

Uncertainties in future projections of extreme precipitation in the Indian monsoon region

A.G. Turner^{1,*} and J.M. Slingo^{2,1}

¹NCAS-Climate, Walker Institute for Climate System Research, University of Reading

²Met Office, Exeter

*Department of Meteorology, University of Reading, Earley Gate, RG6 6BB.
a.g.turner@reading.ac.uk tel: +441183786517 / fax: +441183788905

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Abstract

Uncertainties in changes to the spatial distribution and magnitude of the heaviest extremes of daily monsoon rainfall over India are assessed in the doubled CO₂ climate change scenarios in the IPCC Fourth Assessment Report. Results show diverse changes to the spatial pattern of the 95th and 99th subseasonal percentiles, which are strongly tied to the mean precipitation change during boreal summer. In some models, the projected increase in heaviest rainfall over India at CO₂ doubling is entirely predictable based upon the surface warming and the Clausius-Clapeyron relation, a result which may depend upon the choice of convection scheme.

1) Introduction

The Indian summer monsoon represents one of the largest annual variations of the global climate system and supplies around 80% of the region's annual rainfall total, making its correct forecast essential for agriculture and industry. Variations on interannual timescales, however, are surprisingly small (standard deviation in summer all-India rainfall is around 10%), whereas much shorter timescale events can be much more damaging. For example, during the monsoon break of July 2002, India received only around half its normal rainfall (Annamalai et al., 2007), whereas in late July 2005 Mumbai received nearly one metre of rainfall in a single day (Lal et al., 2006). Therefore, a key goal of monsoon climate change research is to quantify the possible changes to extremes of monsoon rainfall in order to mitigate their associated impacts on groundwater, agriculture, waterborne disease etc.

Several studies have examined changes to the mean Indian summer monsoon and its interannual variability under anthropogenic greenhouse warming scenarios. Turner et al. (2007) showed the Indian monsoon to be quite robust using a doubled CO₂ experiment in the HadCM3 coupled model. Mean summer (JJAS) rainfall increased by 3.5% over the Indian land surface, or just over 5% when measured over a broader region encompassing the Bay of Bengal. In HadCM3, these increases mainly occur over north India, the southern peninsula and in the Bay of Bengal. Others such as Hu et al. (2000) noted increases over only the peninsula, while Ashrit et al. (2003) describe increased rainfall over the dry northwest and far south in similar experiments. In the CMIP3 multi-model database used for the Intergovernmental Panel for Climate Change Fourth Assessment report (hereafter IPCC AR4), Meehl et al. (2007a) showed JJA mean precipitation projections for 2080-2099 in the A1B emissions scenario and found, for the Indian region, that the inter-model spread of projections (noise) was larger than the mean precipitation increase

(signal). It should be noted that most modelling studies, including the integrations in the CMIP3 database, have neglected the effects of increasing black carbon and other aerosol forcings which may lead to decreases in monsoon rainfall (Ramanathan et al. 2005; Lau et al. 2005) or a shift in seasonality (increasing the pre-monsoon at the expense of rainfall during summer; Meehl et al. 2008). Hence there still remains considerable uncertainty among state-of-the-art coupled GCMs in *mean* projections of monsoon rainfall.

Relatively few studies have examined projected changes to rainfall extremes. Although examining India only in the global context, Meehl et al. (2005) showed a general increase in precipitation intensity over the land surface, attributable to increases in water vapour. Tebaldi et al. (2006) further showed that mean precipitation was a function of precipitation intensity and the number of wet days. Turner and Slingo (2009) considered changes to precipitation extremes during the Indian summer monsoon in HadCM3 at doubled CO₂. We showed changes to subseasonal monsoon rainfall extremes with a pattern qualitatively similar to changes in the mean, but of larger magnitude. Turner and Slingo (2009) hypothesized that the close relationship between changes to subseasonal extremes and mean projections would be evident in other models, and this paper aims to test that hypothesis. In addition, Turner and Slingo (2009) examined the proposition of Allen and Ingram (2002) that changes in the magnitude of the heaviest rainfall events were entirely predictable based on the degree of surface warming (the climate sensitivity) and Clausius-Clapeyron related increases in moisture content of the atmospheric column. Turner and Slingo (2009) showed that this predictive relationship not only worked globally, but also locally for the Indian monsoon region during summer. This result is consistent with observed changes in rainfall extremes over India reported by Goswami et al. (2006). Whether such a relationship exists in other coupled GCMs under increased greenhouse warming has not so far been addressed.

