LETTERS
PUBLISHED ONLINE: 28 APRIL 2014 | DOI: 10.1038/NCLIMATE2208

nature climate change

Observed changes in extreme wet and dry spells during the South Asian summer monsoon season

Deepti Singh[1*], Michael Tsiang[1], Bala Rajaratnam[1,2,3] and Noah S. Diffenbaugh[1,2]

The South Asian summer monsoon directly affects the lives of more than 1/6th of the world's population. There is substantial variability within the monsoon season, including fluctuations between periods of heavy rainfall (wet spells) and low rainfall (dry spells)[1]. These fluctuations can cause extreme wet and dry regional conditions that adversely impact agricultural yields, water resources, infrastructure and human systems[2,3]. Through a comprehensive statistical analysis of precipitation observations (1951–2011), we show that statistically significant decreases in peak-season precipitation over the core-monsoon region have co-occurred with statistically significant increases in daily-scale precipitation variability. Further, we find statistically significant increases in the frequency of dry spells and intensity of wet spells, and statistically significant decreases in the intensity of dry spells. These changes in extreme wet and dry spell characteristics are supported by increases in convective available potential energy and low-level moisture convergence, along with changes to the large-scale circulation aloft in the atmosphere. The observed changes in wet and dry extremes during the monsoon season are relevant for managing climate-related risks, with particular relevance for water resources, agriculture, disaster preparedness and infrastructure planning.

The Indian subcontinent receives 85% of its annual rainfall during the South Asian summer monsoon season[3]. As >56% of the total agricultural area in the region is rain-fed, the monsoon is particularly important for the agricultural sector. For example, prolonged dry spells during July–August substantially reduce yields of 'Kharif' (monsoon) crops if the dry spells coincide with soil preparation, transplanting or the critical crop growth period[2]. The occurrence of severe monsoon droughts can also adversely affect 'Rabi' (winter) crops, cause livestock mortality and damage natural ecosystems[4]. As ~60% of India's working population depends on agricultural activities for their livelihood, and agricultural products account for nearly 70% of the country's exports[2], dry extremes can cause cascading impacts on India's economy[2], and national and global food security[3]. Similarly, short periods of extremely wet conditions can have large humanitarian impacts, such as the mortality, disease and homelessness that followed extremely heavy precipitation in Mumbai in July 2005 (ref. 5).

The monsoon 'core' over Central India (18°–28° N and 73°–82° E; ref. 6) experiences high average rainfall and daily-scale variability during the peak-monsoon season (July–August; Supplementary Fig. 1; ref. 7). The interaction between multiple modes of propagating intraseasonal oscillations (10–20 day and 30–50 day) of the Indian summer monsoon[8] causes intermittent wet and dry spells over this region. Extreme wet and dry spells (Fig. 1c–f) are commonly referred to in the literature as active and break spells[6–8]. As Central India encompasses several river basins that contain high population densities and large areas of crop cultivation, rainfall extremes over this region have a particularly strong influence on agriculture and water management.

Using rigorous statistical methods, we evaluate whether extreme wet and dry spell characteristics have changed between two periods of the observed record (1951–1980 and 1981–2011; see Methods for details). Our analyses emphasize the robustness of the employed hypothesis testing method to a number of sources of uncertainty. First, given the daily-scale persistence in atmospheric variables, we employ a methodology to account for temporal dependence in the precipitation time series. Second, we use less-restrictive, non-parametric statistical techniques to evaluate the significance of changes and make comparisons with recent studies that have failed to detect changes in wet and dry spell characteristics[7,9]. Third, we assess the sensitivity of our results to the selection of observational data set, spatial domain and analysis period.

The mean July–August rainfall shows a significant (10% significance level) decreasing trend since 1951 over the monsoon 'core' in the Indian Meteorological Department (IMD) data set (Fig. 1a), consistent with reported decreases in all-India rainfall[3]. This decrease in mean rainfall occurs despite the increases in seasonal-mean low-level moisture convergence and convective available potential energy (CAPE; see seasonal anomalies in Supplementary Fig. 4) expected from increased moisture availability in response to atmospheric warming.

In contrast, the July–August daily rainfall variability shows a statistically significant (5% significance level) increasing trend (Fig. 1a). The contrasting trends in mean rainfall and daily-scale variability collectively arise from the decreasing probability of regional rainfall events (Fig. 1a) and higher variability in the intensity of those events (Supplementary Fig. 2). In addition, we observe a 2 mm d^{-1} decrease in peak rainfall during the 1981–2011 period, along with increases in the frequency of both light (<6 mm d^{-1}) and heavy (>20 mm d^{-1}) rainfall events[10] (Fig. 1b). The statistical significance of these changes is highly sensitive to the modelling of the temporal dependence in daily precipitation. For instance, in testing the difference in means of the daily precipitation distributions in 1951–1980 and 1981–2011 the p value increases from 0.001 when each day is considered independent to 0.06 after accounting for the temporal dependence. Accounting for temporal dependence (daily-scale autocorrelation) using the moving-block boostrap thus more fairly reflects the strength of the scientific conclusion.

