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Key Points:
- Representation of irrigation and paddy fields is added to a regional climate model to study that impacts on Indian Summer Monsoon
- Excess irrigation over northern India causes northwestward shift in September month monsoon rainfall over the land mass
- Irrigation intensifies widespread extreme events over Central India

Supporting Information:
- Supporting Information S1

Correspondence to:
S. Ghosh,
subimal@civil.iitb.ac.in

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Choice of Irrigation Water Management Practice Affects Indian Summer Monsoon Rainfall and Its Extremes

Anjana Devanand[1,2], Maoyi Huang[2], Moetasim Ashfaq[3], Beas Barik[4], and Subimal Ghosh[1,4]

[1]Interdisciplinary Programme in Climate Studies, Indian Institute of Technology Bombay, Mumbai, India, [2]Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, WA, USA, [3]Computational Science and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA, [4]Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India

Abstract There is an emerging understanding toward the importance of land-atmosphere interactions in the monsoon system, but the effects of specific land and water management practices remain unclear. Here, using regional process-based experiments, we demonstrate that monsoon precipitation is sensitive to the choice of irrigation practices in South Asia. Experiments with realistic representation of unmanaged irrigation and paddy cultivation over north-northwest India exhibit an increase in the late season terrestrial monsoon precipitation and intensification of widespread extreme events over Central India, consistent with changes in observations. Such precipitation changes exhibit substantially different spatial patterns in experiments with a well-managed irrigation system, indicating that increase in unmanaged irrigation might be a factor driving the observed changes in the intraseasonal monsoon characteristics. Our findings stress the need for accurate representation of irrigation practices to improve the reliability of earth system modeling over South Asia.

Plain Language Summary South Asia is one of the most heavily irrigated regions of the world, and a large proportion of the water for irrigation is extracted through groundwater pumping. The major summer crop of the region is paddy, which is cultivated in fields flooded with water. Here we study the impact of this agricultural water use on the Indian Summer Monsoon using a climate model. We find that the excess irrigation over northern India shifts the September month monsoon rainfall toward the northwestern part of the subcontinent. This pattern of change is also visible in recorded rainfall over the region in the recent past. Another major impact we see is on the intensity of extreme rainfall events over the central part of the country. Central India has witnessed an increase in extreme rainfall in recent decades, and through this study, we find that irrigation increases the rainfall intensity over Central India during these events. These findings indicate that it is important to represent irrigation practices more accurately in climate models.

1. Introduction

Past several decades have witnessed an increase in irrigated cropland over South Asia. For instance, the irrigated area over India (Pakistan) increased from 25.5 MHa (11.1 MHa) in 1965 to 57.2 MHa (17.8 MHa) in 2002 (Alauddin & Quiggin, 2008). In the Kharif season, which spans from June to September and corresponds to the summer monsoon season, irrigation water use also shows a significant increasing trend over the Indo-Gangetic plains during the 1971 to 2010 period (Huang et al., 2018; Figure 1a). Today, one of the major crops that is cultivated during Kharif season is paddy that requires standing water in the field for cultivation. Paddy was a minor crop in the relatively drier northwest India till early 1970s, but availability of electric power and government subsidies for agriculture-related electricity usage have resulted in an extensive cultivation of paddy over this region as most of the irrigation water comes from groundwater pumping (Suhag et al., 2016; Vatta et al., 2018).

Increasing population and the variability in monsoon rainfall is further exacerbating the reliance of irrigation on depleting groundwater resources (Asoka et al., 2017). The summer monsoon precipitation over India has been decreasing post-1950, and this reduction is thought to be associated with the differential warming of the Indian Ocean and the landmass (Roxy et al., 2015), land use land cover changes (Paul

