The role of the Madden-Julian Oscillation in the El Nino and Indian drought of 2002. *International Journal of Climatology* **26**, 1361-1378, doi:10.1002/joc.1317 (2006).
66 Sperber, K. R. & Annamalai, H. Coupled model simulations of boreal summer intraseasonal (30-50 day) variability, Part 1: Systematic errors and caution on use of metrics. *Climate Dynamics* **31**, 345-372, doi:10.1007/s00382-008-0367-9 (2008).
67 Dhar, O. N. & Nandargi, S. ON SOME CHARACTERISTICS OF SEVERE RAINSTORMS OF INDIA. *Theoretical and Applied Climatology* **50**, 205-212 (1995).
68 Ajayamohan, R. S., Merryfield, W. J. & Kharin, V. V. Increasing Trend of Synoptic Activity and Its Relationship with Extreme Rain Events over Central India. *Journal of Climate* **23**, 1004-1013, doi:10.1175/2009jcli2918.1 (2010).
69 Dash, S. K., Kumar, J. R. & Shekhar, M. S. On the decreasing frequency of monsoon depressions over the Indian region. *Current Science* **86**, 1404-1411 (2004).
70 Trenberth, K. E., Dai, A., Rasmussen, R. M. & Parsons, D. B. The changing character of precipitation. *Bulletin of the American Meteorological Society* **84**, 1205-+, doi:10.1175/bams-84-9-1205 (2003).
71 Chou, C., Neelin, J. D., Chen, C. A. & Tu, J. Y. Evaluating the "Rich-Get-Richer'' Mechanism in Tropical Precipitation Change under Global Warming. *Journal of Climate* **22**, 1982-2005, doi:10.1175/2008jcli2471.1 (2009).
72 Semenov, V. A. & Bengtsson, L. Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM. *Climate Dynamics* **19**, 123-140, doi:10.1007/s00382-001-0218-4 (2002).
73 Turner, A. G. & Slingo, J. M. Subseasonal extremes of precipitation and active-break cycles of the Indian summer monsoon in a climate-change scenario. *Quarterly Journal of the Royal Meteorological Society* **135**, 549-567, doi:10.1002/qj.401 (2009).
74 Tebaldi, C., Hayhoe, K., Arblaster, J. M. & Meehl, G. A. Going to the extremes. *Climatic Change* **79**, 185-211, doi:10.1007/s10584-006-9051-4 (2006).
75 Sun, Y., Solomon, S., Dai, A. & Portmann, R. W. How often does it rain? *Journal of Climate* **19**, 916-934 (2006).
76 Joseph, P. V. & Simon, A. Weakening trend of the southwest monsoon current through peninsular India from 1950 to the present. *Current Science* **89**, 687-694 (2005).
77 Dash, S. K., Kulkarni, M. A., Mohanty, U. C. & Prasad, K. Changes in the characteristics of rain events in India. *Journal of Geophysical Research-Atmospheres* **114**, doi:10.1029/2008jd010572 (2009).
78 Lin, J.-L. *et al.* Subseasonal variability associated with Asian summer monsoon simulated by 14 IPCC AR4 coupled GCMs. *Journal of Climate* **21**, 4541-4567, doi:10.1175/2008jcli1816.1 (2008).
79 Kumar, K. K., Rajagopalan, B. & Cane, M. A. On the weakening relationship between the Indian monsoon and ENSO. *Science* **284**, 2156-2159 (1999).
80 Kumar, K. K., Rajagopalan, B., Hoerling, M., Bates, G. & Cane, M. Unraveling the mystery of Indian monsoon failure during El Nino. *Science* **314**, 115-119, doi:10.1126/science.1131152 (2006).
81 Turner, A. G., Inness, P. A. & Slingo, J. M. The effect of doubled CO2 and model basic state biases on the monsoon-ENSO system. I: Mean response and interannual

