Impacts of Irrigation on Dry Season Precipitation in India

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Impacts of irrigation on dry season precipitation in India

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Abstract There is a lack of observed data-based studies examining the role of enhanced soil moisture conditions (due to irrigation) on the prevailing precipitation. Therefore, in the present study, we have examined the impacts of the Green Revolution (GR) related expansion of irrigation and changes in dry season (the *rabi* (November to May) and the *zaid* (March to June)) precipitation in India. The results for some regions indicated decreasing and increasing trend in precipitation during the pre- and post-GR periods, respectively. For example, in eastern Madhya Pradesh, the pre- and post-GR precipitation trends for the zaid season were −0.45 and 2.40 mm year^{-1}, respectively. On the other hand, some regions reported lower rate of decline in precipitation during the post-GR period. This paper suggests that both positive and lower declining trend during the post-GR period were linked to increased precipitation due to the introduction of irrigation. The study has found up to 69 mm (121%) increase in total amount of precipitation for growing seasons during the post-GR period. Moreover, a 175% increase in average precipitation was also recorded. *All* irrigated regions show a notable increase in precipitation during post-GR growing seasons. It was found that differences in growing season average precipitation between the pre- and post-GR periods were statistically significant for most of the regions. For further verification of results, the MM5 and Noah land surface model were applied. These applications show changes in precipitation and various precipitation controlling factors due to changes in soil moisture.

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1 Introduction

In recent years, land use and land cover change (LULCC) and its impacts on weather and climate have received notable attention in the scientific literature (e.g., Adegoke et al. 2007; Feddema et al. 2005; Mahmood et al. 2010; Narisma and Pitman 2003; Pielke et al. 2007a, b; Raddatz 2007). LULCC modifies biophysical properties of land surfaces including aerodynamic character, roughness length, vegetation architecture, vegetation fraction, and albedo (e.g., Barlage and Zeng 2004; Chang and Wetzel 1991; Pielke 2001). These changes also alter energy balance/ energy partitioning and atmospheric vapor content. It is noted that the increase in available energy from vegetated surfaces has profound effects on the development of convectively driven thunderstorms and precipitation (Pielke et al. 2007a, b; Pielke 2001). Recently, Sen et al. (2004) have found that replacing desert and semi-desert areas with grass has increased precipitation in northwestern China.

LULCC also modifies soil moisture content of the root zone and subsequently affects sensible and latent heat fluxes and the Bowen ratio (the ratio of sensible to latent heat flux). It is found that a small Bowen ratio, together with horizontal gradients of soil moisture and a lifting mechanism, could initiate deep cumulus convection (Anthes 1984; Betts et al. 1996; Pielke 2001; Lanicci et al. 1987; Segal and Arrit 1992; Segal et al. 1995). A number of studies have suggested that increased soil water content enhanced the possibility of cloud cover and potential for convection due to higher moist static stability in shallower atmospheric boundary layer (Aligo et al. 2007; Alonge et al. 2007; Gallus and Segal 2000; Findell and Eltahir 2003; Pal and Eltahir 2001; Sutton et al. 2006). It has also been noted that moderate changes in soil moisture can bring about changes in the initiation and location of convection (Sutton et al. 2006).

A detailed global scale study by Ramankutty and Foley (1999) found widespread changes in land use from forested lands to croplands (hence changes in soil moisture). One of the regions that stand out in terms of widespread conversion to agricultural land uses from forests and woodlands since 1940s is northern India. Note that this is also a region of very low dry season (November through June) precipitation. One of the main drivers for the expansion of agricultural croplands in this region was the development of extensive irrigation infrastructure that led to the rapid increase of agricultural production referred to as the Green Revolution (GR). Recently, Gordon et al. (2005) reported globally up to a 2,600-km^3 $year^{-1}$ increase in vapor flux due to irrigation. Their study clearly showed that northern India has been experiencing one of the most intense levels of vapor flux (500 mm $year^{-1}$) due to irrigation (Figs. 3 and 4 of Gordon et al. 2005). In addition, the authors of this paper have recently investigated the impacts of introduction of irrigation and enhanced soil moisture on temperatures in northwestern India (Sen Roy et al. 2007) for *dry season* (non-monsoon conditions). They have shown that the introduction of widespread irrigation has lowered dry season near-surface temperature up to 0.51°C and increased atmospheric moisture content. The results from Sen Roy et al. (2007) have encouraged the authors of the current paper to conduct a follow-up assessment of LULCC in northwestern India. Specifically, the objective of this study is to investigate impacts of widespread irrigation (thus, enhanced soil moisture) on precipitation during the dry crop growing season (November through June) in northwestern India. Relatively, a much larger number of studies have focused on LULCC and temperature, while there is a lack of assessments of potential impacts of LULCC on precipitation. Thus, in our opinion, the present assessment would help fill this void in the scientific literature.