This paper aims to extend the work of Turner and Slingo (2009) using the CMIP3 multi-model database to test whether changes to the spatial pattern of subseasonal extremes can be qualitatively related with those in mean summer rainfall. In addition, we examine if the thermodynamic predictive relationship for the heaviest extremes in Indian monsoon rainfall applies across all the CMIP3 models, and possible reasons why this holds in only some cases.

The model data used are described in section 2, while results are shown in section 3. Discussion follows in section 4.

2) Model data

Coupled model data submitted to the IPCC AR4 have been obtained from the 3rd Coupled Model Intercomparison Project (CMIP3) database archived at the Program for Climate Model Diagnostics and Intercomparison (PCMDI) and described in Meehl et al. (2007b). Only those 15 models for which daily precipitation diagnostics were available for control and 1pctto2x¹ integrations have been used in this study (the models are named in Fig. 1). For most modelling groups, the control integration used pre-industrial levels of CO₂ (hereafter picntrl); however the miub_echo_g and mri_cgcm2_3_2a simulations started from present day control conditions (pdcntrl). Daily data provided for picntrl covered typically 40 years, while 20 years centred on the time of CO₂ doubling (*i.e.*, years 60-80) of the 1pctto2x integrations were available. Nine models also provide 20-years of data from the end of their 1pctto2x integrations, after the stabilization period. This data is assessed separately.

Surface air temperature data derived from the same model experiments and time periods were used to calculate changes in local climate sensitivity (the area averaged temperature response to CO₂ doubling). Zonal wind data were also used to assess changes in windshear. Only boreal summer (JJA) data were used.

3) Results

a) Spatial distribution of subseasonal extremes

To assess the range of projections in the regional distribution of Indian summer monsoon subseasonal rainfall extremes at time of CO₂ doubling, we calculate various upper percentiles at each gridpoint and for each season, before averaging over the number of available years. We emphasize that in this section we are describing changes to those extreme events which happen every year (for example, the 99th percentile is one event per hundred days, which we sample approximately once per season). In this way, the influence of any clustering of extreme events (*e.g.*, in ENSO years) can be reduced. For comparison, we also show changes to JJA mean rainfall.

Projected changes in mean precipitation and in the 95th and 99th subseasonal percentiles at time of CO₂ doubling are shown in Fig. 1 for the 15 models. Immediately clear from the upper panel is the predominant strengthening of

¹ The 1pctto2x experiment ramps up atmospheric CO₂ concentration at 1% per year from control conditions and after 70 years (the time of doubling) CO₂ concentration is fixed for the remainder of the integration.

mean monsoon rainfall over the broad Asian monsoon region. In some cases this occurs mainly over the Indian land surface (e.g., cnrm_cm3, mri_cgcm2_3_2a), while in others the precipitation increase is more widespread (e.g., cccma_cgcm3_1, miroc3_2_medres). Some models demonstrate similar greenhouse warming-induced precipitation changes to HadCM3 (Turner et al., 2007; Turner and Slingo, 2009), with precipitation increases over north India and the head of the Bay of Bengal (e.g., bccr_bcm2_0, gfdl_cm2_0). Among the 15 tested models, decreases in mean summer monsoon rainfall over India are rare (e.g., giss_model_e_r).

Examining changes to the subseasonal precipitation extremes (middle and lower panels of Fig. 1) confirms that the pattern of changes to extreme rainfall days in each monsoon season is closely tied to that of mean rainfall. However, the changes in the magnitude of the 95th and 99th percentiles far exceed those in the mean. Thus the Indian monsoon region will suffer, almost exclusively among these models, much heavier extremes of monsoon rainfall at the upper percentiles.