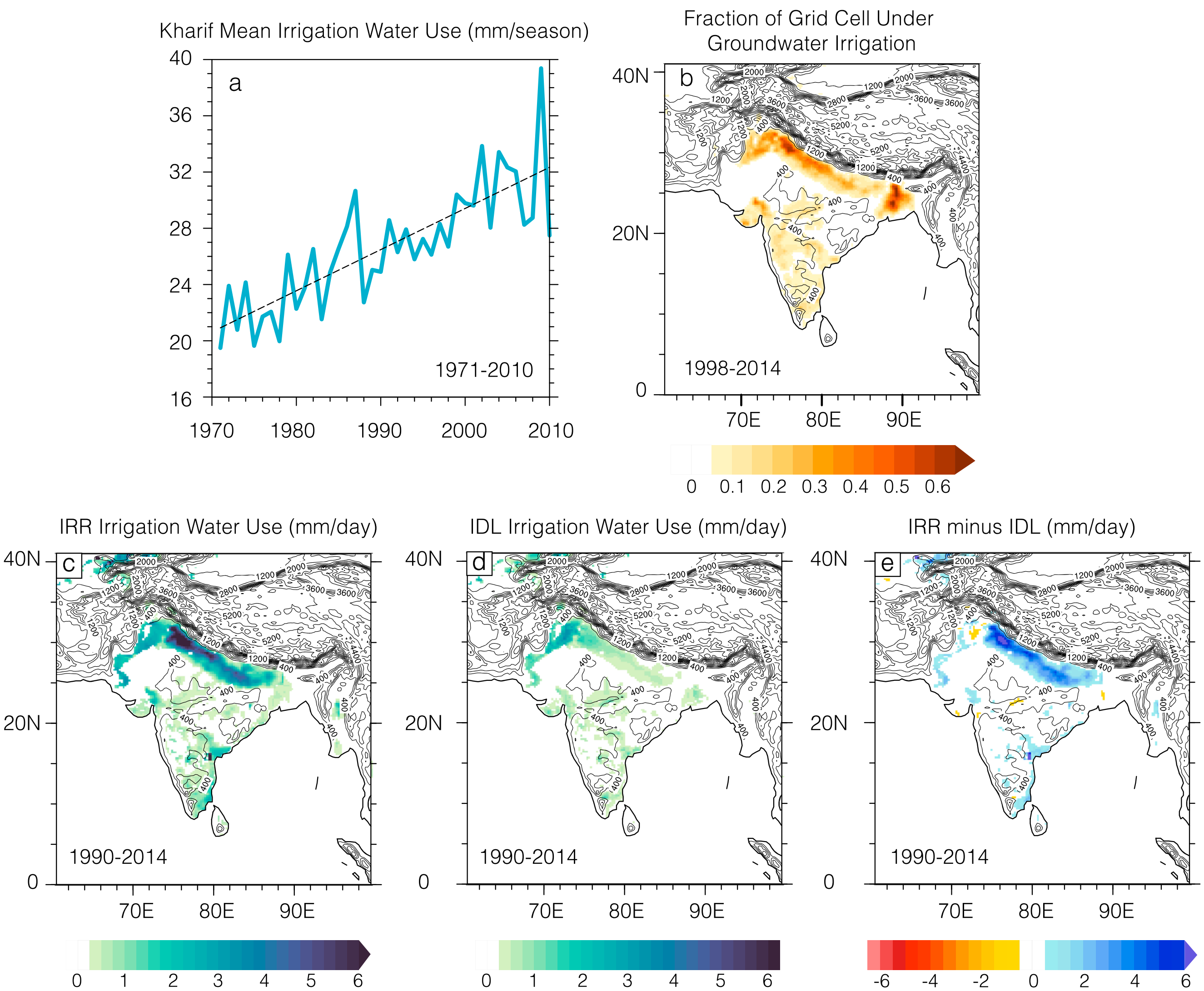

Figure 1. (a) Mean Kharif season irrigation water use, averaged over land grid cells in the South Asian model domain from 1971 to 2010, from the water use estimation of Huang et al. (2018). (b) Mean fraction of the grid cell under groundwater irrigation for years 1998 to 2014 from agricultural census over northern India combined with the area estimates of Siebert et al. (2013). Mean daily irrigation water applied in the (c) IRR experiment (d) IDL experiment. (e) Mean daily difference in the irrigation water between the IRR and IDL experiments. The contours in panels (b)–(e) are orography in meters.

et al., 2016), and changes in the anthropogenic aerosols (Bollasina et al., 2011; Turner & Annamalai, 2012). Observations also exhibit changes in the spatiotemporal characteristics of monsoon precipitation. For instance, Central India (region between 19°N to 26°N and 76°E to 86°E, hereafter CI) has been experiencing extremes with higher intensity (Roxy et al., 2017; Singh et al., 2014) and spatial heterogeneity (Ghosh et al., 2011). Despite substantial evidence, the intrinsic interplay of regional land-atmosphere dynamics and large-scale teleconnections makes it difficult to disentangle the causalities of these observed changes, making the use of model simulations necessary.

South Asian Monsoon (SAM) is historically understood to be predominantly influenced by large-scale changes, with global teleconnections affecting the inter annual to intra seasonal variability of the monsoon rainfall (Goswami, 2005). Therefore, improvements in the modeling of such large-scale teleconnections have thus far been the main focus of monsoon research aimed at improving dynamical seasonal and long-term climate predictions (Narapusetty et al., 2016; Wang et al., 2015). However, recently, the Global Land Atmosphere Coupling Experiment identified northern India as one of the hot spots for land-atmosphere coupling during the boreal summer (Koster et al., 2004), which is further supported by research that

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demonstrates the influence of land surface processes on the summer monsoon rainfall. The new scientific evidence suggests that changes in land-atmosphere interactions affect both the north-northwestward progression of monsoon precipitation over land (Bollasina & Ming, 2013; Devanand et al., 2018) and the moisture recycling over the subcontinent (Ashfaq et al., 2016; Pathak et al., 2014), which indicate that agricultural water management has the potential to influence SAM through modulating land surface processes.