variability. *Quarterly Journal of the Royal Meteorological Society* **133**, 1143-1157, doi:10.1002/qj.82 (2007).
82 Meehl, G. A., Teng, H. Y. & Branstator, G. Future changes of El Nino in two global coupled climate models. *Climate Dynamics* **26**, 549-566, doi:10.1007/s00382-005-0098-0 (2006).
83 Meehl, G. A. & Arblaster, J. M. Mechanisms for projected future changes in south Asian monsoon precipitation. *Climate Dynamics* **21**, 659-675, doi:10.1007/s00382-003-0343-3 (2003).
84 Turner, A. G., Inness, P. M. & Slingo, J. M. The role of the basic state in the ENSO-monsoon relationship and implications for predictability. *Quarterly Journal of the Royal Meteorological Society* **131**, 781-804, doi:10.1256/qj.04.70 (2005). Demonstrates the importance of capturing mean state SST in a coupled model in order for accurate portrayal of the monsoon-ENSO teleconnection.
85 Joseph, R. & Nigam, S. ENSO evolution and teleconnections in IPCC's twentieth-century climate simulations: Realistic representation? *Journal of Climate* **19**, 4360-4377 (2006).
86 AchutaRao, K. & Sperber, K. R. ENSO simulation in coupled ocean-atmosphere models: are the current models better? *Climate Dynamics* **27**, 1-15, doi:10.1007/s00382-006-0119-7 (2006).
87 Lloyd, J., Guilyardi, E., Weller, H. & Slingo, J. The role of atmosphere feedbacks during ENSO in the CMIP3 models. *Atmospheric Science Letters* **10**, 170-176, doi:10.1002/asl.227 (2009).
88 Collins, M. *et al.* The impact of global warming on the tropical Pacific ocean and El Nino. *Nature Geoscience* **3**, 391-397, doi:10.1038/ngeo868 (2010). Succinct review of the projected climatic changes to the mean state of the tropical Pacific and our uncertainty in changes to ENSO frequency and amplitude.
89 Wang, B. in *Intraseasonal Variability of the Atmosphere-Ocean Climate System* (eds K. M. Waliser & D. E. Waliser) 307-362 (Springer, 2005).
90 Prasanna, V. & Annamalai, H. Moist dynamics of extended monsoon breaks. *Journal of Climate* **in press** (2011).
91 Goswami, B. N., Ajayamohan, R. S., Xavier, P. K. & Sengupta, D. Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. *Geophysical Research Letters* **30**, doi:10.1029/2002gl016734 (2003).
92 Wang, C. A modeling study on the climate impacts of black carbon aerosols. *Journal of Geophysical Research-Atmospheres* **109**, doi:10.1029/2003jd004084 (2004).
93 Lau, K. M. & Kim, K. M. Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophysical Research Letters* **33**, doi:10.1029/2006gl027546 (2006).
94 Lau, K. M., Kim, M. K. & Kim, K. M. Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. *Climate Dynamics* **26**, 855-864, doi:10.1007/s00382-006-0114-z (2006).
95 Meehl, G. A., Arblaster, J. M. & Collins, W. D. Effects of black carbon aerosols on the Indian monsoon. *Journal of Climate* **21**, 2869-2882, doi:10.1175/2007jcli1777.1 (2008).
96 Nigam, S. & Bollasina, M. "Elevated heat pump" hypothesis for the aerosol-monsoon hydroclimate link: "Grounded" in observations? *Journal of Geophysical Research-Atmospheres* **115**, doi:10.1029/2009jd013800 (2010).
97 Lau, K. M. & Kim, K. M. Comment on '"Elevated heat pump' hypothesis for the aerosol-monsoon hydroclimate link: 'Grounded' in observations?" by S. Nigam and