To examine the relationship between the spatial patterns of change to mean monsoon rainfall and those of subseasonal extremes more closely, we analyse pattern correlations between mean and extreme changes at various upper percentiles for India (65-90°E, 10-30°N) and the broad Asia monsoon region (40-180°E, 25°S-40°N after Annamalai et al., 2007). The correlations in Fig. 2 reveal that roughly 80% of the spatial pattern of change in the 90th percentile can be explained by changes in the mean, for both India and the much broader Asian region. There is considerable consistency between models. Even at the 99th percentile (approximately one day per season), around 50% of the variance in the spatial pattern of change is explained by the mean. Once models agree more closely on the outcome of greenhouse warming-induced changes to the mean monsoon, then this information will prove useful for climate impacts studies. If precipitation extremes are instead calculated with no interannual meaning constraint, then such an association is lost, *i.e.*, patterns of change to very extreme events (localized storms etc) bear no resemblance to the seasonal mean change.

b) Magnitude of the heaviest extremes

In order to examine the potential for predictability in changes to the magnitude of the heaviest monsoon rainfall events in a warming climate, we follow the methodology of Allen and Ingram (2002). They analysed daily data in control and 2xCO₂ integrations of HadCM3 and calculated precipitation levels associated with each percentile in the upper two quartiles for each scenario. Each available gridpoint was considered and no area or time-averaging was performed. The ratio between the two scenarios was expressed as a percentage increase and was found to be consistent with that predicted using

the global climate sensitivity and the theoretical increased moisture holding capacity of the atmospheric column from the Clausius-Clapeyron relationship. Turner and Slingo (2009) repeated this methodology for the Indian monsoon region in HadCM3 and showed that this result was robust even at a regional level.

Here, we repeat these calculations for the CMIP3 models. Figure 3a shows the 15-model ensemble spread of projections for the upper two quartiles over the Indian region (65-90°E, 10-30°N) during boreal summer (JJA). All model curves used in producing Fig. 3 are first smoothed using a 51-point boxcar filter, which has more impact at higher percentiles due to the wider spread of data on the log-scale (this is appropriate given the lower sampling at higher percentiles). The right hand y-axis of Fig. 3 represents the percentage change in the intensity of the heaviest precipitation events in the model data relative to the control simulation. Box-and-whisker diagrams shown at the 99.99th percentile indicate the spread of the theoretical predictions of changes in the heaviest rainfall events based on the Clausius-Clapeyron atmospheric moisture content and the simulated local surface warming in response to doubling of CO₂ concentration, approximately 6%/K based on temperatures typical for India. The *local climate sensitivity* is calculated as the JJA change in surface air temperature for each model. We do not average temperature over the Indian subcontinent, but instead further west (over the Arabian Sea 55-70°E, 5-20°N) to account for the fact that the atmospheric moisture content over India is largely determined by the Somali Jet. However results are found to be fairly invariant to the precise region chosen.

The results shown in Fig. 3a at the time of CO₂ doubling suggest a fairly narrow spread of predicted increases in maximum rainfall based on Clausius-Clapeyron, centred on a median of around 9% above the levels in the control simulations. The median of the actual, simulated values (solid curve) is higher than this at around 12%, with a much broader interquartile range, reflecting the generally greater uncertainty in projections of precipitation versus surface temperature. Curves for the nine modelling groups which also provided data for CO₂ stabilization are shown in Fig. 3b. Thus towards the end of the integrations, after the coupled ocean-atmosphere system has been allowed to equilibrate, there are substantially higher estimates of the measured (23%) and predicted (12.5%) increases in the strength of heaviest rainfall events owing to larger climate sensitivity, although greater uncertainty is shown by the interquartile range.

To examine whether there is any predictability in projected changes to the heaviest monsoon rainfall as suggested in Turner and Slingo (2009), Table 1 lists the models used ranked in descending order based on the ratio of measured increase in heaviest rainfall to the Clausius-Clapeyron predictions.

We stratify the models according to whether the simulated changes in the heaviest events fall below ($\text{ratio} < 0.5$; 3 models), are close to ($0.5 < \text{ratio} < 1.5$; 6 models) or far exceed ($\text{ratio} > 1.5$; 6 models) those expected from the Clausius-Clapeyron relationship. Here we attempt to partially explain the diverse behaviour based on the convective parameterization used. We suggest that those models in the former two categories predominantly (though not exclusively) feature bulk mass-flux schemes (eg, cnrm_cm3 with Kuo closure). These strongly depend on surface evaporation (eg, Slingo et al, 1994; Pattanaik and Satyan, 2000) and consist of single entraining plumes reliant on adiabatic ascent from the lowest model level, are hence surface temperature changes provide a strong constraint. Others such as the Betts scheme (in inmcm3_0) employ convective adjustment to a defined thermodynamic reference profile (as described in Slingo et al, 1994) and are also strongly constrained. Such simple classification fails to explain why some models should have near zero changes to the heaviest rainfall despite warming temperatures. While the giss_e_r model even showed clear decreases in mean rainfall over India, no such monsoon weakening occurred in bccr_bcm2_0 and ipsl_cm4. None of these three models was judged to successfully simulate the seasonal cycle of the monsoon in Annamalai et al. (2007) however. The result from the six near-Clausius-Clapeyron models suggests that in their case the increase in the heaviest rainfall *is* predictable based on the moisture holding capacity of the atmospheric column and the local surface warming. Given that there is currently much greater predictability in changes to future mean surface temperature than mean precipitation, this result indicates that the degree of change to very extreme monsoon rainfall may, in some way, also be predictable.

