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Suppression of south Asian summer monsoon precipitation in the 21st century

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[1] We used a high-resolution nested climate modeling system to investigate the response of South Asian summer monsoon dynamics to anthropogenic increases in greenhouse gas concentrations. The simulated dynamical features of the summer monsoon compared well with reanalysis data and observations. Further, we found that enhanced greenhouse forcing resulted in overall suppression of summer precipitation, a delay in monsoon onset, and an increase in the occurrence of monsoon break periods. Weakening of the large-scale monsoon flow and suppression of the dominant intraseasonal oscillatory modes were instrumental in the overall weakening of the South Asian summer monsoon. Such changes in monsoon dynamics could have substantial impacts by decreasing summer precipitation in key areas of South Asia. **Citation:** Ashfaq, M., Y. Shi, W.-w. Tung, R. J. Trapp, X. Gao, J. S. Pal, and N. S. Diffenbaugh (2009), Suppression of south Asian summer monsoon precipitation in the 21st century, *Geophys. Res. Lett.*, 36, L01704, doi:10.1029/2008GL036500.

1. Introduction

[2] More than 22% of the world's population depends inextricably on the South Asian summer monsoon, which contributes as much as 75 percent of the total annual rainfall in major parts of the region [Dhar and Nandargi, 2003]. The substantial variability of onset and duration of the summer monsoon exerts a strong control on water resources, agriculture, economics, ecosystems, and human mortality throughout South Asia. Given the dependence of large populations on monsoon rainfall, the response of South Asian monsoon dynamics to elevated atmospheric greenhouse gas concentrations is an issue of both scientific and societal importance.

[3] To date, this response has been primarily studied through the application of general circulation models (GCMs), which show an uncertain response of summer monsoon precipitation [Intergovernmental Panel on Climate Change (IPCC), 2007]. Although they can capture large-scale climate features, current GCMs are more challenged by fine-scale climate processes, particularly those controlling climate extremes [e.g., Duffy et al., 2003]. To better simulate the response of such fine-scale climate system processes to

enhanced greenhouse forcing, we conducted a suite of high-resolution nested climate model simulations, offering an improved representation of the dynamics associated with physiographic complexity, land cover heterogeneity, and atmospheric convection.

2. Methods

[4] We applied the RegCM3 nested climate model, with parameterizations of convective, boundary layer, and land-surface processes following those of Pal et al. [2007]. Our main experiment was conducted at 25-km horizontal grid spacing with lateral boundary conditions provided by the NASA FVGCM [Atlas et al., 2005]. To test the robustness of simulated changes in this main experiment, we also conducted four additional experiments with 50 km horizontal grid spacing: two with varying initial conditions, one with increased vertical resolution, and one with boundary conditions provided by the NCAR CCSM3 [Collins et al., 2006]. For each experiment, we generated two model integrations, one covering the period 1961–1990 (“RF”) and one covering the late 21st century (“A2”) (see auxiliary material).¹

[5] We analyzed the simulated changes in the South Asian summer monsoon using multiple summer monsoon indices. Following Parthasarathy et al. [1992], we defined the precipitation index as the departure of rainfall from the climatological mean (1961–1990), averaged over land points between 70°–90°E and 5°–25°N. Following Goswami et al. [1999], we defined the local Hadley circulation index as the departure of the vertical meridional wind shear (between 850 mb and 200 mb) from the climatology (1961–1990), averaged over 70°–105°E and 5°–30°N. Observations show a positive correlation between the precipitation index and the local Hadley circulation index at interannual time-scale [Goswami et al., 1999]. Following Wang and LinHo [2002], we defined the climatological monsoon onset at each grid point for each 30-year model integration as the first pentad (5-day mean) in which the climatological mean precipitation exceeded 5 mm/day and the grid-point January mean. Following Webster et al. [1998], we defined the meridional tropospheric temperature gradient (MTG) as the difference of the five-day climatological mean temperature between the upper tropospheric layers (200mb to 500mb) at 30°N and 5°N, averaged over the zonal belt between 52°E and 85°E. The positive (negative) difference indicates that the upper tropospheric air is warmer (cooler) at 30°N than that at 5°N, representing the reversal of the MTG in the upper troposphere. The positive reversal of the MTG is concurrent with the monsoon onset and produces zonal winds with easterly vertical shear [Li and Yanai,