M. Bollasina. *Journal of Geophysical Research-Atmospheres* **116**, doi:10.1029/2010jd014800 (2011).
98 Ackerman, A. S. *et al.* Reduction of tropical cloudiness by soot. *Science* **288**, 1042-1047 (2000).
99 Norris, J. R. Has northern Indian Ocean cloud cover changed due to increasing anthropogenic aerosol? *Geophysical Research Letters* **28**, 3271-3274 (2001).
100 Rayner, N. A. *et al.* Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research-Atmospheres* **108**, doi:10.1029/2002jd002670 (2003).
101 Dee, D. P. *et al.* The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**, 553-597, doi:10.1002/qj.828 (2011).
102 Huffman, G. J. *et al.* The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology* **8**, 38-55, doi:10.1175/jhm560.1 (2007).
103 Webster, P. J. & Yang, S. MONSOON AND ENSO - SELECTIVELY INTERACTIVE SYSTEMS. *Quarterly Journal of the Royal Meteorological Society* **118**, 877-926 (1992).
104 Sardeshmukh, P. D., Compo, G. P. & Penland, C. Changes of probability associated with El Nino. *Journal of Climate* **13**, 4268-4286, doi:10.1175/1520-0442(2000)013<4268:copawe>2.0.co;2 (2000).

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Display items

Box 1: The role of aerosol

Carbon dioxide and other greenhouse gases are not the only atmospheric constituents known to affect monsoon climate. South Asia's increasing industrialisation 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 (c.f. Figure 2) as to why seasonal mean rainfall over India has not shown increases in the recent observed record despite rising CO_2.

At the simplest level, the direct radiative effect limits the solar radiation reaching the surface, reducing the surface meridional thermal contrast and partially countering the impact of rising CO_2. Indeed, scattering and absorbing aerosol may have masked up to 50% of the potential surface warming due to GHG[30]. Such a mechanism may also cool the northern Indian Ocean, reducing monsoon rainfall[30]. In future projections, the inclusion of sulphate aerosol in addition to increasing CO_2 leads to a more restrained increase in monsoon rainfall[56]. Recently, attempts have been made to attribute historical negative trends in regional rainfall over India to the increasing aerosol burden[38], however one questions what may have caused apparent rising trends in monsoon rainfall in the first half of the 20th century as shown in Figure 2. Further, there is considerable work to be done to establish the species and effects involved and to carefully evaluate the effects of non-standardized forcings used in different models. The suggestion at present is that the indirect effects on cloud lifetime or albedo could dominate[38]. The role of absorbing aerosol such as black carbon is more uncertain. While it reduces insolation at the surface, the aerosol layer itself is warmed, heating the troposphere. This intensifies the thermally-driven circulation and results in monsoon rainfall increase[92], 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[93,94]. 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 somewhat supported by other observations[35], however 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 due to reduced incident solar radiation prior to the monsoon onset, causing both monsoon circulation and rainfall to weaken slightly[95]. There is considerable ongoing debate over the ability of black carbon to enhance the monsoon[96,97].

A further consideration is the semi-direct effect, whereby the presence of absorbing aerosol may lead to evaporation in cloud layers, *burning off* the cloud. Model results have suggested this possibility[98] however observations of cloud cover over the northern Indian Ocean actually show increases[99], suggesting 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.

Figure 1: Schematic of summer and winter climate in the South Asian monsoon region

Schematic diagram of boreal summer (JJAS) and winter (DJF) atmospheric conditions in the South Asian monsoon region. In each case, the lower slice shows: orography (>1000m, shaded grey); sea surface temperatures from HadISST[100] data 1979-2010 (shaded yellow/red); sea-level pressure from ERA-Interim Reanalysis[101] for 1979-2010 (blue contours, interval 2hPa); lower tropospheric (850hPa) winds from ERA Interim. The upper slice shows upper tropospheric (200hPa) wind vectors and TRMM 3B43[102] monthly rainfall 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 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 representing the location of maximum vertically integrated moist static energy, bounding the northward extent of the monsoon Hadley-type circulation. Over the ocean, rainfall locates over the warmest SST while 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[103].