The observed decrease in seasonal precipitation has been previously reported[3,11], with large-scale multi-decadal climate

[1]Department of Environmental Earth System Science, Stanford University, California 94305, USA, [2]Woods Institute for the Environment, Stanford University, California 94305, USA, [3]Department of Statistics, Stanford University, California 94305, USA. *e-mail: singhd@stanford.edu

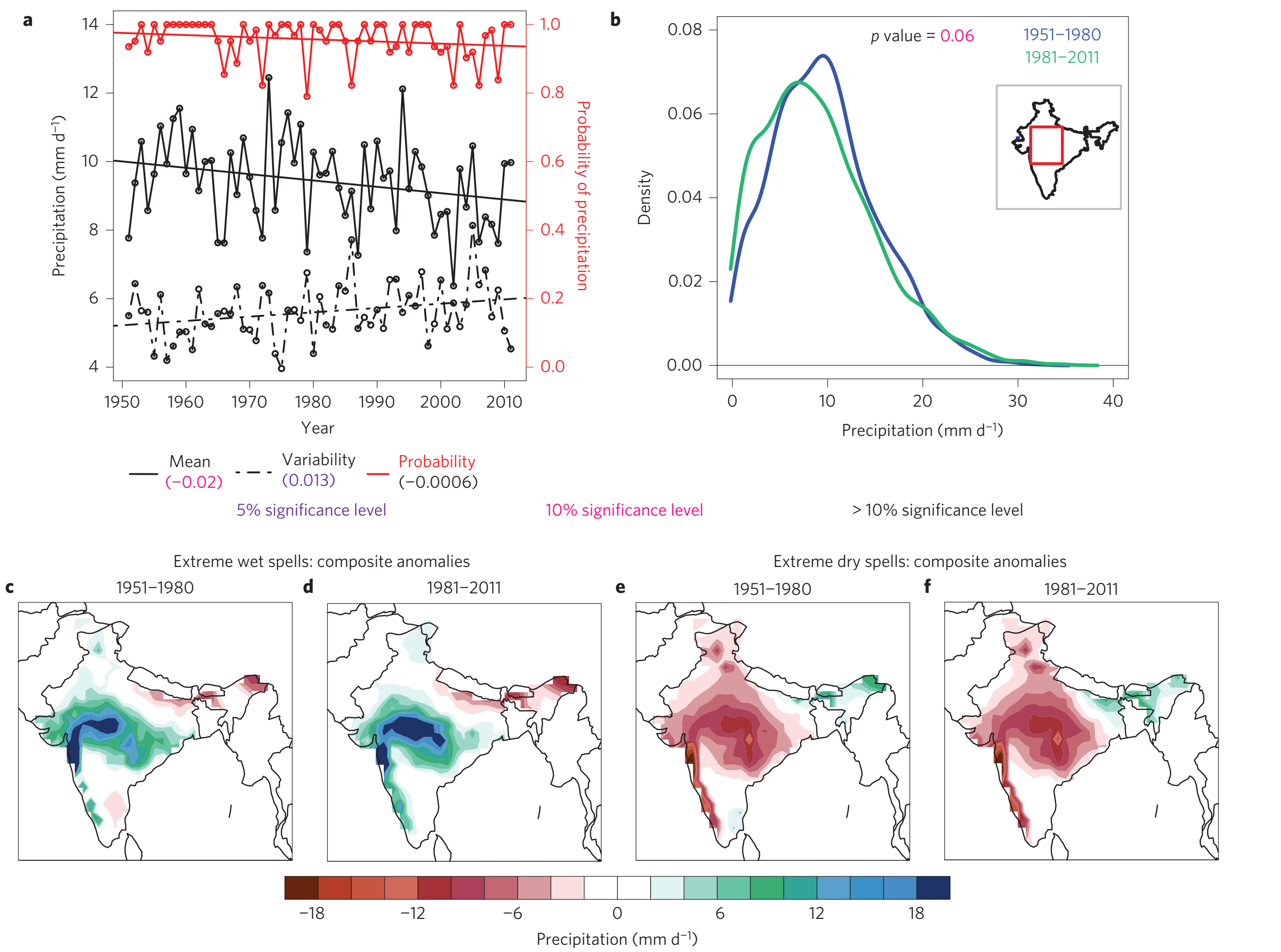

Figure 1 | July–August precipitation characteristics. **a**, Time series of mean precipitation, daily-variability and probability of daily precipitation (fraction of total days with precipitation >1 mm d^{-1}) over the monsoon 'core' (red rectangle in the inset map in **b**, 18°–28° N, 73°–82° E; ref. 6). Numbers indicate linear trend magnitudes of the time series. **b**, Daily precipitation distributions over the 'core' in 1951–1980 and 1981–2011 and the *p* value obtained from testing the difference in means of the distributions. Colours indicate the significance of trends (**a**) and *p* values (**b**). **c**–**f**, Composite precipitation anomalies from the July–August 1951–2011 mean for all extreme wet/dry spells in 1951–1980 (**c**,**e**) and 1981–2011 (**d**,**f**).