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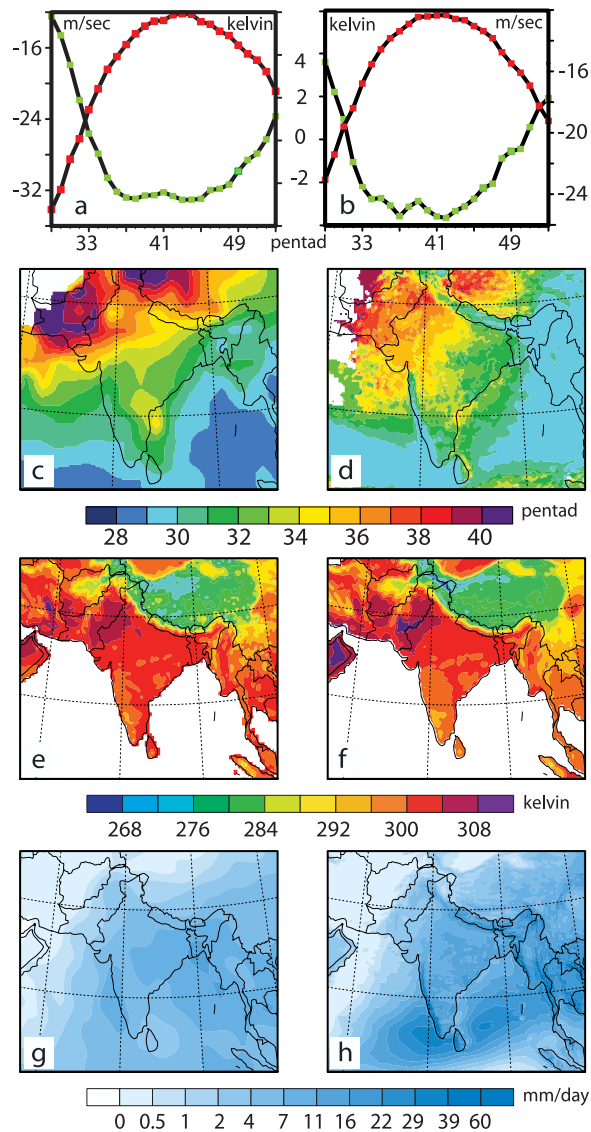


Figure 1. Climatological (1961–1990) meridional tropospheric temperature gradient (red) (K) and easterly vertical shear of zonal winds (green) (m/sec). (a) NCEP/NCAR reanalysis. (b) RegCM3. Climatological (1979–1990) summer monsoon onset (pentad). (c) CMAP observations. (d) RegCM3. Climatological (1961–1990) JJAS surface temperature (K). (e) Willmott Masure observations. (f) RegCM3. Climatological (1979–1990) JJAS precipitation (mm/day). (g) CMAP observations. (h) RegCM3.

1996]. Following *Goswami and Xavier* [2005] and *Li and Yanai* [1996], we calculated the easterly vertical shear of zonal winds as the difference of the five-day climatological mean of zonal winds between 200mb and 850mb averaged over 52° – 90° E and 0° – 15° N. A sustained easterly vertical shear of zonal winds with magnitudes stronger than 20 m/sec is important for the poleward propagation of the ITCZ that in turn maintains the South Asian summer monsoon strength [*Goswami and Xavier*, 2005].