In contrast, the super-thermodynamic category mainly features variants on the Arakawa-Schubert scheme (relaxed as in the GFDL models - Moorthi and Suarez, 1992; or prognostic closure as in the MIROC models - Pan and Randall, 1998). The Zhang—McFarlane scheme is also of similar concept (Zhang and McFarlane 1995). These schemes parameterize deep convection with plume ensembles able to initiate from several levels in the vertical and are hence not so constrained by changes in surface conditions. In a direct comparison of the impact of cumulus parameterization on the Indian monsoon, Pattanaik and Satyan (2000) used the COLA GCM to demonstrate much stronger convective latent heating rates and mean precipitation over the Indian region using the relaxed_Arawaka-Schubert scheme compared to the Kuo mass-flux, consistent with the results here. In addition, testing the relaxed AS scheme from the GFDL models as part of a non-rotating radiative-convective model, Held et al (2007) demonstrated increasing large-scale precipitation in the tropics with temperature, above a critical threshold. Those authors suggest that such changes in these 'gridpoint' storms may have an undesirable impact on model climate response. Allan and Soden (2008)

compared the occurrence of extreme rainfall events in the tropics in observations during cold and warm periods and noted a clear link between rainfall extremes and temperature. Using *gfdl_cm2_1* as an example, they also suggest that GCMs may be under-predicting the increase in heavy event (frequency) during warm periods when compared to observations. The results presented here, however, suggest that *gfdl_cm2_1* is an outlier compared with the other GCMs in the CMIP3 database (with heaviest rainfall increasing by around 30% at CO₂ doubling). We note however that its basic monsoon simulation was judged by Annamalai et al (2007) to be one of the six best performers.

A clear anomaly in Table 1 is that of the two CSIRO models, which feature identical bulk mass-flux convection scheme (and the same as HadCM3). The *csiro_mk3_0* model is strongly super-thermodynamic while the level of heavy rainfall in *csiro_mk3_5* is quite predictable, suggesting that other factors play a role. Other model pairs such as GFDL and MIROC behave similarly however.

Other factors were also examined. A cursory analysis of horizontal resolution in the models' atmospheric component (not shown) reveals no clear bias in magnitude of the heaviest events (nor in spatial changes to extremes). Simple metrics of wind behaviour over the monsoon domain were also examined. As an example the table lists changes in mean JJA zonal windshear ($U_{850}-U_{200}$) over the broad Asian region (40-110°E, 5-20°N). One might expect those models with strong decreases in zonal windshear to undergo increases in tropical storms (as noted in the observed record by Muni Krishna 2009). However, no such relationship is noted.

4) Discussion and conclusions

This study has examined the uncertainty in projected changes to the spatial pattern and magnitude of rainfall extremes during the Indian summer monsoon in the 1pctto2x scenario of the CMIP3 models. In an earlier study based on a single model, Turner and Slingo (2009) raised some questions which this paper has sought to address. Firstly, to what extent are changes to subseasonal extremes of monsoon precipitation under greenhouse gas warming tied to changes in the mean rainfall, and secondly, whether regional surface warming (local climate sensitivity) may lend predictability to changes in magnitude of the heaviest rainfall events, in this case over the Indian monsoon region, through the Clausius-Clapeyron relationship.

Despite much uncertainty in their local distribution, mean rainfall changes over the Indian monsoon region predominantly range from zero to positive, and are negative in only one model (we reiterate the caveat that black carbon and

some other aerosol forcings are not represented in these model outputs). As hypothesized, changes to subseasonal precipitation extremes occurring in each season, are quite predictable based on the model-dependent pattern of mean change.