In addition, most of the precipitation–soil moisture feedback studies on India have focused on the wet season (e.g., Koster et al. 2004). Moreover, scientific literature on LULCC-linked enhancement of soil moisture due to irrigation and its impacts on the dry growing season (rather than wet monsoon) precipitation in northwestern India is non-existent. The latest Intergovernmental Panel on Climate Change report discusses only about wet monsoon rainfall without any reference to dry season rainfall (Christensen et al. 2007). Hence, this paper provides an opportunity to address this important research theme.

2 Data and methods

We obtained monthly precipitation data for six meteorological subdivisions/regions over northwestern and north central India from 1947 to 2005. Seasonal time series were derived for each of these subdivisions from the monthly data. The monthly time series were developed by the Indian Institute of Tropical Meteorology (IITM) using an original network of 306 relatively uniformly distributed precipitation-gauge stations, which provided adequate representation for each district (administrative unit) in India. Subsequently, the monthly area-weighted precipitation for each meteorological subdivision demarcated by the India Meteorological Department was calculated by assigning the district area to its representative station. Meteorological subdivisions are regional level units, which retain the homogenous regional climate characteristics while removing the noise due to highly localized influences on climate data (Pant and Rupa Kumar 1997). Further details about the methodology regarding the construction of this dataset are available in Parthasarathy et al. (1995). The selected six meteorological subdivisions over northwestern India benefited most from adoption of irrigation due to the GR (Fig. 1). The Indian states within these subdivisional boundaries include Punjab, Haryana, Rajasthan, and Madhya Pradesh.

To fulfill the objectives of this research, we have analyzed growing season rainfall (November through June) for the pre-GR (1947 to 1964) and the post-GR (1980 to 2005) periods. The period from 1965 to 1980 was not taken into consideration in order to exclude the transitional processes associated with the maturation of the GR. These periods also correspond with the earlier study by Sen Roy et al. (2007) that investigated the impact of GR-related irrigation on temperatures and thus will enable effective comparison of findings for the two studies. All six regions had continuous records of precipitation throughout the study period. The main cropping seasons in India consist of the *kharif* (June to September), the *rabi* (November to May), and the *zaid* (March to June; Fig. 2). During kharif season, most of the water needs for agricultural activity are met through the summer monsoon precipitation. However, during the drier months of November to June, irrigation is necessary for agricultural activities. Introduction of the extensive irrigation network in northwestern India has resulted in successful crop production during the rabi and the zaid season. The main crops grown during the rabi season include wheat, while during the zaid season, it is predominantly oil seeds and other cash crops. Among the three major agricultural seasons over the Indian subcontinent, zaid is the driest season. Therefore, the main focus of the present study is to analyze the impact of greater availability of irrigated water and soil moisture on precipitation during the rabi and the zaid seasons.