variability[3,12] and anthropogenic aerosol forcing[11,13] both suggested as possible causes. However, the observed record of wet and dry spells, which are weakly correlated to seasonal precipitation[8], has received considerably less attention[7,9]. The use of different spatial domains, statistical thresholds and definitions of wet and dry spells[1,6,7] leads to contradictory results[7,9,10]. Given the severe impact of hydroclimatic extremes in the present climate, effectively managing climate-related risks[14] requires rigorous evaluation of whether the characteristics of such events have changed substantially in recent decades[15].

Wet spells vary in frequency from 0 to 3 events per year over the observed record (Fig. 2a). Although trend identification is difficult given multi-decadal climate variability, our analyses reveal an increasing trend in wet spell frequency from 1951 to 1980, and a decreasing trend thereafter. Heavy rainfall during wet spells results from monsoon depressions and cyclonic storms that typically form in the Bay of Bengal and move northwestward into the monsoon trough[8]. The decreasing trend in wet spell frequency in the more recent period is therefore consistent with the decreasing number of monsoon depressions over the Bay of Bengal[16]. However, the difference in wet spell frequency between 1951–1980 and 1981–2011 is not statistically significant (Fig. 2a). Similarly, 1981–2011 exhibits more years with seasonal-mean wet spell duration exceeding 4 days but the mean duration has not changed significantly (Fig. 2c). Given that the wet spell duration depends on the timescale of synoptic systems (typically 3 to 4 days), the mean duration may not change without substantial changes in the general circulation of the atmosphere. In addition, we find no substantial difference in the average cumulative wet spell days between 1951–1980 and 1981–2011 (Fig. 2d). However, a significant increasing trend (5% significance level) in wet spell intensity is evident after 1980, and the mean wet spell intensity is significantly higher in 1981–2011 relative to 1951–1980 (Fig. 2b).

Dry spell frequency typically ranges from 0 to 4 events per season over the observed record (Fig. 2e). A number of hypotheses predict that global-warming-induced intensification of the hydrologic cycle should increase dry spell lengths (for example, ref. 17). This phenomenon has been observed over India in the late twentieth century annually[17] and during the monsoon season[18]. Although we find an increasing trend in the duration and cumulative length of extreme dry spells during the peak monsoon season (Fig. 2g,h), their average values are not significantly different between 1951–1980 and 1981–2011. However, there are more than twice as many years with 3 or more dry spells in 1981–2011 as in 1951–1980, and the dry spell frequency is 27% greater in 1981–2011 (1.4 events per season compared with 1.1 events per season in 1951–1980), a difference that is statistically significant at the 5% level. In addition, dry spells are