Recognition of the importance of land surface processes in regulating SAM has resulted in efforts to represent irrigation in global and regional simulations of the monsoon. These include the use of high soil moisture thresholds or continuous application of water to represent irrigation in the regional modeling experiments (Douglas et al., 2009; Saeed et al., 2009; Tuinenburg et al., 2014), and irrigation water use estimates based on global water balance models in global modeling experiments (Chou et al., 2018; Cook et al., 2015; Shukla et al., 2014; Singh et al., 2018). These studies indicate a reduction or redistribution of monsoon rainfall due to weakening or shift in the large-scale circulation as a result of irrigation-induced changes. However, such simplified prescriptions of irrigation in the modeling frameworks lack the level of accuracy needed for reliable estimation of irrigation-driven changes in surface energy fluxes and their impacts on land-atmosphere interactions. In general, these modeling experiments potentially overestimate the impacts of irrigation on SAM as irrigation application over entire vegetated area of the grid cell or over entire model grid cell leads to an overestimation of the irrigation-induced energy fluxes. Moreover, the impact of specific irrigation practices (Lawston et al., 2015) such as overexploitation of ground water and paddy cultivation on surface water and energy cycles are not fully understood. Here we address these limitations by using a relatively fine resolution regional modeling framework that considers more realistic representation of the irrigation practices over South Asia to improve our understanding toward land-atmosphere feedbacks resulting from anthropogenic agricultural water management.

2. Materials and Methods

We employ the Weather Research and Forecasting model (Skamarock et al., 2008) coupled to the Community Land Model version 4 (WRF-CLM4) to simulate the impact of agricultural water management practices on SAM. Modules to represent irrigation, groundwater pumping (Leng et al., 2013), and the biogeophysical effects of flooded paddy fields (Barik et al., 2017; Fishman et al., 2015; Janssen et al., 2010; Masutomi et al., 2016; Mishra et al., 2008; Neumann et al., 2009; Xie & Cui, 2011) are added into WRF-CLM4 (details in supporting information Texts S1–S3). The dependence of irrigation on groundwater pumping over north-northwestern India is reflected in Figure 1b that combines agricultural census data over northern India for years 1998 to 2014 and the irrigated area estimates from Siebert et al. (2013) to show the fraction of grid making use of groundwater pumping (details in supporting information Text S4).

WRF-CLM4 is configured at 25-km horizontal grid spacing and 30 levels in the vertical over a domain covering 59.5°E to 107°E in the longitude and 3.7°S to 41.5°N in the latitude. Seasonal (15 May to 31 October) monsoon simulations for 25 years (1990 to 2014) are performed using lateral and lower boundary conditions from European Centre for Medium Range Weather Forecast Interim Re-Analysis (ERA Interim; Dee et al., 2011; details in supporting information Text S5). In total, we conduct three sets (control, realistic irrigation, ideal irrigation) of WRF-CLM4 experiments, each containing 25 years of seasonal simulations. Control experiment (hereafter CTL) does not contain any representation of irrigation, groundwater pumping, and paddy field representation. Realistic irrigation experiment (hereafter IRR) uses a combination of water use estimates from agricultural census and Huang et al. (2018) to prescribe irrigation water application. The IRR experiment includes representation of groundwater pumping and paddy fields. Ideal irrigation experiment (hereafter IDL) represents irrigation using the soil moisture deficit where the amount of water required to raise the root zone soil moisture to field capacity is calculated and applied as irrigation. The applied irrigation water is removed proportionally from groundwater and surface water sources.

The key difference between IRR and IDL experiments is the higher irrigation water application and representation of flooded paddy fields in the IRR experiment. In the IDL experiment, the amount of water for irrigation is based on the soil moisture deficit that results in lower amount of irrigation application. The differences between IRR and IDL in the representation of irrigation water use and application is aimed at understanding the sensitivity of model simulations to the treatment of irrigation over northern India. The IRR simulation reflects the excess water use over northern India, which does not exist in the soil moisture deficit based irrigation experiments (IDL). The strongest differences in irrigation water use between IRR and IDL are over the Indo-Gangetic plains (Figures 1c–1e).