The CMIP3 database was also examined to determine if models other than HadCM3 display a close relationship between simulated changes in the heaviest monsoon rainfall events and theoretical predictions based on local surface warming and the Clausius-Clapeyron relationship. We have shown here that six of the 15 models tested suggest this to be the case. Of the remainder, six show that measured increases in the strength of the heaviest rainfall events exceed predicted changes by quite some margin, suggesting that there is some additional contribution to these extremes which is unrelated to local surface warming. This is in agreement with a hypothesis of Turner and Slingo (2009), that the local warming may provide a lower bound to the increase in the heaviest monsoon rainfall. It is intriguing why there is a small subset of models that do not even obey this lower bound and show virtually no change in heaviest rainfall despite, in some cases, an increase in the mean.

Although we have suggested that differences in the convective parameterization used may be at the root of this diversity, there remains scope for more careful analysis of these results. Of most interest is that some models which generally feature variants on the Arakawa-Schubert scheme show an additional component in their heaviest extremes, whereas others using bulk mass-flux schemes are more closely dependent on surface thermodynamic changes. Clearly the reasons for such differences, and the suitability of different schemes to the climate change problem, need to be urgently addressed.

Finally, it should be stressed that this study only applies to extremes over the Indian region, which represents an environment that is well supplied by atmospheric moisture through the south-west monsoon flow, such that the Clausius-Clapeyron relationship is likely to be a major constraint. It is not obvious that this result can be extended to more continental environments which are moisture limited and where changes in advection and dynamical feedbacks may be more critical.

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Captions

Figure 1: JJA precipitation differences between control and 1pctto2x at time of CO₂ doubling: (top) mean, (middle) 95th percentile (bottom) 99th percentile. Positive contours are solid, negative contours are dashed. Shown as 3 blocks of 5 models.

Figure 2: Spatial correlations between mean JJA precipitation change and change to various percentile extremes for India and the broad Asian monsoon region.

Figure 3: Model spread of precipitation magnitude increase due to greenhouse warming for the upper two quartiles for all points in the Indian region: (top) at time of CO₂ doubling (bottom) at CO₂ stabilization. Thick curves show median, spread gives interquartile range. Boxplots indicate max/min, interquartile range and median of the predicted increases to the heaviest rainfall.

Table 1: List of CMIP3 models used showing measured and predicted increases in intensity of the heaviest rainfall, and ranked by their ratio. Detailed references for convection schemes can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php Colouring indicates models using identical convection schemes. “AS” indicates Arakawa-Schubert. Also shown are changes in wind shear (U_{850} - U_{200} ; for region see text).