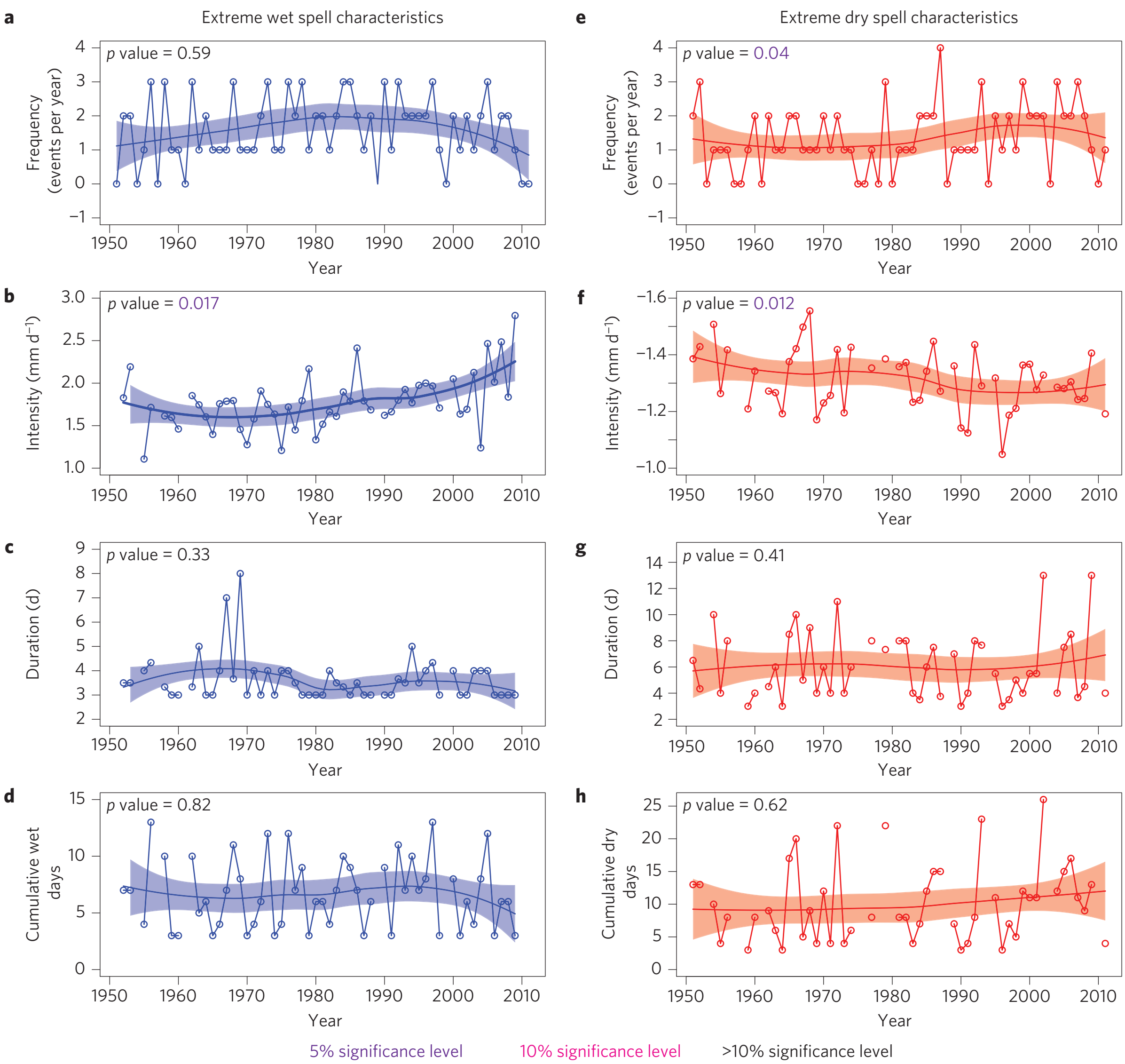

Figure 2 | Extreme wet and dry spell characteristics. a–h, Time series of wet (blue) and dry (red) spell frequency, duration, intensity and cumulative days over the core monsoon domain (see Methods for definitions). Missing links in the time series are years with no wet or dry spells. Trend lines are estimated using the non-parametric LOESS regression technique; shading represents the 90% confidence intervals of the estimated trends. *p* values are obtained from testing the difference in means of the distributions of each variable between 1951–1980 and 1981–2011 using the non-parametric moving block bootstrap test. Colours indicate the significance level of the *p* values.

on average 5% less intense in 1981–2011 (Fig. 2f), a difference that is also statistically significant at the 5% level.

Taken together, our analyses indicate a shift in the recent period towards more intense wet spells and more frequent but less intense dry spells (Figs 1d,f and 2). We use the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis to create composites of the atmospheric conditions during individual events in 1951–1980 and 1981–2011. This analysis reveals changes in the atmospheric conditions in which extreme wet and dry spells have occurred (with the important caveat that the number and quality of observations assimilated into the reanalysis has changed through time, including assimilation of satellite observations in the later period).

First, wet spells are typically associated with a strengthened low-level (850 mb) cyclonic circulation over the monsoon 'core' (Fig. 3a). We find that the wet spells during 1980–2011 exhibit enhanced moisture convergence and increases in CAPE over much of this region, without substantial changes in the low-level cyclonic circulation anomalies (Fig. 3f,g). These conditions are supportive of stronger convective activity[19], particularly over the southern and eastern parts of the region. Further, increased CAPE over the Bay of Bengal (Fig. 3g) is also a likely contributor to the observed intensification of severe storms[20] that should support more intense rainfall during wet spells.

Second, dry spells are often associated with anomalous anti-cyclonic circulation in the lower troposphere, which leads to divergence over the monsoon 'core' (Fig. 3c). In addition, the anomalous upper-tropospheric cyclonic anomaly over Central Asia leads to cold air advection from the mid-latitudes[21] (Fig. 3e). The statistically significant decreases in dry spell intensity in the more recent period (Fig. 2f) are consistent with the weaker low-level divergence and greater CAPE seen in the 1981–2011 period, and the reduced strength of the upper-level cyclonic anomaly (which reduces the extent of cold air advection that would otherwise dampen deep-convective activity; Fig. 3h–j).