Selected WRF-CLM4 configuration exhibits reasonable skill in the simulation of SAM characteristics. The spatial pattern of monsoon rainfall is well represented, but with a slight positive bias in regionally averaged all India monsoon precipitation (supporting information Figure S3). Similarly, interannual and intraseasonal variability in precipitation over the heavily irrigated belt is captured in the model experiments. The nature of precipitation biases remains similar in all three experiments (CTL, IRR, and IDL). There is an overestimation bias in the simulation of near surface air temperatures that has also been reported in earlier regional monsoon simulations (Lucas-Picher et al., 2011). Addition of irrigation slightly reduces this temperature bias during the early phase of monsoon in both the irrigation experiments. The CTL experiment exhibits a mean seasonal bias of 1.86 K over the heavily irrigated region of northern India. Irrigation-induced cooling reduces this seasonal bias by 0.26 K (average cooling in June is 0.83 K; Figure S3j). Soil moisture over the irrigated areas from all experiments is generally within the spread of the long-term satellite-based soil moisture estimates from European Space Agency (ESA), with the IRR experiment showing slightly higher values during the late season (supporting information Figure S4c). The irrigation experiments (IRR and IDL) show higher values than CTL throughout the season, as expected. It should be noted that soil moisture measurements that are retrieved from recently deployed microwave sensors over this region are higher. Therefore, it is expected that the planned integration of measurements from these newer sensors in the next phase will increase the ESA soil moisture estimates. Overall, the regional modeling framework displays reasonable spatial and temporal skills in the simulation of land-atmosphere characteristics during SAM.

3. Results

3.1. Changes in Mean Rainfall due to Irrigation

The summer monsoon (June to September) precipitation exhibits an irrigation-induced increase over northwest India and a decrease over south CI in the IRR experiment with respect to the CTL experiment, which are absent in the IDL experiment (Figures 2a–2c). The northwestward shift in seasonal precipitation is most prominent during the withdrawal phase of SAM in September (Figure 2e). The IDL experiment shows a different spatial pattern of change where the increase in September precipitation is more distributed over south CI. Interestingly, the spatial pattern of increase (decrease) in September rainfall over northern India (southern India) in the IRR experiment (IRR minus CTL) bears similarity to the changes seen in the observations in the recent decades. Figure 2g shows precipitation changes during September in the observations as the difference between two periods (i.e., 1990 to 2014 vs. 1965 to 1989). The similarity between precipitation changes in the observations (Figure 2g) and differences of the IRR experiment from the CTL experiment (Figure 2e) indicates that the intensifying agricultural water application could be one of the factors driving the changes in the observed rainfall during September in recent decades. We note that similar west-northwest shift in the precipitation was also noted by Tuinenburg et al. (2014) who represented irrigation by keeping soil moisture at 90% of the maximum soil moisture storage capacity. However, to our knowledge, our study is the first time in literature that a comparison between the simulations and the observed precipitation changes is documented.

The physical connection of irrigation to the observed changes in precipitation can be the intensified moisture transport that impacts the terrestrial redistribution of atmospheric moisture. It should be noted that precipitation contribution from local moisture recycling is the strongest during the monsoon withdrawal phase (Mei et al., 2015; Tuinenburg et al., 2012). Our analyses indicate that irrigation through groundwater pumping increases local moisture availability over northern India and induces a cyclonic pattern of change in monsoon circulation that lead to a local increase in the vertically integrated moisture transport over the region (Figures 3a–3c). While differences between IDL and CTL (i.e., IDL minus CTL) regarding the moisture transport are stronger than those between IRR and CTL experiment (i.e., IRR minus CTL), simulated increase in the moisture transport in the IRR experiment extends to the drier northwestern part of the subcontinent where background moisture transport is relatively weak (CTL experiment, Figure 3a). Given the highly complex and nonlinear nature of land-atmosphere interactions during monsoon, a linear dynamical response to changes in the amount of irrigation is unwarranted. Nonetheless, enhanced irrigation over northern South Asia in the IRR experiment induces circulation changes that favor excessive moisture