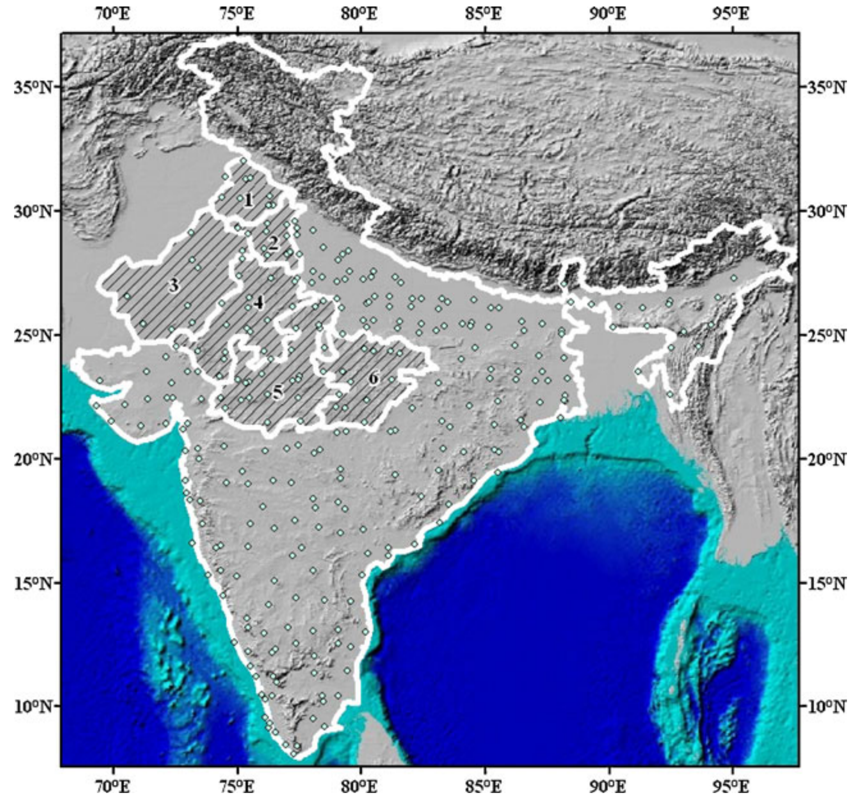

Fig. 1 Meteorological subdivisions for precipitation analysis in northwestern and north central India. *Shaded regions* indicate the specific homogenous rainfall regions taken into consideration. It includes *1* Punjab, *2* Haryana, *3* Western Rajasthan, *4* Eastern Rajasthan, *5* Western Madhya Pradesh, and *6* Eastern Madhya Pradesh. The *blue dots* indicate the location of the 306 rain gauge stations used for developing the original rainfall dataset by IITM. More information regarding this precipitation dataset is available in Parthasarathy et al. (1995)

In addition, to further understand the impacts of irrigation and enhanced soil moisture, the MM5 and Noah land surface models were applied and a series of sensitivity tests were completed for four precipitation events. The MM5 is a non-hydrostatic model which can resolve local-scale impacts on synoptic-scale systems through nested grids (Dudhia 1993). This model uses a set of four-dimensional (*x*, *y*, *z*, *t*) equations for a fully compressible atmosphere in a rotating frame of reference at user defined resolutions (Dudhia 1993). Moreover, the MM5 includes terrain following coordinates, real-time data assimilation, three-dimensional Coriolis torque, and a suite of physics options. The latter is comprised of cumulus parameterization, planetary boundary layer, explicit moisture, and surface radiation schemes. Moreover, the MM5 is coupled with a land surface model (LSM), known as the Noah, of medium complexity and the latter is capable of simulating land surface–atmosphere interactions. The Noah has been compared with a number of other LSMs, and it reasonably reproduces observed energy fluxes, temperature, and atmospheric and subsurface moisture (Chen and Dudhia 2001). The analysis of results from sensitivity experiments demonstrated changes in planetary boundary layer conditions that have potentially impacted precipitation.

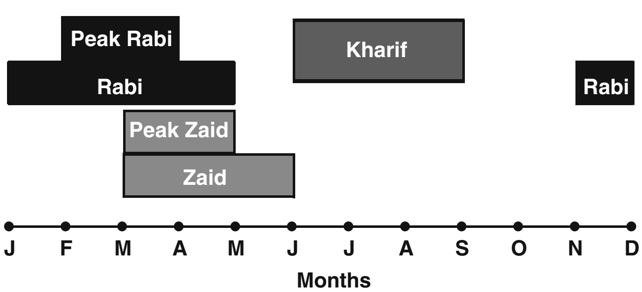

Fig. 2 Schematic presentation of the different agricultural seasons throughout the year over the Indian subcontinent

3 Results

3.1 Analysis of long-term precipitation data

First, we have analyzed the average growing season precipitation, for the pre- and post-GR periods (Fig. 3a–f). In Punjab, the average precipitation during the post-GR period was higher than the pre-GR during all seasons (Fig. 3a). We also further determined the statistical significance (*t* test) of differences between the pre- and post-GR average growing season precipitation for each region (Table 1). The maximum increase in average precipitation was observed during the zaid season (58.81 mm). It was an 80% increase compared to the pre-GR period. In view of the significant differences in seasonal precipitation, we also calculated the average precipitation during the peak growing seasons for pre- and post-GR periods. The precipitation for the peak zaid season