Figure 2: Historical and SRES-A1B projection of South Asian monsoon rainfall

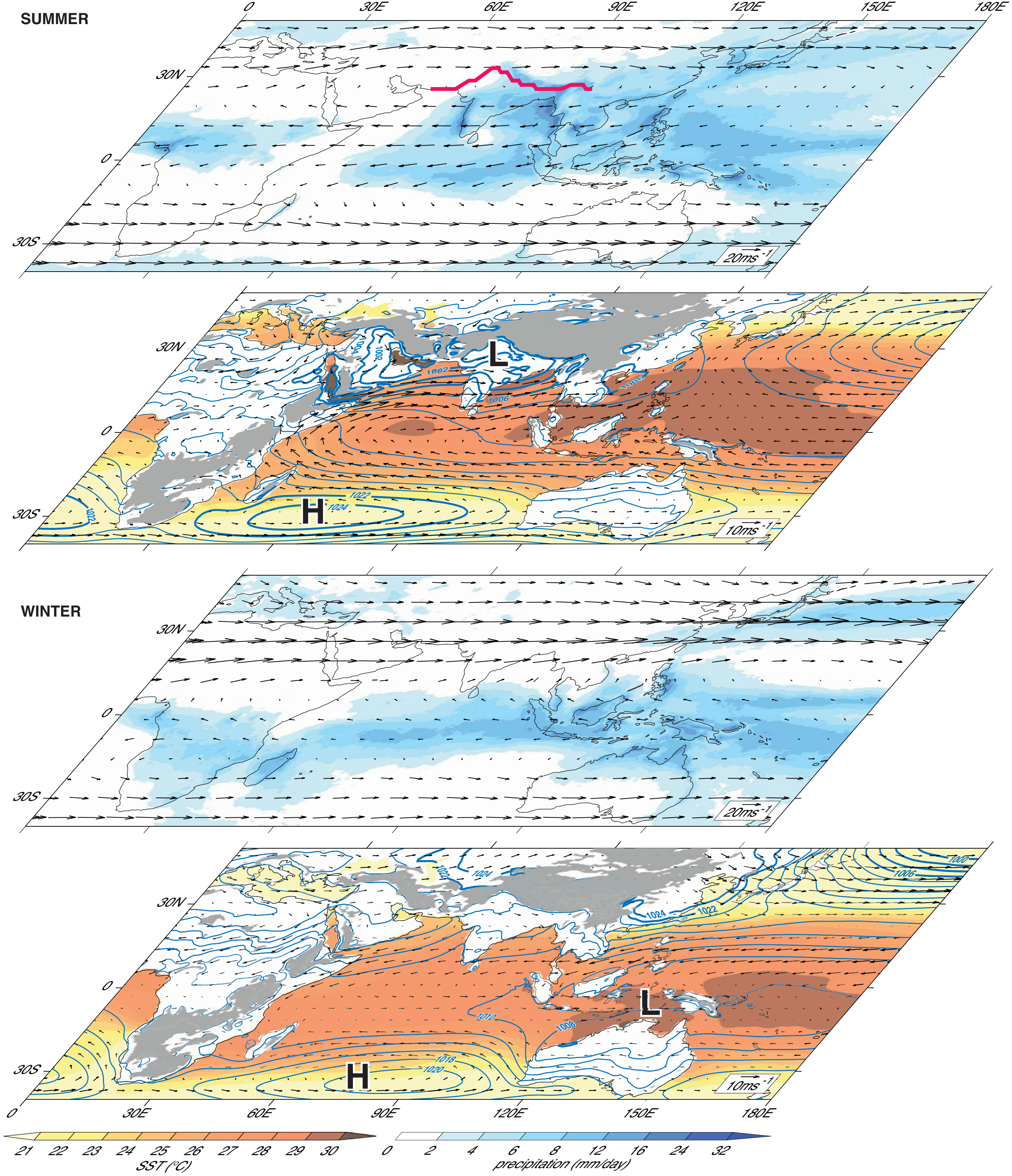
Time series of mean summer (JJAS) precipitation averaged over land points within 60-90°E, 7-27°N in the historical ("20c3m"; 1861-1999) and SRES-A1B (2000-2100) future projection CMIP3 experiments. Only four models shown[40] to have a reasonable simulation of the spatial pattern, seasonal cycle and interannual variability of monsoon rainfall are depicted; the black curve shows their ensemble mean. Observations from the All-India Rainfall 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 diagram compares the All-India Rainfall 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 are for JJAS mean rainfall and interannual standard deviation, in mm.