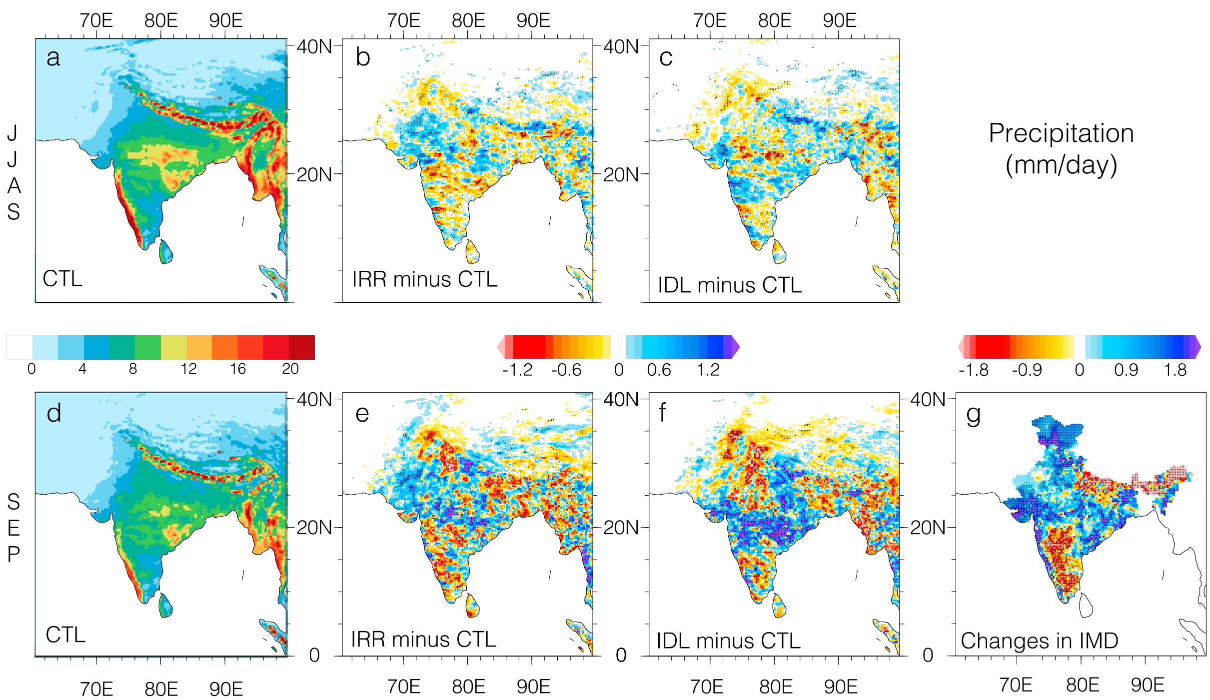

Figure 2. (a) Daily mean precipitation (mm/day) during 1990–2014 JJAS in the CTL experiment. Difference in mean daily precipitation (mm/day) during 1990–2014 JJAS between (b) the IRR and CTL experiments, (c) the IDL, and CTL experiments. (d) Daily mean precipitation (mm/day) during 1990–2014 September in the CTL experiment. Difference in mean daily precipitation (mm/day) during 1990–2014 September between (e) the IRR and CTL experiments, (f) the IDL and CTL experiments. (g) Difference in mean daily precipitation (mm/day) during September between two 25-year periods (1990 to 2014 minus 1965 to 1989) in the IMD observations. Dotted grids are statistically significant at 90%. JJAS = June to September.

transport during September to the northwest, potentially causing a shift in the precipitation pattern that is exhibited in this experiment. There are accompanying changes in the lower tropospheric temperature and specific humidity over the South Asian land. We present the irrigation-induced changes in atmospheric temperature, humidity, and equivalent potential temperature as latitude pressure cross section averaged over 70–80°E (Figures 3d–3l) where croplands with maximum irrigation application are located. Irrigation cools and moistens the lower troposphere, which has opposing effects on atmospheric stability. The net effect is an increase in equivalent potential temperature (associated with decrease in stability) at latitudes above ~15°N and decrease in equivalent potential temperature (associated with increase in stability) over the southern latitudes, which causes a northward shift in precipitation over land.

As previously mentioned, during withdrawal phase in September, background monsoon circulation and oceanic moisture transport is relatively weak (Mei et al., 2015) and, hence, the local moisture recycling, including that sourced through irrigation activities, exerts a stronger influence on the tropospheric temperature and humidity. Similar relatively weak background monsoon circulations and limited moisture supply from oceanic sources are present during the break spells of SAM. Given the similarity in the regional thermodynamic characteristics of SAM during the break spells and the withdrawal phase, an increase in irrigation-induced precipitation over northern India is also witnessed in the break spells composites (supporting information Figure S5). The associated changes in vertically integrated moisture transport and equivalent potential temperature during the break periods also exhibit a northwestward extension in the simulations with realistic irrigation representation.

3.2. Changes in Widespread Extremes due to Irrigation

IMD observations exhibit a rise in the frequency of extreme events as well as an increase in their spatial variability over CI (Ghosh et al., 2011; Singh et al., 2014). Roxy et al. (2017) reported a significant increase in the frequency of widespread extreme events, defined as days when more than 10 grid points receive precipitation ≥150 mm/day, over CI post 1950. In our analyses, the widespread extreme events, identified by