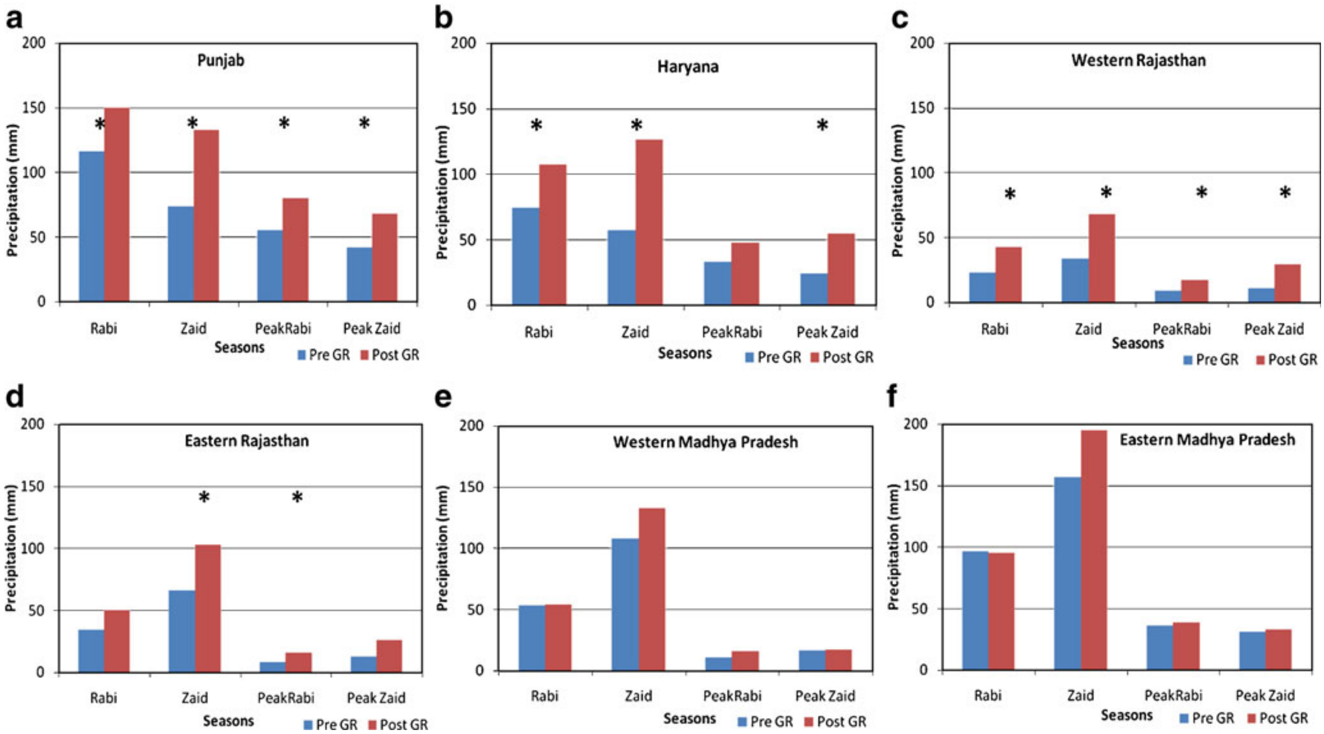

Fig. 3 Average seasonal precipitation amounts during pre- and post-Green Revolution periods across subdivisions located in northwestern and north central India. **a** Punjab; **b** Haryana; **c** Western Rajasthan; **d** Eastern Rajasthan; **e** Western Madhya Pradesh; **f** Eastern Madhya Pradesh. *Asterisk* marks on the different time periods denote statistical significance at 0.05 or higher level of confidence