[6] Following *Trapp et al.* [2007], we calculated the occurrence of CAPE–days as the number of days in which convective available potential energy (CAPE) was greater than 0.0 J/Kg. We applied the smoothed-periodogram

method to calculate the power spectrum of precipitation, using 30 years JJAS daily precipitation data averaged over 70° – 90° E and 5° – 25° N, which was passed through a 90-day lanczos high-pass filter to retain only the intraseasonal oscillatory modes. Finally, we defined active and break periods using the time-series of seven-day running averaged daily precipitation anomalies, which was normalized by its own standard deviation. An active (break) period was considered to occur when the precipitation anomaly was 0.5 SD (-0.5 SD).

3. Results

3.1. Model Performance

[7] RegCM3 reproduced a number of important features of the South Asian summer monsoon dynamics, including the seasonal structure of the MTG and easterly vertical shear (Figures 1a and 1b), the timing of monsoon onset over land (Figures 1c and 1d), the pattern of summer precipitation (Figures 1e and 1f) and temperature (Figures 1g and 1h), the correlation between local Hadley circulation and precipitation over land (Figures 2a and 2c), and the summer atmospheric circulation (Figure S1). Areas of disagreement

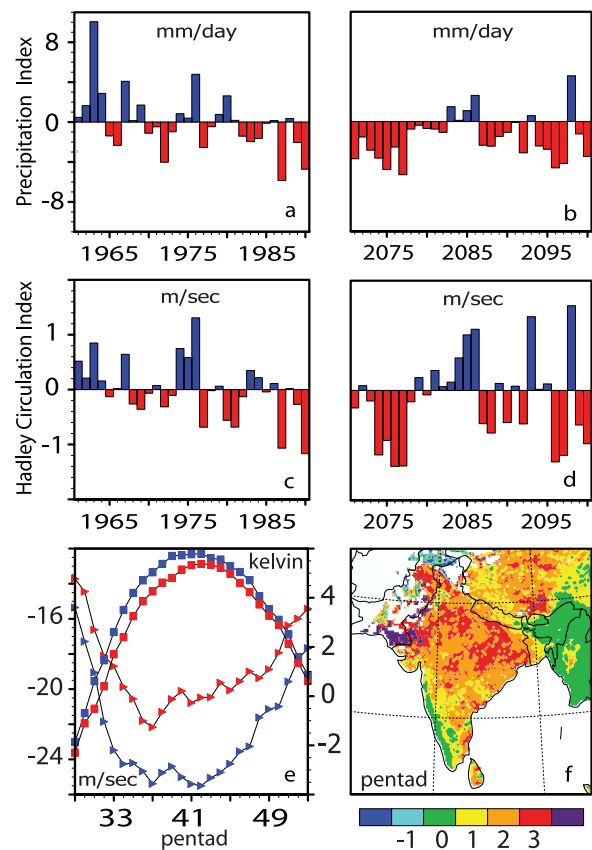


Figure 2. RegCM3 simulated interannual variation in precipitation index (mm/day) in (a) RF and (b) A2. RegCM3 simulated interannual variation in local Hadley circulation index (m/sec) in (c) RF and (d) A2. (e) RegCM3 simulated tropospheric temperature gradient (squares) (K) and easterly vertical shear of zonal winds (triangles) (m/sec) in RF and A2 integrations. RF is shown in blue and A2 is shown in red. (f) RegCM3 simulated changes (A2 minus RF) in summer monsoon onset dates (pentad).