Third, the frequency of occurrence of both wet and dry events is influenced by the northward propagation of convective instabilities that originate in the equatorial Indian Ocean and northwest tropical

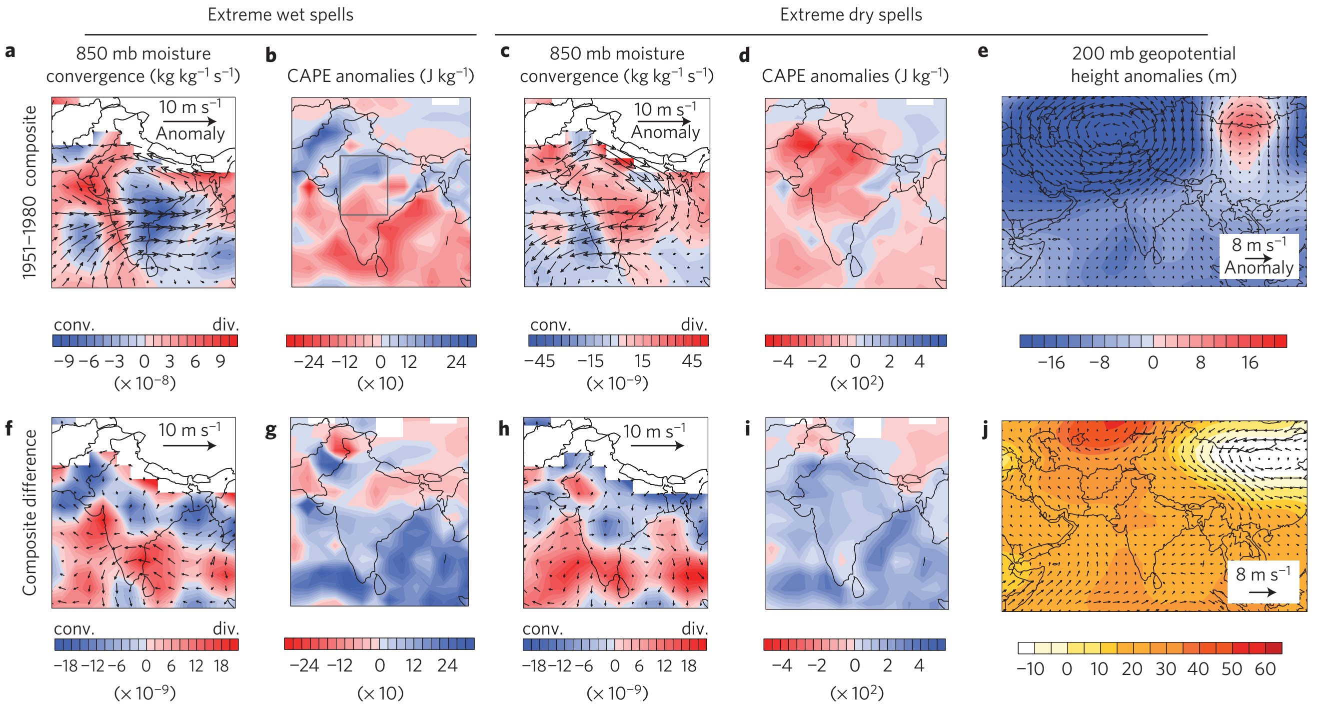

Figure 3 | Dynamics of extreme wet and dry spells. **a–e**, Composite values of 850 mb moisture convergence (conv.) or divergence (div.), and composite anomalies of 200 mb and 850 mb winds, 200 mb geopotential heights and CAPE, for 1951–1980. Composite values are calculated by averaging the variable on all extreme wet/dry days. Composite anomalies are differences between composite values and the average of all July–August days in the analysis period. **f–j**, Differences in composite values/anomalies in 1981–2011 relative to 1951–1980. (See Supplementary Fig. 3 for significance of differences.) Grey rectangle in **b** defines the primary analysis domain.

Pacific[1]. High vertical-wind shear in these regions is conducive to the formation of these convective instabilities[21]. Weakened seasonal-mean upper and lower-level winds in the 1981–2011 period have reduced the zonal wind shear over the equatorial Indian Ocean (see seasonal anomalies in Supplementary Fig. 4), a change that would be expected to lead to fewer wet periods and more dry periods by suppressing the formation of moist convective anomalies.

Given the statistical significance of the identified trends in wet and dry spell characteristics, and the changes in the associated atmospheric conditions, we test the sensitivity of the statistical analysis to potentially arbitrary climate definitions. In comparing the IMD data set to a second precipitation synthesis, we find similar trends in mean precipitation, daily-scale variability and dry spell characteristics (Supplementary Section 4). We also explore the sensitivity of the significance testing to the choice of analysis periods, particularly given the abrupt shift towards warmer sea surface temperatures in the central-Pacific, eastern-Pacific and Indian oceans[22] around 1976–1977. We find that the changes in the wet and dry spell characteristics are robust (at the 10% significance level) to the selection of the cutoff year of the analysis periods (Supplementary Table 1 and Section 4).