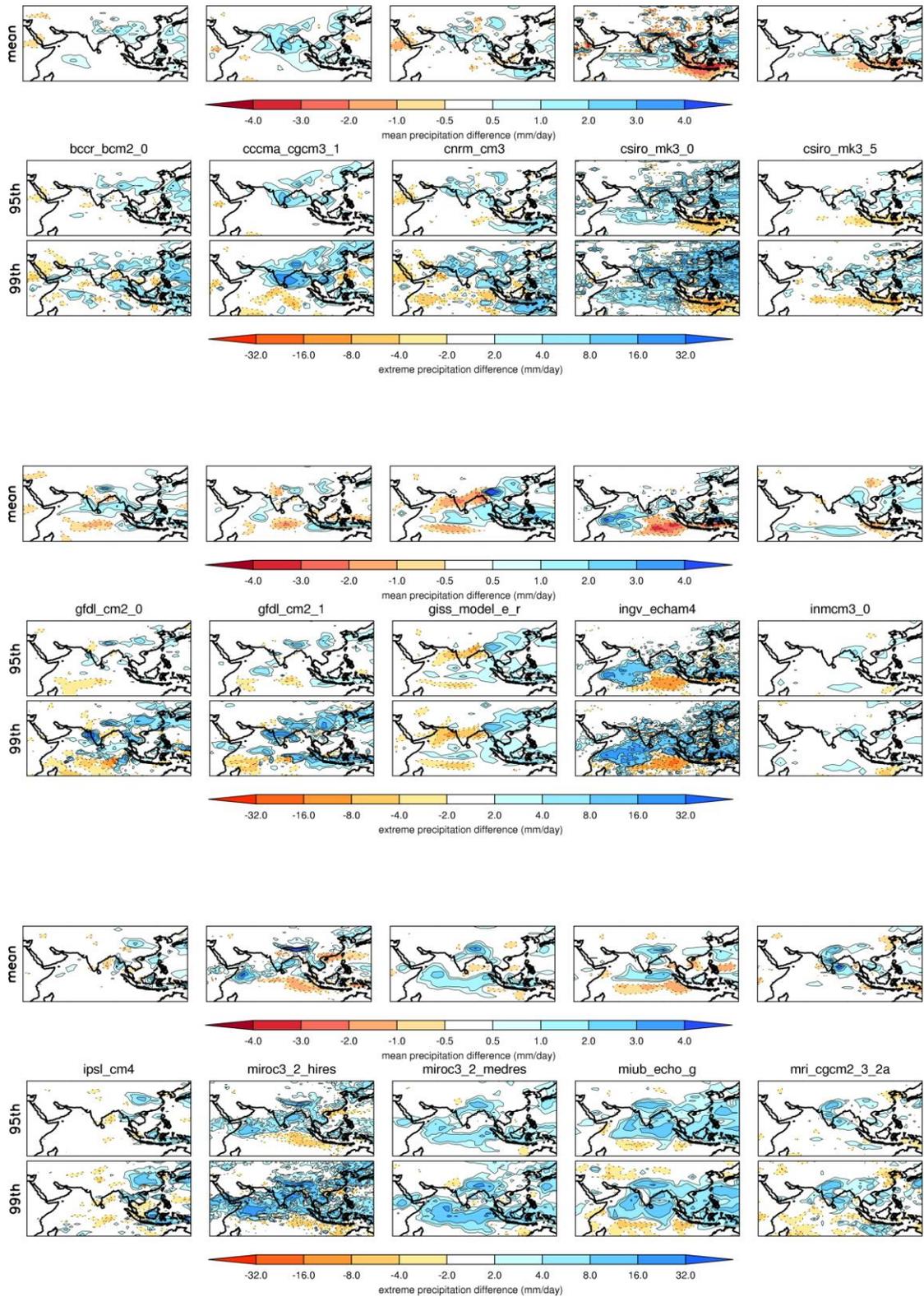
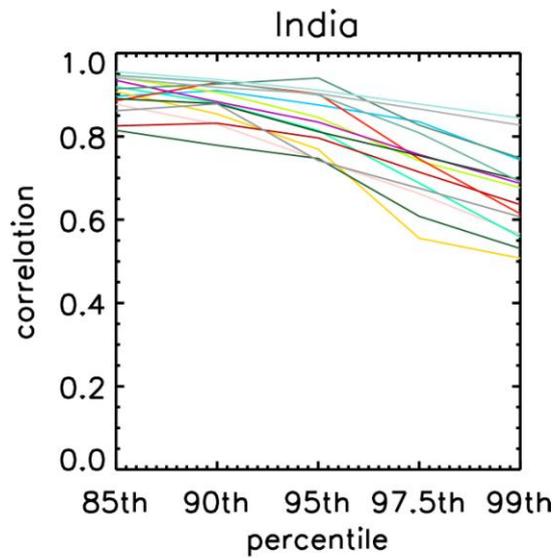


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- 1 bccr_bcm2_0
- 2 cccma_cgcm3_1
- 3 cnrm_cm3
- 4 csiro_mk3_0
- 5 csiro_mk3_5
- 6 gfdl_cm2_0
- 7 gfdl_cm2_1
- 8 giss_model_e_r
- 9 ingv_echam4
- 10 inmcm3_0
- 11 ipsl_cm4
- 12 miroc3_2_hires
- 13 miroc3_2_medres
- 14 miub_echo_g
- 15 mri_cgcm2_3_2a