Figure 3: Precipitation response to doubling of CO_2 concentrations

Mean summer (JJAS) precipitation projections in the 1% per year increasing carbon dioxide experiment (1pctto2x) of the CMIP3 multi-model database after doubling of CO_2 concentrations relative to control conditions: (a) shows the mean across 20 models; (b) takes a subset of four of these models judged[40] to reasonably simulate the monsoon seasonal cycle, interannual variability and the teleconnection between monsoon rainfall and ENSO. Models were first bi-linearly interpolated onto a common 5-degree grid in order to compute ensemble means. Stippling in panel a indicates where more than two-thirds of the models agree on the sign of change.

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 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[40]: (a) gfdl_cm2_0; (b) gfdl_cm2_1; (c) mri_cgcm2_3_2a; and (d) mpi_echam5. Region of averaging is as in Figure 2. Pre-industrial control PDF (solid line) and future climate (1% increase per year increase in carbon dioxide experiments - 1pctto2x) PDF (dotted line) are shown. The future variations are scaled by the pre-industrial control interannual standard deviations whose values (in mm) are also shown. The differences in the shape of the PDFs have been tested for significance based on K-S test[104]. While all models suggest a reduction in the occurrences of normal monsoon years (+/- 1.0 standard deviation in monsoon rainfall) the changes in the tails of the distribution are significant only in one model, mri_cgcm2_3_21 (panel 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 Figure 2 as well as in Figure 4). In the model that has the best agreement with observations, gfdl_cm2_1 (panel b), changes in the tails are not significant.