We also compare the core-monsoon domain to two larger domains (Fig. 4). We find that all three domains exhibit similar trends in mean precipitation and daily-scale variability, although the magnitude and significance of these trends differ (Supplementary Fig. 7). These differences are not unexpected given the observed spatially heterogeneity in rainfall trends across the subcontinent[18,23]. In addition, as with our core-monsoon domain (Fig. 1b), daily rainfall distribution over the all-India domain of ref. 1 exhibits a similar statistically significant (10% significance level) shift (Supplementary Fig. 7). We also find agreement in the direction of trends in dry spell characteristics across domains, although the changes in dry spell characteristics over the two larger domains are not significant at the 10% level (Fig. 4b and Supplementary Fig. 8). For the wet spell characteristics only the positive trend in wet spell frequency shows a consistent sign across the three domains (Fig. 4a). As with the observed spatial heterogeneity in daily rainfall trends (Supplementary Fig. 7), the changes in wet spell characteristics over the past 60 years vary within all three domains (Supplementary Fig. 8). These discrepancies are expected as a result of the spatial patterns associated with the occurrence of wet and dry spells[7,8] (Fig. 1d,f), and with the spatial heterogeneity of the changes in atmospheric conditions (Fig. 3f–j).

The heterogeneous spatial response of the wet and dry spell characteristics (Supplementary Fig. 7) and associated atmospheric conditions (Fig. 3f–j) within the larger monsoon domain highlight the need to investigate different scales of atmospheric variability, and the impact of local- and regional-scale forcings such as aerosols and land-use change. Aerosol accumulation over the Ganges basin and the Himalayan foothills can potentially influence the transition of dry to wet spells by modifying the lower-atmosphere meridional temperature gradient that drives moisture convergence[24]. However, understanding the relative influence of individual anthropogenic forcings[25] on the observed trends requires a formal attribution framework.

Given the heavy dependence of agriculture on rainfall[2] and the acute human vulnerability to flood events, the increases in dry spell frequency and wet spell intensity identified in our results represent increasing climate-related risks in the Indian subcontinent[26]. Rapid population growth and land-use change combined with groundwater depletion[27] suggest simultaneously increasing exposure and vulnerability to these events. Although we have identified proximal changes in the atmospheric environment that are supportive of the trends identified in our statistical analyses, improved understanding of the root causes of the identified trends is essential for formulating effective strategies for managing the evolving risks of extreme wet and dry events[28].

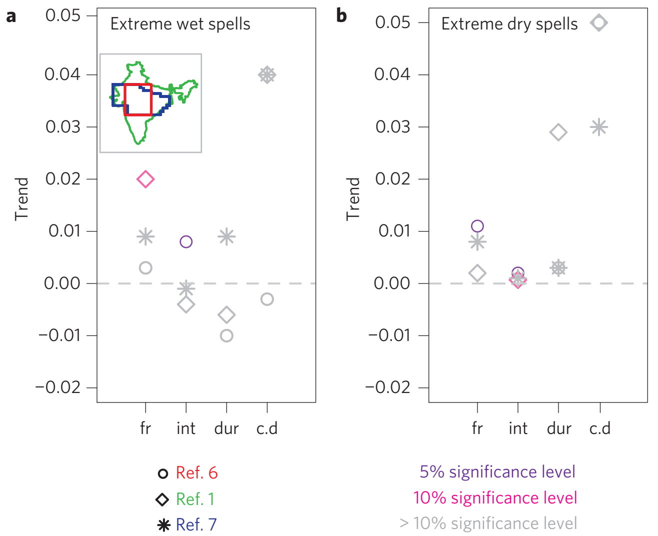

Figure 4 | Sensitivity of statistical results to spatial domain. a,b, Trends in extreme wet (**a**) and dry (**b**) spells characteristics (frequency (fr) events in a year per year), intensity (int) mm d^{-1} per year, duration (dur) days per year and cumulative days (c.d.) days per year derived from precipitation over three domains (see inset map—ref. 6 (red), ref. 1 (green), and ref. 7 (blue)). Colours indicate the significance level of *p* values from the significance test comparing the mean of the distributions of wet and dry spell characteristics in 1951–1980 and 1981–2011. (Supplementary Fig. 7 for the time series of these characteristics over the three domains.)

Methods

Data sets. The primary data set for our analysis is the 1° × 1° gridded daily precipitation data from the IMD (ref. 7). This is developed from approximately 2,140 rain-gauge stations using the Shepard interpolation methodology[7], and has been extensively used in the literature[9,18,23]. We test the sensitivity of the results using the newer APHRODITE data set[29], which includes fewer stations over India (see Fig. 11b in ref. 29), and has not yet been used in published studies of daily precipitation characteristics over India (Supplementary Section 1).