increased to 25.89 mm (62%) for the post-GR period. Peak growing seasons for the rabi and the zaid are February through April and March through May, respectively. During the rabi season, the post-GR precipitation increases for the entire season, and the peak growing seasons were 33.90 mm (29%) and 24.90 mm (45%), respectively. Furthermore, the *t* test statistics for the peak rabi and zaid seasons in Punjab subdivision were significant at the 0.04 and 0.035 level, while the levels of significance for the overall seasonal patterns were slightly lower at 0.047 and 0.00 confidence level. In case of Haryana, the average precipitation was higher during the post-GR period (Fig. 3b). The increases during the post-GR rabi and zaid seasons were 32.53 mm (44%) and 69.27 mm (121%), respectively. The peak rabi and zaid seasons recorded 14.30 mm (43%) and 30.11 mm (123%) increases in precipitation, respectively, during the post-GR period. Similar to Punjab, in the Haryana subdivision, the *t* test statistics were also significant (at 0.004 level) for zaid peak growing season. On the other hand, results for the overall rabi and zaid seasons were significant at 0.017 and 0.00 confidence levels, respectively. In absolute terms, among all regions, Punjab and Haryana experienced the largest increase in the post-GR precipitation. These two regions have adopted the most widespread irrigation during the GR, and we suggest that these precipitation increases are linked to the introduction of irrigation. Therefore, overall the results revealed statistically significant differences in average precipitation during the pre- and post-GR periods for all regions, except western and eastern Madhya Pradesh subdivisions. For Punjab, Haryana, eastern Rajasthan, and western Rajasthan, the *t* test statistics were significant at 0.05 confidence level for both the peak and the entire rabi and zaid seasons. In case of Haryana and Punjab subdivisions, the significance levels were higher during the peak seasons compared to the overall seasonal averages.

In two subdivisions of Rajasthan, precipitation during the post-GR period was substantially higher than the pre-GR rabi and zaid seasons (Fig. 3c, d). For example, in western Rajasthan, the increases in precipitation were 19.2 mm (85%) for the rabi season and 34.73 mm (104%) for the zaid season during the post-GR period (Fig. 3c). On the other hand, during the post-GR period, the increases in precipitation were 8.08 mm (92%) and 18.45 mm (176%) for the peak rabi and the zaid seasons, respectively. In addition, the significance levels of the *t* test statistics during the peak growing seasons were lower than 0.05 for all seasons. Similarly, in eastern Rajasthan, the post-GR increases in precipitation were 16.1 mm (47%) and 37.07 mm (56%) for the rabi and zaid seasons, respectively (Fig. 3d). Moreover, the peak rabi and zaid seasons recorded 7.48 mm (89%) and 13.3 mm (103%) increases in precipitation, respectively. The results of the *t* test statistics were significant at greater than 0.05 confidence level

Table 1 Statistical significance of difference between average precipitation for pre- and post-GR period as revealed by *T* test statistics

Subdivisions/regions	Statistical significance
Punjab: *rabi* (November–May)	**0.047**
Punjab: *zaid* (March–June)	**0.00**
Punjab: peak *rabi* (February–April)	**0.04**
Punjab: peak *zaid* (March–May)	**0.035**
Haryana: *rabi* (November–May)	**0.017**
Haryana: *zaid* (March–June)	**0.00**
Haryana: peak *rabi* (February–April)	0.082
Haryana: peak *zaid* (March–May)	**0.004**
W. Rajasthan: *rabi* (November–May)	**0.025**
W. Rajasthan: *zaid* (March–June)	**0.012**
W. Rajasthan: peak *rabi* (February–April)	**0.035**
W. Rajasthan: peak *zaid* (March–May)	**0.008**
E. Rajasthan: *rabi* (November–May)	0.061
E. Rajasthan: *zaid* (March–June)	**0.006**
E. Rajasthan: peak *rabi* (February–April)	**0.015**
E. Rajasthan: peak *zaid* (March–May)	0.17
W. Madhya Pradesh: *rabi* (November–May)	0.944
W. Madhya Pradesh: *zaid* (March–June)	0.102
W. Madhya Pradesh: peak *rabi* (February–April)	0.165
W. Madhya Pradesh: peak *zaid* (March–May)	0.859
E. Madhya Pradesh: *rabi* (November–May)	0.93
E. Madhya Pradesh: *zaid* (March–June)	0.107
E. Madhya Pradesh: peak *rabi* (February–April)	0.732
E. Madhya Pradesh: peak *zaid* (March–May)	0.829

Bold values indicate statistically significant differences at greater than or equal to 0.05 between the two periods

for differences in precipitation during all seasons. Finally, both subdivisions of Madhya Pradesh also observed higher average precipitation during the post-GR period (Fig. 3e, f). For example, the results suggested 1 mm (1%), 25.32 mm (24%), 4.98 mm (47%), and 1 mm (4%) increases in precipitation for the rabi, zaid, peak rabi, and peak zaid seasons, respectively, in western Madhya Pradesh (Fig. 3e).