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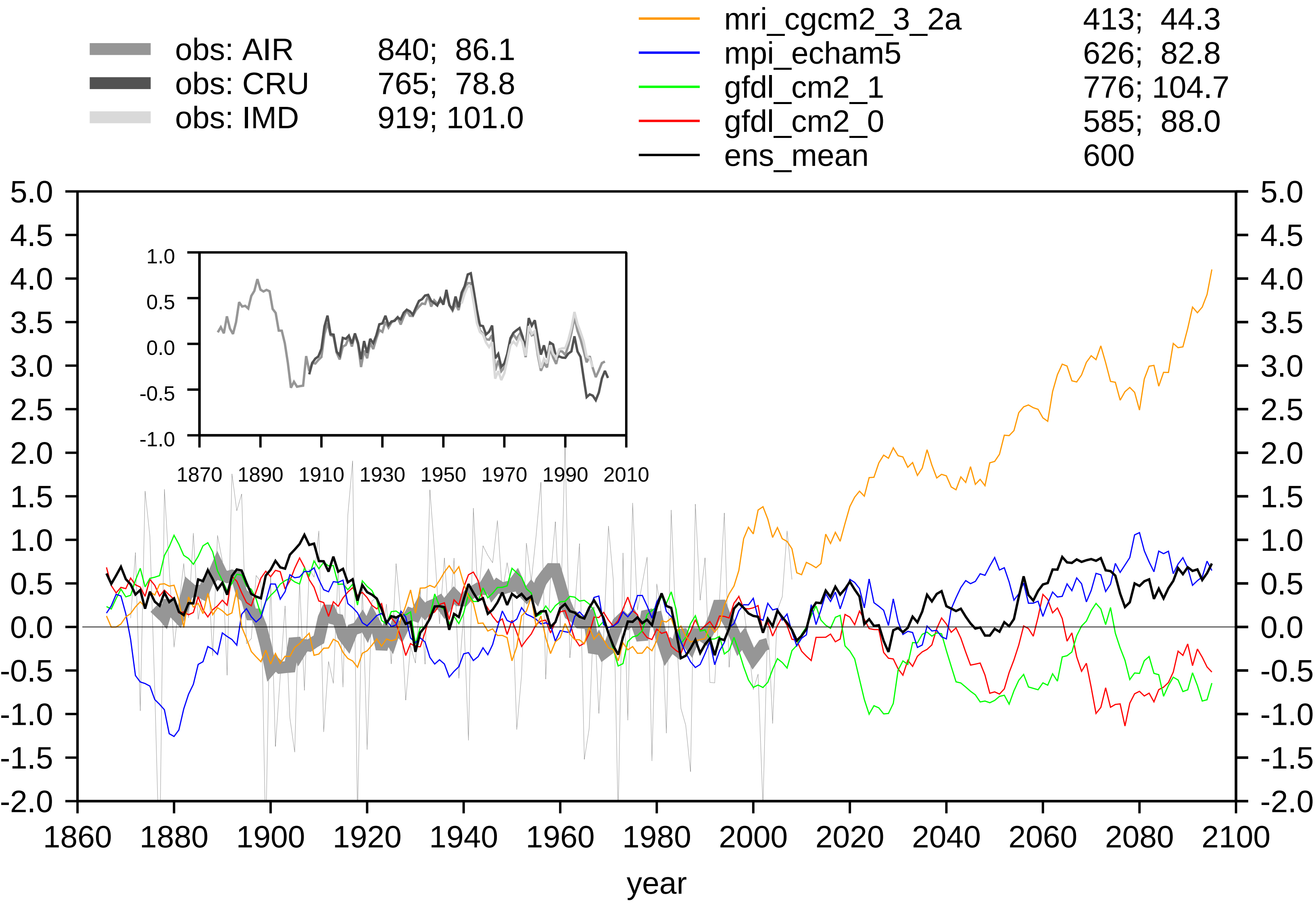
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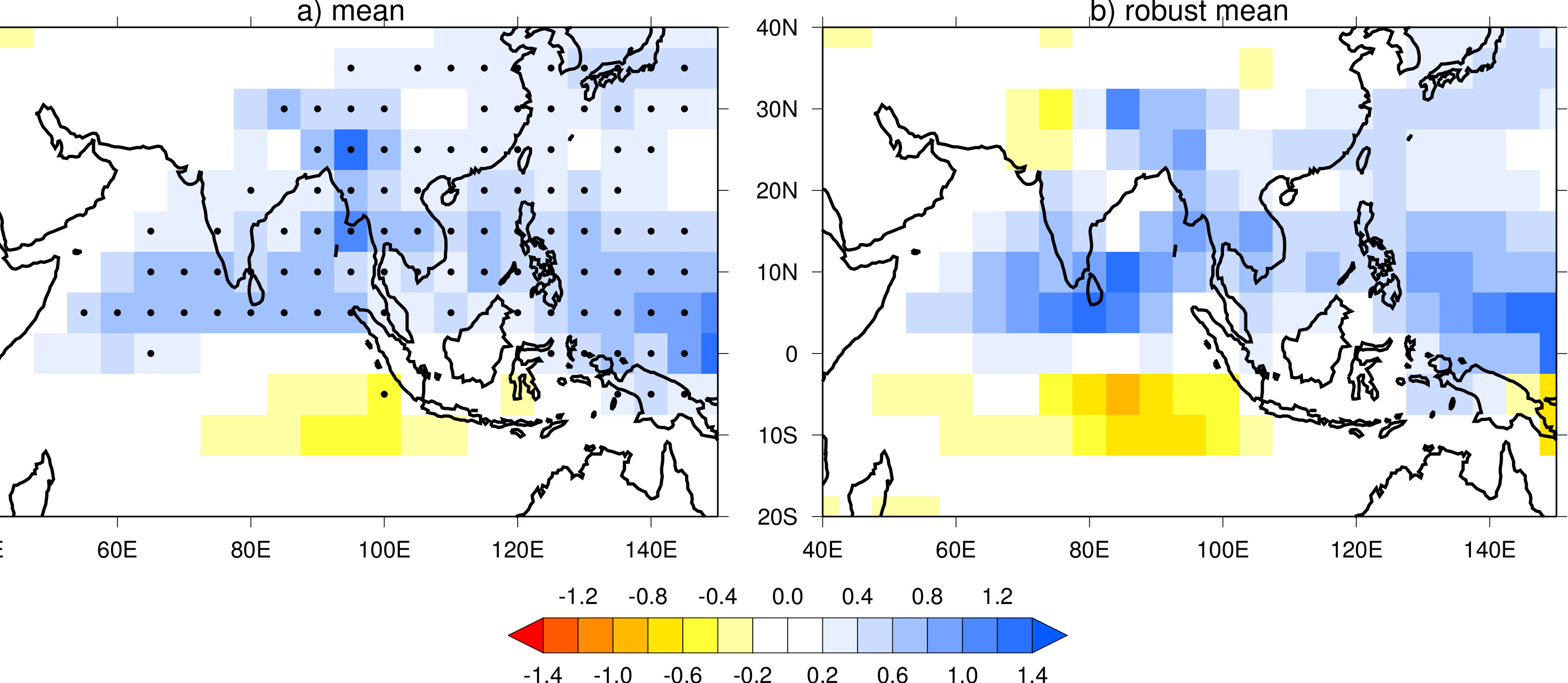