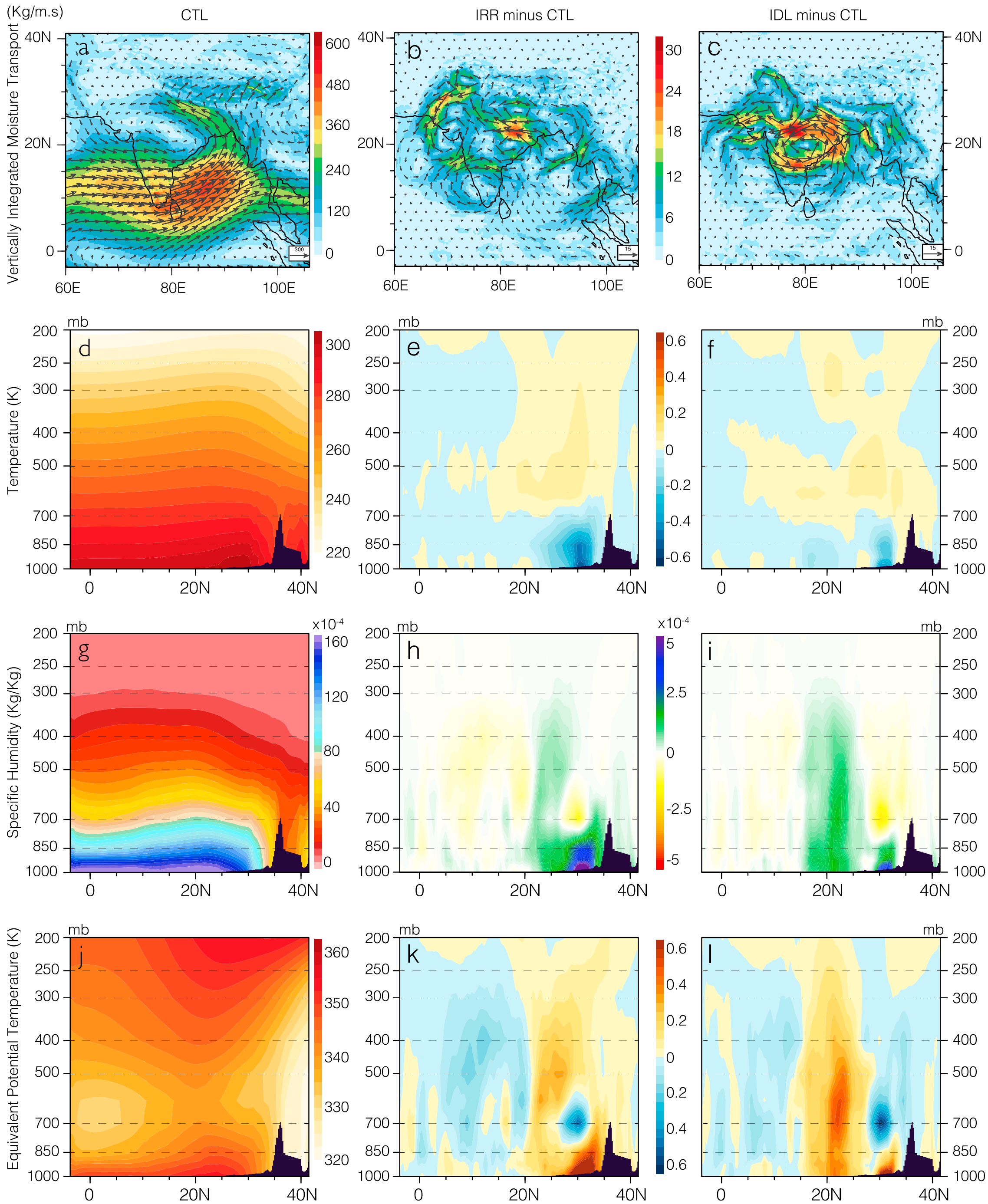

Figure 3. Daily mean vertically integrated moisture transport (kg/m·s) during September in the (a) CTL experiment (b) IRR minus CTL, and (c) IDL minus CTL. Daily mean tropospheric temperature (K) over latitude pressure (mb) section averaged over 70–80°E in the (d) CTL, (e) IRR minus CTL, and (f) IDL minus CTL. (g–i) Same as in (d)–(f) but for daily mean tropospheric humidity (kg/kg). (j–l) Same as in (d)–(f) but for daily mean equivalent potential temperature θe (K).

Roxy et al. (2017) in the IMD observations, also exhibit a progressive increase in their intensity in terms of the area mean precipitation over CI and this intensification is stronger after 1970 (Figure 4a).

In contrast to a northwestward shift in rainfall over the landmass during September and monsoon break spells in our experiments, the mean precipitation changes during the active spells (Rajeevan et al., 2010) do not exhibit any distinct spatial pattern (supporting information Figure S6). Given that the irrigation-