Subsequently, we analyzed the linear trends in growing season precipitation totals for the pre- and post-GR time periods for the different subdivisions (Fig. 4a–f). Precipitation during the rabi season in Punjab indicated negative trends for the both pre- and post-GR periods (Fig. 4a). However, this negative trend was stronger during the pre-GR period (−1.63 mm year^{-1}) compared to the post-GR period (−1.5 mm year^{-1}). In other words, the decline in negative trend can also be interpreted as a response to increasing irrigation during the post-GR period. During the zaid season, trends were positive during both pre- and post-GR periods, with a slower rate of increase during the post-GR period. It was 0.51 mm year^{-1} (pre-GR period) and 0.29 mm year^{-1} (post-GR period). The trends were also calculated for the peak rabi and the peak zaid growing seasons (period of maximum crop growth) across all meteorological subdivisions. During the peak rabi season, the trends were negative for both periods, with slower rates of increase during the post-GR period. On the other hand, during the peak zaid season, the trends were positive during the pre-GR period (0.27 mm year^{-1}) and negative for the post-GR period (−1.89 mm year^{-1}).

In neighboring Haryana, similar negative trends were observed during both regular and peak rabi seasons (Fig. 4b). However, these negative trends were notably muted during the post-GR period. The strongest negative trends were observed during the pre-GR peak rabi season (−1.77 mm year^{-1}), and the trend during the post-GR peak rabi season was significantly moderated (−0.84 mm year^{-1}). The overall zaid season trends were negative (−0.20 mm year^{-1}) and positive (1.23 mm year^{-1}) during the pre- and post-GR periods, respectively. During the peak zaid season, the trends were similar to those observed in the peak rabi season with negative trends during both periods, with a lower rate of decrease during the post-GR period. The linear trends in precipitation patterns for western Rajasthan were contrary to that observed in the case of the other regions, showing a negative trend during the post-GR period as opposed to positive trends in the pre-GR period (Fig. 4c). Similarly, in case of eastern Rajasthan, the trends were negative for all seasons during the post-GR period except during regular zaid season (Fig. 4d). For western Madhya Pradesh, the