Characteristics of extreme wet and dry spells. Our analyses focus on the characteristics of extreme wet and dry spells during the July–August period, when the monsoon is established over the entire subcontinent[7]. Our core-monsoon region (18°–28° N and 73°–82° E) is similar to that of refs 6,21, and is defined over central India, a region that exhibits high mean seasonal precipitation and high daily-scale precipitation variability (Supplementary Fig. 1). This region experiences wet and dry spells associated with fluctuations in the location of the continental tropical convergence zone, which lead to strong precipitation anomalies[7]. We test the sensitivity of our results by comparison with the domains of refs 1,7.

Previous studies have used different atmospheric variables such as outgoing long-wave radiation[21], upper-level winds[30] and precipitation[1,6,7] to define active and break periods within the monsoon season. Following several studies[1,6,7,9], we use precipitation anomalies to focus on extreme wet and dry spells. We define extreme wet and dry spells based on de-trended precipitation anomalies to exclude the influence of the seasonal mean precipitation trend. We first remove the time-varying mean from the area-averaged daily precipitation time series over the selected domain and normalize those anomalies by the standard deviation (daily-scale variability) of precipitation over the entire record (1951–2011 for IMD, and 1951–2007 for APHRODITE). Next, we define wet and dry spells as events of at least 3 consecutive days with precipitation anomalies consistently exceeding one standard deviation of daily precipitation[7]. We then calculate the time series of frequency, duration intensity and cumulative days of wet and dry spells, where the frequency is the total number of wet (dry) spells in a given season, the duration of each spell is the number of consecutive days with precipitation anomalies exceeding one standard deviation, the intensity of each spell is the average precipitation anomaly divided by its duration, and the cumulative days are the total number of days accumulated over all wet (dry) spells in a season.

Time dependence. Several precipitation characteristics exhibit substantial temporal auto-correlation, although the lag time varies between characteristics (Supplementary Figs 9–11). To account for this autocorrelation (temporal dependence), we assess the time-dependence structure of the data time series using the autocorrelation function and the partial autocorrelation function (PACF) to fit an autoregressive moving-average model (ARMA). The augmented Dickey–Fuller test and Kwiatkowski–Phillips–Schmidt–Shin test confirm the validity of the assumption of stationarity in the temporal-dependence structure required for inference within the ARMA framework (Supplementary Section 2.2). We then use the Ljung–Box–Pierce (LBP) test to evaluate the adequacy of this model in capturing the autocorrelation (Supplementary Section 2.1). For example, we fit an ARMA model of order 6 (AR6) to the IMD daily precipitation time series based on the PACF showing significant temporal dependence up to 5 days (Supplementary Fig. 8). LBP statistics confirm that the residuals of this AR6 model exhibit no remaining autocorrelation. We similarly model the time dependence of other characteristics using the PACF and the LBP test to determine the appropriate auto-regressive model. (See Supplementary Section 2.1 for LBP test details.)

Significance testing. On the basis of the Q–Q plots and the Anderson–Darling normality test (see Supplementary Section 2.3 and 2.4), we reject our null hypothesis of normal distributions of the variables (Supplementary Fig. 12). Given the temporal dependency of the variables, we use a non-parametric, moving-block bootstrap test for significance testing (Supplementary Section 2.5), which does not assume a specific underlying distribution for the test variable. The block size for this test is informed by the order (lag) of the ARMA model as discussed in Supplementary Section 2.1.

We select 1951–1980 as our primary baseline period, and apply the moving-block bootstrap test on the distributions of each characteristic in the baseline and post-baseline periods to test the null hypothesis that the mean of the distributions is equal in the two periods. Further, we test the sensitivity of our results to the selection of the baseline period by varying the cutoff year between the two periods. We also assess the significance of linear trends in the precipitation characteristics from 1951 to 2011 to test the null hypothesis that the trend is not significantly different from zero.

We report statistical significance at the 5% significance level, unless otherwise specified.