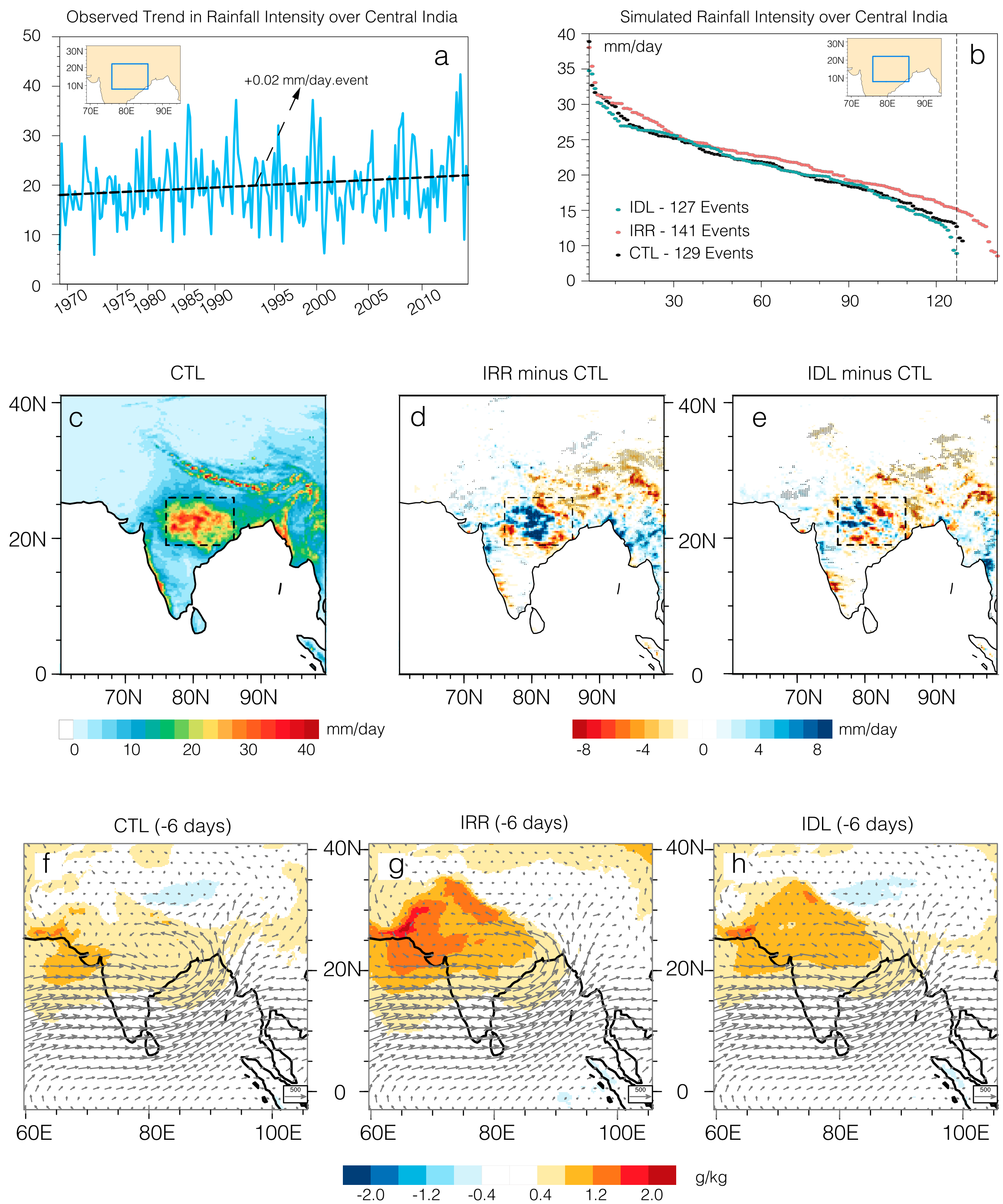

Figure 4. (a) Observed trend in area mean precipitation intensity over Central India during 1970 to 2014 (19–26°N, 76–86°E) during the widespread extreme events (significant at 95%, widening of *x* axis ticks denote the increase in frequency of extremes). (b) Area mean precipitation over Central India during widespread extreme events in the model experiments sorted by intensity. (c) Intensity (mm/day) of widespread extreme events in CTL experiment. (d, e) Differences (mm/day) in the widespread extreme events intensity in the IRR and IDL experiments from the CTL experiment for the most intense 127 events from all experiments. Dotted grids are statistically significant at 90%. Composite anomalies of vertically integrated moisture transport (vectors) and 1,000–500 hPa specific humidity (colors) 6 days prior to the 127 widespread extreme events over Central India in the model experiments (f) CTL, (g) IRR, and (h) IDL.