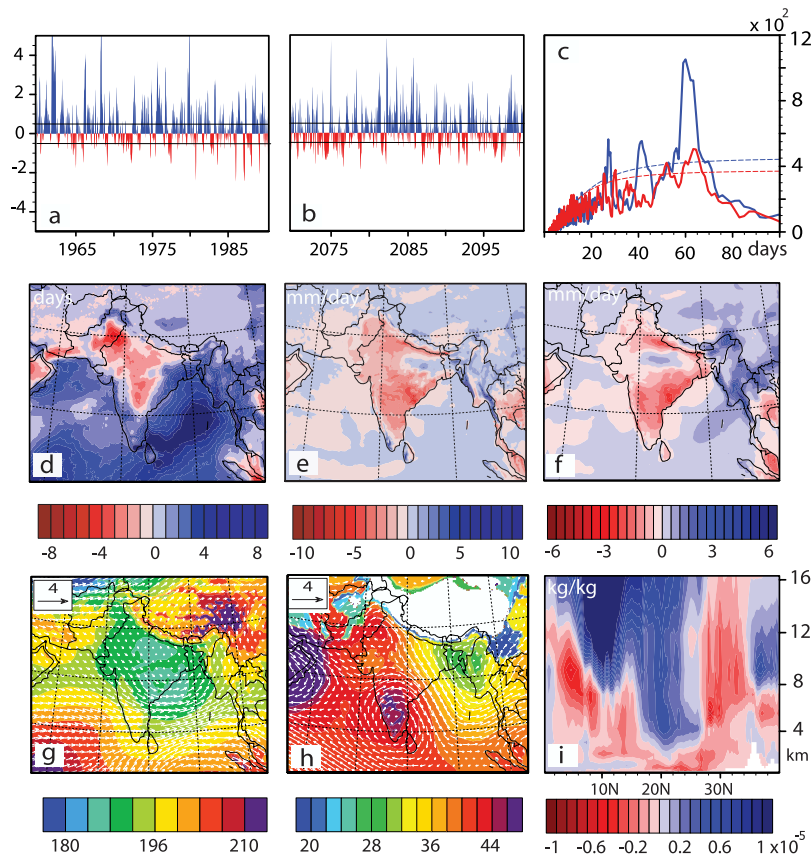


Figure 3. Summer monsoon active and break periods in (a) RF and (b) A2. (c) Power spectrum of summer monsoon precipitation in RF (blue) and A2 (red) integrations. The dotted lines represent 90% confidence level with respect to the red noise null hypothesis. RegCM3 simulated changes (A2 minus RF) in (d) number of JJAS CAPE-days (days/year), (e) convective precipitation (25km) (mm/day), (f) convective precipitation (ensemble mean) (mm/day) (g) JJAS 200 hPa geopotential height (m) and winds (m/sec), (h) JJAS 700 hPa geopotential height (m) and winds (m/sec), (i) zonal averaged (70E–90E) vertical distribution of cloud mixing ratio.

included warm bias over some desert and semi-desert regions, and wet bias over the ocean, the west coasts of India and Myanmar, and the lee side of the Western Ghats (Figures 1e–1h). However, some RegCM3 errors confirmed the dynamical link between the MTG and monsoon onset, with slightly early positive reversal of the MTG and occurrence of earliest monsoon onset over land in RegCM3. Similarly, although a weaker easterly flow in the upper-level (200mb) and a stronger westerly flow in the lower-level (850mb) (Figure S1) resulted in a relatively weaker easterly vertical shear in RegCM3 than that observed in the reanalysis data, it remained stronger than the critical value (20 m/sec) throughout the summer season in the reference simulation (Figures 1a and 1b).

3.2. Twenty-First Century Climate Change

[8] RegCM3 simulated a suppression of the summer monsoon in the A2 scenario, with increases in regional precipitation during the rest of the annual cycle (Figure S2). The local Hadley circulation index and the precipitation index, which were significantly correlated (2-sided t-test; 99% confidence level) in both the RF (0.67) and A2 (0.86) integrations, showed substantially greater occurrence of dry years in the A2 integration than in the RF integration (Figures 2a–2d). Further, the precipitation index from the ensemble mean of all RegCM3 integrations showed a

similar pattern of changes (Figure S3). This preponderance of dry years indicates an overall suppression of the South Asian summer monsoon precipitation and weakening of the local Hadley circulation.