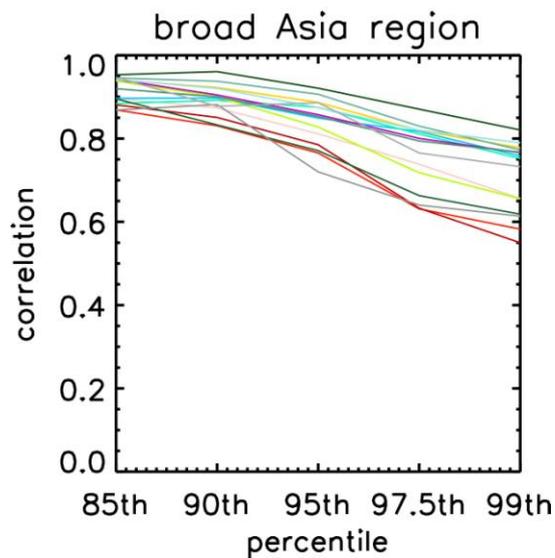


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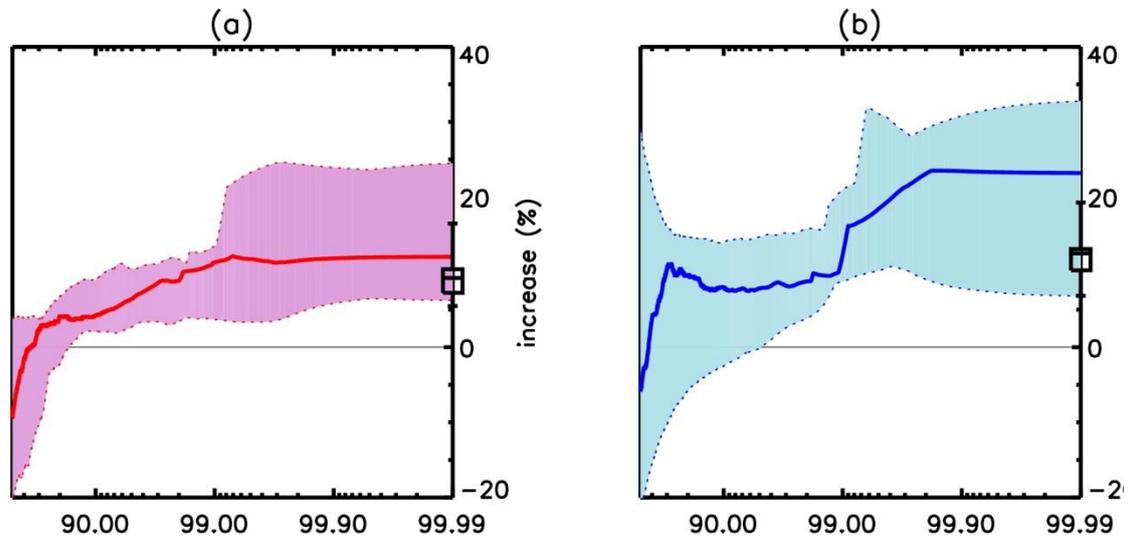


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model	measured (%)	predicted (%)	ratio	convection	Δ shear (m/s)
gfdl_cm2_0	50.71	8.65	5.86	Moorthi-Suarez relaxed AS	-1.84
csiro_mk3_0	34.16	9.97	3.43	Gregory-Rowntree mass flux	-1.51
gfdl_cm2_1	30.24	9.30	3.25	Moorthi-Suarez relaxed AS	-2.74
cccma_cgcm3_1	27.26	10.26	2.66	Zhang-MacFarlane variant on AS	-4.66
miroc3_2_medres	24.72	13.02	1.90	Pan-Randall prognostic AS	-6.47
miroc3_2_hires	23.33	14.81	1.58	Pan-Randall prognostic AS	-11.27
miub_echo_g	15.89	11.11	1.43	Tiedke mass flux	-1.96
csiro_mk3_5	7.09	5.23	1.36	Gregory-Rowntree mass flux	-1.51
mri_cgcm2_3_2a	12.07	10.79	1.12	Pan-Randall prognostic AS	-9.51
cnrm_cm3	8.92	9.78	0.91	mass flux with Kuo closure	2.63
ingv_echam4	8.87	9.93	0.89	Tiedke mass flux	-5.19
inmcm3_0	6.15	8.51	0.72	Betts; convective adjustment	-0.71
bccr_bcm2_0	1.87	8.15	0.23	mass flux with Kuo closure	-0.82
ipsl_cm4	-1.06	11.31	-0.09	Grandpeix variant on Emanuel mass flux	-2.87
giss_model_e_r	-1.33	12.21	-0.11	Del Genio-Yao mass flux	-12.01

Table 1: List of CMIP3 models used showing measured and predicted increases in intensity of the heaviest rainfall, and ranked by their ratio. Detailed references for convection schemes can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php. Colouring indicates models using identical convection schemes. “AS” indicates Arakawa-Schubert. Also shown are changes in wind shear ($U_{850}-U_{200}$; for region see text).