induced changes in the atmospheric moisture has the potential to influence the amount of precipitation during extreme events, we investigate the possibility of impacts of irrigation on the widespread extreme events over CI. If extremes are defined using a threshold of 150 mm/day as in Roxy et al. (2017), a mixed pattern of positive and negative changes over CI emerges that is similar to the mean precipitation changes during the active spells of SAM (supporting information Figure S6). However, it should be noted that the regional simulations exhibit a positive bias in SAM precipitation (supporting information Figure S3). When compared with observations over the same time period, such an overestimation of the simulated precipitation results in the classification of excessive simulated events as extreme days (supporting information Figure S6). In order to avoid this issue in threshold based classification, we match the exceedance probability of a grid point precipitation of 150 mm/day over CI in the observations to a corresponding exceedance probability in the simulations, which results in a grid point threshold of 165 mm/day or more for the identification of statistically equivalent widespread extremes in the simulated data. We identify widespread extreme events in the model simulations as days when more than 10 grid points over CI receive precipitation ≥165 mm/day. Interestingly, use of new statistically equivalent threshold results in an increase in both the frequency and the intensity of widespread extremes over CI in the IRR experiment, consistent with the changes exhibited in observations (Figure 4b). The IRR experiment exhibits ~9% more frequent occurrence of such extreme events over the 25-year simulation period compared to the CTL experiment, but this change in frequency is not statistically significant. Apparently, irrigation has more pronounced impact on the intensity of extreme events compared to its impact on the frequency of extremes. We examine the difference in the intensity of precipitation for equal number of widespread extremes (127 events) in the three experiments (Figure 4b). Considering the 127 events that result in most intense rainfall over CI in the three experiments, we find that the IRR experiment exhibits an increase in the extreme rainfall intensity by 1.2 mm/day (significant at 90%) on average compared to the CTL experiment. The change in intensity of extreme events in the IDL experiment is not significant (Figures 4b–4e).

Roxy et al. (2017) used reanalysis data to identify the mechanism behind widespread extreme rainfall events over CI. They found a buildup of atmospheric specific humidity over north Arabian Sea and northwestern South Asian land approximately 6 days prior to the occurrence of extreme event, which was transported to CI by anomalously strong westerlies (Figure 2, Roxy et al., 2017). We examine these prerequisites for the occurrence of extreme events over CI in our simulations (Figures 4f–4h and supporting information Figures S7 and S8) and find mechanistic consistency in our experiments with irrigation. We note that the application of excess irrigation strengthens the lower tropospheric specific humidity anomalies over the northwestern areas of the domain prior to the event, which in turn affects the moisture surges and eventually leads to an occurrence of extreme event by increasing the intensity of widespread precipitation over CI.

4. Conclusions

We use relatively fine scale regional modeling framework to understand the impact of agricultural water management activities on SAM precipitation. The analysis reveals that monsoon precipitation is sensitive to the choice of irrigation practice over South Asia. Irrigation changes the terrestrial moisture transport through variations in the dynamic and thermodynamic feedbacks that subsequently influences the terrestrial precipitation distribution. Regional simulations with realistic representation of irrigation and paddy cultivation reveal dominant controls of irrigation on the observed variations in the intraseasonal characteristics of monsoon precipitation, including a northwestward shift in withdrawal phase (September) and an increase in the intensity of widespread extremes over CI. Irrigation induced northwestward shift in precipitation patterns in the IRR experiment is also supported by the findings of an earlier modeling study by Tuinenburg et al. (2014) that reported a similar northward shift in the annual precipitation while using a higher soil moisture threshold—potentially comparable to the irrigation application used in the IRR experiment. Changes in the spatial pattern of late season precipitation have implications for the decisions relevant to crop rotation and agricultural planning. Similarly, large-scale flooding due to widespread extremes has devastating impact on natural and human systems (Revadekar & Preethi, 2012). To this end, these findings can help increase the potential predictability of such extreme events 2–3 weeks in advance through improvements in the extended range forecast systems (Joseph et al., 2015; Roxy et al., 2017). However, while our conclusions regarding mean precipitation response are supported by previously published findings, we acknowledge that our conclusions regarding extreme precipitation require further investigations using additional models to eliminate the impact of modeling uncertainties. Similarly, presence of implicit irrigation signal in the reanalysis data used as a boundary forcing (Tuinenburg & de Vries, 2017) may have an effect on these results.

Nonetheless, the sensitivity of the monsoon precipitation to choices of irrigation practice reported here has important implications. Current-generation global and regional modeling systems employed for seasonal to centennial scale simulations lack realistic representation of irrigation. More recently, there has been a push to incorporate irrigation as a climate forcing (Cook et al., 2015); however, our experiments indicate that the response is also sensitive to the specific irrigation practices, which needs to be accounted for to adequately represent irrigation in models. This issue is of immediate concern in the context of agricultural water management over South Asia and seasonal and subseasonal monsoon predictions aimed at informed decision making. At longer time scales, the declining groundwater resources and changing patterns of monsoon rainfall elevate the concerns toward water, food, and socioeconomic security, as well as the efficiency and sustainability of the current irrigation practice over South Asia. To address these concerns in a coupled modeling framework, the modeling system needs to take into account the land-atmosphere feedbacks particularly those related with the agricultural water management practices over the subcontinent.

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