[9] Similarly, the progress of monsoon onset towards the northwest was inhibited in the A2 integration, with onset dates over central India and northwest India and Pakistan delayed by 2–4 pentads (relative to the RF integration) (Figure 2f). The changes (A2 minus RF) in the monsoon onset reflected the changes in the MTG reversal, which was suppressed due to preferential warming of the upper troposphere in the south of the domain (Figure 2e). This MTG suppression was particularly pronounced between the 29th and 41st pentads, which at present encompass the period of monsoon onset over land (Figure 1c). Likewise, the easterly vertical shear of the zonal winds, which reached the critical strength (20 m/sec) in the 31st pentad in the RF integration, remained weaker than that threshold for much of the 29–41 pentad period in the A2 integration (Figure 2e). Further, the occurrence of break periods was greater in the A2 integration, due mainly to the suppression of the dominant intra-seasonal oscillatory modes (Figures 3a–3c).

[10] Changes in the occurrence of CAPE-days were generally negative throughout South Asia, with the largest decreases occurring over southern and central Pakistan, central India, and the southeastern part of the domain (Figure 3d).

Similarly, changes in convective precipitation were mostly negative over land (Figure 3e), and the spatial pattern of changes in mean convective precipitation was very similar between the 25 km simulation and the ensemble mean of all RegCM3 integrations (Figure 3f).

[11] In the upper troposphere (200 mb), changes in JJAS circulation were cyclonic over the Bay of Bengal and the Indian Peninsula, and anticyclonic over the northeast of South Asia (Figure 3g). These changes in upper-level monsoon circulation were associated with an eastward shift in the Tibetan anticyclone (Figure S4). Moreover, the anomalous westerly flow represented a weakened upper-level tropical easterly jet across the Indian subcontinent (Figure 3g). In the lower troposphere (700 mb), the changes in the JJAS wind circulations showed a decrease in the westerly flow over the Arabian Sea, indicating a weakening of the low-level westerly jet (Figure 3h). Additionally, east–west juxtaposition of cyclonic and anticyclonic changes in the circulation showed deepening of the monsoon trough over Bangladesh and the Bay of Bengal, and weakening of the monsoon flow over Pakistan and southwestern, central, and northwestern India. These changes in circulation were also associated with an eastward shift of the westerly jet (Figure 3h), as well as a northeastward shift in the southwesterly inland flow over the Bay of Bengal (Figure S4).

4. Discussion and Conclusions

[12] The monsoon suppression in the 21st century simulation is supported by the modern monsoon dynamics. For instance, the local Hadley circulation, which is driven by the north–south temperature gradient, determines the strength of cross equatorial flow and is correlated with the South Asian summer monsoon precipitation [Goswami *et al.*, 1999]. In the A2 integration, negative changes in the local Hadley circulation index (Figure 2d) associated with the increased subsidence over the Indian subcontinent acted to decrease the strength of cross equatorial flow, suppressing the overall summer monsoon precipitation (Figure 2b). Likewise, the MTG drives monsoon onset and development of the easterly vertical shear of zonal winds, which in turn maintains the seasonal migration of the ITCZ [e.g., Li and Pan, 2006]. In addition to the hot and dry conditions in June over Central India (Figures 3i and S5), the pronounced suppression of the MTG in the A2 integration contributed to the delay in monsoon onset (Figures 2e and 2f). Similarly, the wind shear sets up a necessary environment for baroclinic instability, which, combined with convective heating, results in disturbances such as monsoon depressions [e.g., Shukla, 1977]. In the A2 integration, the sub-critical easterly vertical shear associated with suppressed MTG weakened the baroclinic instability, which, combined with the weak cross equatorial flow, restricted development of northward propagating intraseasonal oscillations. This suppression of the intraseasonal oscillatory modes in turn increased the occurrence of break periods in the A2 integration (Figures 3a–3c). In addition, the simulated eastward shift of the Tibetan anticyclone (Figure S4) and weakening of the easterly jet (Figure 3g) also contributed to the overall suppression of the summer monsoon precipitation in the A2 integration, as is seen in observational correlations [Rao *et al.*, 2004].