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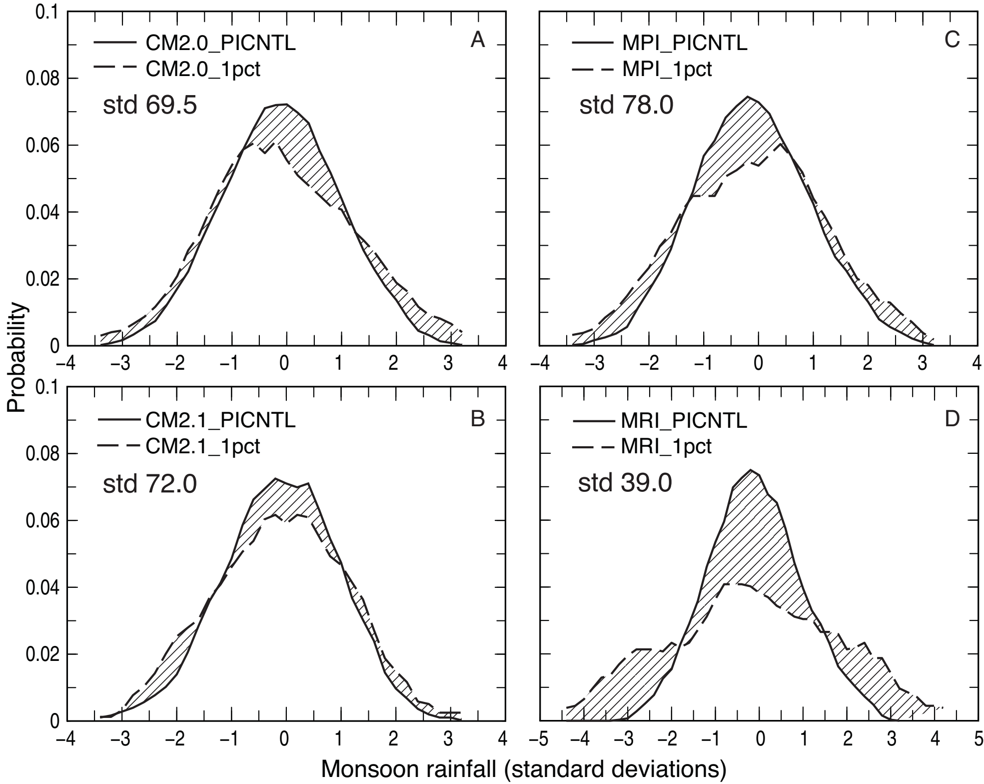
CM2.0_PICNTL
CM2.0_1pct
A
std 69.5
MPI_PICNTL
MPI_1pct
C
std 78.0
CM2.1_PICNTL
CM2.1_1pct
B
std 72.0
MRI_PICNTL
MRI_1pct
D
std 39.0
Probability
Monsoon rainfall (standard deviations)