Received 6 January 2014; accepted 27 March 2014; published online 28 April 2014

References

1. Annamalai, H. & Slingo, J. M. Active/break cycles: Diagnosis of the intraseasonal variability of the Asian Summer Monsoon. *Clim. Dynam.* **18,** 85–102 (2001).
2. Gadgil, S. & Kumar, K. R. in *The Asian Monsoon* (ed. Wang, B.) Ch. 18, (Springer/Praxis Publishing, 2006).
3. Turner, A. G. & Annamalai, H. Climate change and the South Asian summer monsoon. *Nature Clim. Change* **2,** 587–595 (2012).
4. Sivakumar, M. V. K. & Stefanski, R. in *Climate Change and Food Security in South Asia* (eds Lal, R. *et al.*) Ch. 2, (Springer Science+Business Media, 2011).
5. Kshirsagar, N. A., Shinde, R. R. & Mehta, S. Floods in Mumbai: Impact of public health service by hospital staff and medical students. *J. Postgrad Med.* **52,** 312–324 (2006).
6. Mandke, S. K., Sahai, A. K., Shinde, M. A., Joseph, S. & Chattopadhyay, R. Simulated changes in active/break spells during the Indian summer monsoon due to enhanced CO2 concentrations: Assessment from selected coupled atmosphere–ocean global climate models. *Int. J. Climatol.* **27,** 837–859 (2007).
7. Rajeevan, M., Gadgil, S. & Bhate, J. Active and break spells of the Indian summer monsoon. *J. Earth Syst. Sci.* **119,** 229–247 (2010).
8. Krishnamurthy, V. & Shukla, J. Intraseasonal and seasonally persisting patterns of Indian monsoon rainfall. *J. Clim.* **20,** 3–20 (2007).
9. Singh, C. Characteristics of monsoon breaks and intraseasonal oscillations over central India during the last half century. *Atmos. Res.* **128,** 120–128 (2013).
10. 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 (2006).
11. Bollasina, M. A., Ming, Y. & Ramaswamy, V. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *Science* **334,** 502–505 (2011).
12. Wang, B. *et al.* Northern Hemisphere summer monsoon intensified by mega-El Niño/Southern Oscillation and Atlantic Multidecadal Oscillation. *Proc. Natl Acad. Sci. USA* **110,** 5347–5352 (2013).
13. Ramanathan, V. *et al.* Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proc. Natl Acad. Sci. USA* **102,** 5326–5333 (2005).
14. Kunreuther, H. *et al.* Risk management and climate change. *Nature Clim. Change* **3,** 447–450 (2013).
15. IPCC, Summary for Policymakers in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) (Cambridge Univ. Press, 2013).
16. Dash, S. K., Jenamani, R. K., Kalsi, S. R. & Panda, S. K. Some evidence of climate change in twentieth-century India. *Climatic Change* **85,** 299–321 (2007).

17. Giorgi, F. *et al.* Higher hydroclimatic intensity with global warming. *J. Clim.* **24,** 5309–5324 (2011).
18. Dash, S. K., Kulkarni, M. A., Mohanty, U. C. & Prasad, K. Changes in the characteristics of rain events in India. *J. Geophys. Res.* **114,** D10109 (2009).
19. Ajayamohan, R. S., Merryfield, W. J. & Kharin, V. V. Increasing trend of synoptic activity and its relationship with extreme rain events over Central India. *J. Clim.* **23,** 1004–1013 (2010).
20. Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H-R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309,** 1844–1846 (2005).
21. Krishnan, R., Zhang, C. & Sugi, M. Dynamics of breaks in the Indian summer monsoon. *J. Atmos. Sci.* **57,** 1354–1372 (2000).
22. Terray, P. An evaluation of climatological data in the Indian ocean area. *J. Meteorol. Soc. Jpn* **72,** 359–386 (1994).
23. Ghosh, S., Das, D., Kao, S-C. & Ganguly, A. R. Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes. *Nature Clim. Change* **2,** 86–91 (2012).
24. Manoj, M. G., Devara, P. C. S.,, Safai, P. D. & Goswami, B. N. Absorbing aerosols facilitate transition of Indian monsoon breaks to active spells. *Clim. Dynam.* **37,** 2181–2198 (2011).
25. Turner, A. G. & Slingo, J. M. Subseasonal extremes of precipitation and active-break cycles of the Indian summer monsoon in a climate-change scenario. *Quart. J. R. Meteorol. Soc.* **135,** 549–567 (2009).
26. Mishra, S. *Monsoon Weather Variation and its Impact on Agriculture* (Department of Information and Cultural Affairs, 2006).
27. Tiwari, V. M., Wahr, J. & Swenson, S. Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophy. Res. Lett.* **36,** L18401 (2009).
28. Pande, P. & Akermann, K. *Adaptation of Small Scale Farmers to Climatic Risks in India* (Sustainet India, 2009).
29. Yatagai, A. *et al.* APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bull. Am. Meteorol. Soc.* **93,** 1401–1415 (2012).
30. Webster, P. J. *et al.* Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.* **103,** 14451–14510 (1998).

Acknowledgements

We thank the Indian Meteorological Department (IMD) and the APHRODITE (Asian Precipitation-Highly Resolved Observational Data Integration towards the Evaluation of Water Resources) project members for making the daily rainfall gridded data sets available. This work was supported in part by National Science Foundation Grant 0955283 to N.S.D. B.R. was supported in part by the National Science Foundation under Grant Nos DMS-CMG 1025465, AGS-1003823 and DMS-1106642, AFOSR Grant FA9550-13-1-0043, and the UPS Foundation Fund.

Author contributions

D.S., B.R. and N.S.D. conceived and designed the study; D.S. and M.T. implemented the analytical tools; B.R. developed and supervised the statistical analyses; and D.S., M.T. and N.S.D. analysed the data and co-wrote the manuscript. All authors discussed the results and commented on the draft.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.S.

Competing financial interests

The authors declare no competing financial interests.