[13] The shift towards weaker lower-level southwesterly flow and less cyclonic lower-level circulation over land reduced the inland flow of moist air from the Bay of Bengal (Figures 3h and S4), possibly decreasing the cloud moisture (Figure 3i) through the entrainment of ambient dry air and limiting the development of deep convection over South Asian land areas (Figures 3d–3f). In fact, although RegCM3 simulated an increase in non-convective summer precipitation over most of the subcontinent (Figure S5), it showed a decrease in the convective precipitation (Figure 3e), which dominated the net regional precipitation change over land (Figures 2b and S5). At the same time, cyclonic changes in monsoon circulation and enhanced moisture supply over Bay of Bengal, Bangladesh and Northeastern India made conditions conducive for deep convection and hence increased precipitation in the east of the domain (Figures 3e and S5).

[14] GCM projections show an equivocal response of South Asian summer monsoon circulation [IPCC, 2007], particularly if we consider only those GCMs which can realistically simulate the basic state of the South Asian summer monsoon [Annamalai *et al.*, 2007] (Figure S6). Moreover, simulated increases in South Asian precipitation are reduced when the CMIP3 GCM experiments are calibrated—and in some areas the sign of change is reversed—highlighting the uncertainty in the GCM simulations that were used in the IPCC AR4 [Palmer *et al.*, 2008]. In our experiments, RegCM3 and FVGCM simulated similar changes in precipitation throughout the summer months, with the exception of Central India in June, where FVGCM simulated increases in precipitation (Figure S6). This difference can be attributed to the RegCM3-simulated negative changes in CAPE-days and strongly positive changes in June surface temperature over Central India (Figures 3d and S5), which, along with the depleted cloud moisture in the lower-levels (Figure 3i), made conditions less conducive for the moist convection over Central India (Figure 3e).

[15] The simulated response of South Asian summer monsoon precipitation in the high-resolution climate model experiment was robust to variations in initial conditions, vertical resolution, and driving GCM (e.g., Figures 3f and S3). However, we note a number of caveats in our results. First, biases do exist in the nested climate model. In some cases, these biases may cancel when considering the net climate change. For instance, RegCM3 shows a similar precipitation bias over the lee side of Western Ghats in both the reference and future periods (not shown). However, biases that affect threshold responses, such as snow-albedo feedback, may affect the magnitude of the simulated climate change. Second, although we have used a modeling configuration with substantially greater horizontal resolution than previous high-resolution climate change experiments for South Asia [Kumar *et al.*, 2006], our convective parameterization was inadequate to resolve the relationship among convective organization, orography and the diurnal cycle, which influences the life cycle and spatial coherence of large-scale circulations in the tropics [Neale and Slingo, 2003]. In addition, we did not consider regional-scale atmosphere–ocean feedbacks (which could influence Indian Ocean sea surface temperatures [Seo *et al.*, 2007]), and the possibility of differences introduced by the nesting procedure requires further exploration.

[16] Despite these caveats, the projected changes in the South Asian summer monsoon could have important implications for human health, ecosystems, and already-stressed natural resources. For instance, agricultural production, water availability and hydroelectric power generation could be substantially affected by delayed monsoon onset and reduced surface runoff [e.g., Mall *et al.*, 2006]. Alternatively, increases in precipitation over Bangladesh could exacerbate seasonal flood risks. Intensified heat stress associated with increased monsoon breaks could increase heat-related morbidity and mortality [Patz *et al.*, 2005], as well as local extinction of temperate vegetation types [Malcolm *et al.*, 2002]. The variations in the sign and magnitude of precipitation change throughout South Asia highlight the importance of spatial complexity in the climate response, and suggest that understanding the potential impacts of future climate change in this region requires improved understanding of a host of climate processes.

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References

- Annamalai, H., et al. (2007), The south Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations, *J. Clim.*, *20*, 1071–1092.
- Atlas, R., O. Reale, B.-W. Shen, S.-J. Lin, J.-D. Chern, W. Putman, T. Lee, K.-S. Yeh, M. Bosilovich, and J. Radakovich (2005), Hurricane forecasting with the high-resolution NASA finite volume general circulation model, *Geophys. Res. Lett.*, *32*, L03807, doi:10.1029/2004GL021513.
- Collins, W. D., et al. (2006), The Community Climate System Model version 3 (CCSM3), *J. Clim.*, *19*, 2122–2143.
- Dhar, O. N., and S. Nandargi (2003), Hydrometeorological aspects of floods in India, *Nat. Hazards*, *28*, 1–33.
- Duffy, P. B., et al. (2003), High-resolution simulations of global climate, part 1: Present climate, *Clim. Dyn.*, *21*, 371–390.
- Goswami, B. N., and P. K. Xavier (2005), ENSO control on the south Asian monsoon through the length of the rainy season, *Geophys. Res. Lett.*, *32*, L18717, doi:10.1029/2005GL023216.
- Goswami, B. N., et al. (1999), A broad-scale circulation index for the interannual variability of the Indian summer monsoon, *Q. J. R. Meteorol. Soc.*, *125*, 611–633.
- Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Kumar, K. R., et al. (2006), High-resolution climate change scenarios for India for the 21st century, *Curr. Sci.*, *90*, 334–345.
- Li, C. F., and M. Yanai (1996), The onset and interannual variability of the Asian summer monsoon in relation to land sea thermal contrast, *J. Clim.*, *9*, 358–375.
- Li, C. Y., and J. Pan (2006), Atmospheric circulation characteristics associated with the onset of Asian summer monsoon, *Adv. Atmos. Sci.*, *23*, 925–939.
- Malcolm, J. R., et al. (2002), Estimated migration rates under scenarios of global climate change, *J. Biogeogr.*, *29*, 835–849.
- Mall, R. K., et al. (2006), Impact of climate change on Indian agriculture: A review, *Clim. Change*, *78*, 445–478.
- Neale, R., and J. Slingo (2003), The maritime continent and its role in the global climate: A GCM study, *J. Clim.*, *16*, 834–848.
- Pal, J. S., et al. (2007), Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET, *Bull. Am. Meteorol. Soc.*, *88*, 1395–1409.
- Palmer, T. N., et al. (2008), Toward seamless prediction: Calibration of climate change projections using seasonal forecasts, *Bull. Am. Meteorol. Soc.*, *89*, 459–470.
- Parthasarathy, B., et al. (1992), Indian-summer monsoon rainfall indexes—1871–1990, *Meteorol. Mag.*, *121*, 174–186.
- Patz, J. A., et al. (2005), Impact of regional climate change on human health, *Nature*, *438*, 310–317.
- Rao, B. R. S., D. V. B. Rao, and V. B. Rao (2004), Decreasing trend in the strength of Tropical Easterly Jet during the Asian summer monsoon season and the number of tropical cyclonic systems over Bay of Bengal, *Geophys. Res. Lett.*, *31*, L14103, doi:10.1029/2004GL019817.
- Seo, H., et al. (2007), The Scripps Coupled Ocean Atmosphere Regional (SCOAR) model, with applications in the eastern Pacific sector, *J. Clim.*, *20*, 381–402.
- Shukla, J. (1977), Barotropic-baroclinic instability of mean zonal wind during summer monsoon, *Pure Appl. Geophys.*, *115*, 1449–1461.
- Trapp, R. J., et al. (2007), Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 19,719–19,723.
- Wang, B., and LinHo (2002), Rainy season of the Asian-Pacific summer monsoon, *J. Clim.*, *15*, 386–398.
- Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari (1998), Monsoons: Processes, predictability, and the prospects for prediction, *J. Geophys. Res.*, *103*, 14,451–14,510.
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