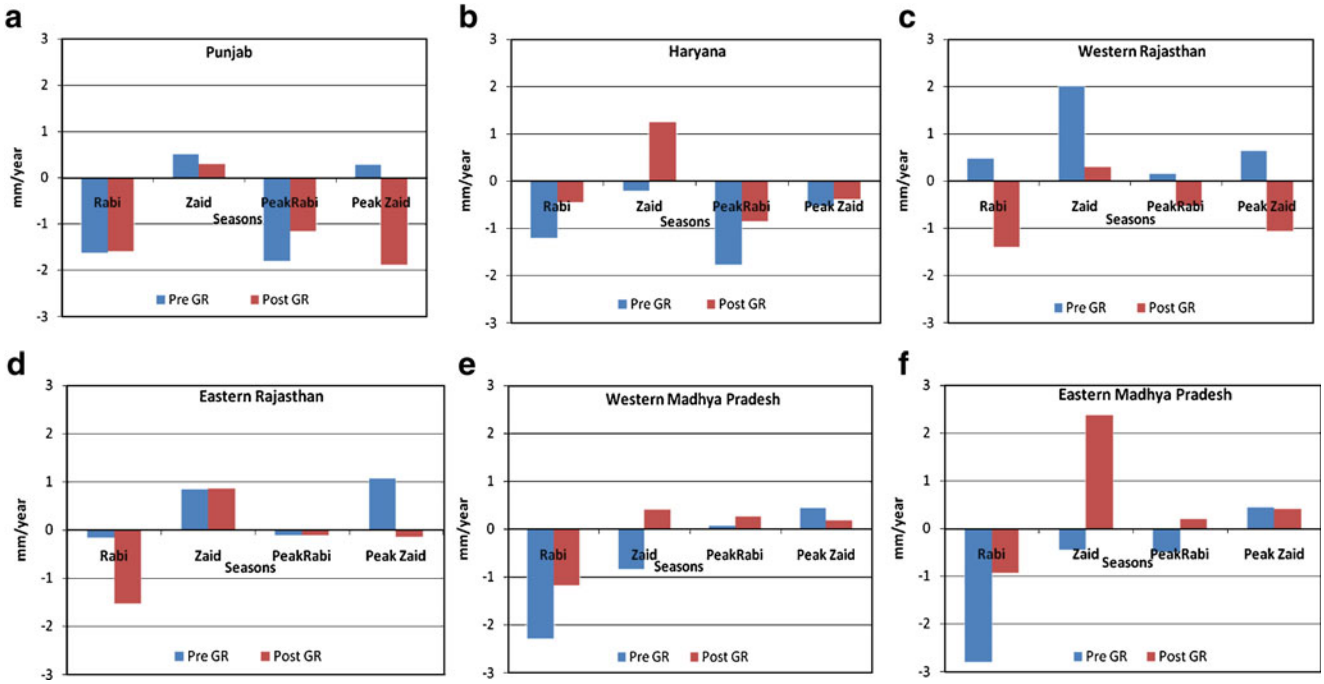

Fig. 4 Trends in seasonal precipitation amounts during pre- and post-Green Revolution periods across subdivisions located in northwestern and north central India. **a** Punjab; **b** Haryana; **c** Western Rajasthan; **d** Eastern Rajasthan; **e** Western Madhya Pradesh; **f** Eastern Madhya Pradesh

results were similar to that of Punjab and Haryana, where the rates of declining precipitation during the post-GR periods were lower than those observed during the pre-GR period (Fig. 4e). Furthermore, positive trends in precipitation were observed during the peak rabi season and the overall zaid and the peak zaid seasons. Finally, in case of eastern Madhya Pradesh, the trends were similar to that of western Madhya Pradesh (Fig. 4f). During the pre-GR period, the observed trends in precipitation were negative (ranging between 2.81 and −0.45 mm year^{-1}), except during the peak zaid season. On the other hand, for the post-GR period, the trends were mostly positive except during the rabi season. Note that the latter showed lower negative trends in precipitation change compared to the pre-GR period. The highest positive trend was 2.4 mm year^{-1}, observed during the post-GR zaid season.

3.2 Application of the MM5 and Noah LSM

To better understand the possible climate physical processes and further verify the impacts of SM changes due to irrigation and their impacts on precipitation, the MM5 version 3 was coupled to the Noah LSM (see Chen and Dudhia 2001) and applied. The current version of the Noah LSM in the MM5 uses four soil layers (10, 30, 60, and 100 cm thickness) to predict soil moisture, soil temperature, and snow cover. In the LSM, total soil depth is 2 m with the root zone in the upper 1 m of soil. In addition, the Kain–Fritsch deep and shallow convection parameterization (Kain 2004) was adopted. The medium-range forecast planetary boundary layer scheme was adopted (Hong and Pan 1996) for the specification of turbulent fluxes. A single domain of about 2,100 km (S–N)×2,700 km (W–E; Indian subcontinent and surrounding region) with 15 km horizontal resolution centered at 26.50 N and 81.00 W was used (Fig. 5). The size of the domain was considered sufficiently large to contain the synoptic events described below while minimizing the effects of the lateral walls.

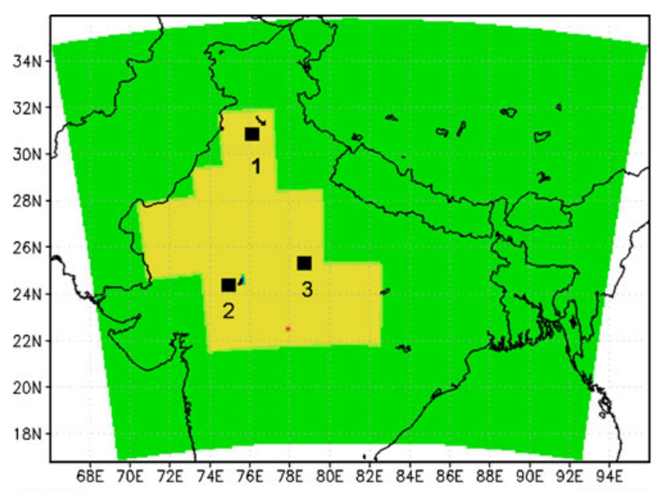

Fig. 5 Computational domain and surface stations within the irrigated area (soil moisture change; shown in *yellow*). The stations include *1* Ludhiana (30.93 N, 75.87 E), *2* Neemuch (24.47 N, 74.9 E), and *3* Jhansi (25.45, 78.58 E)

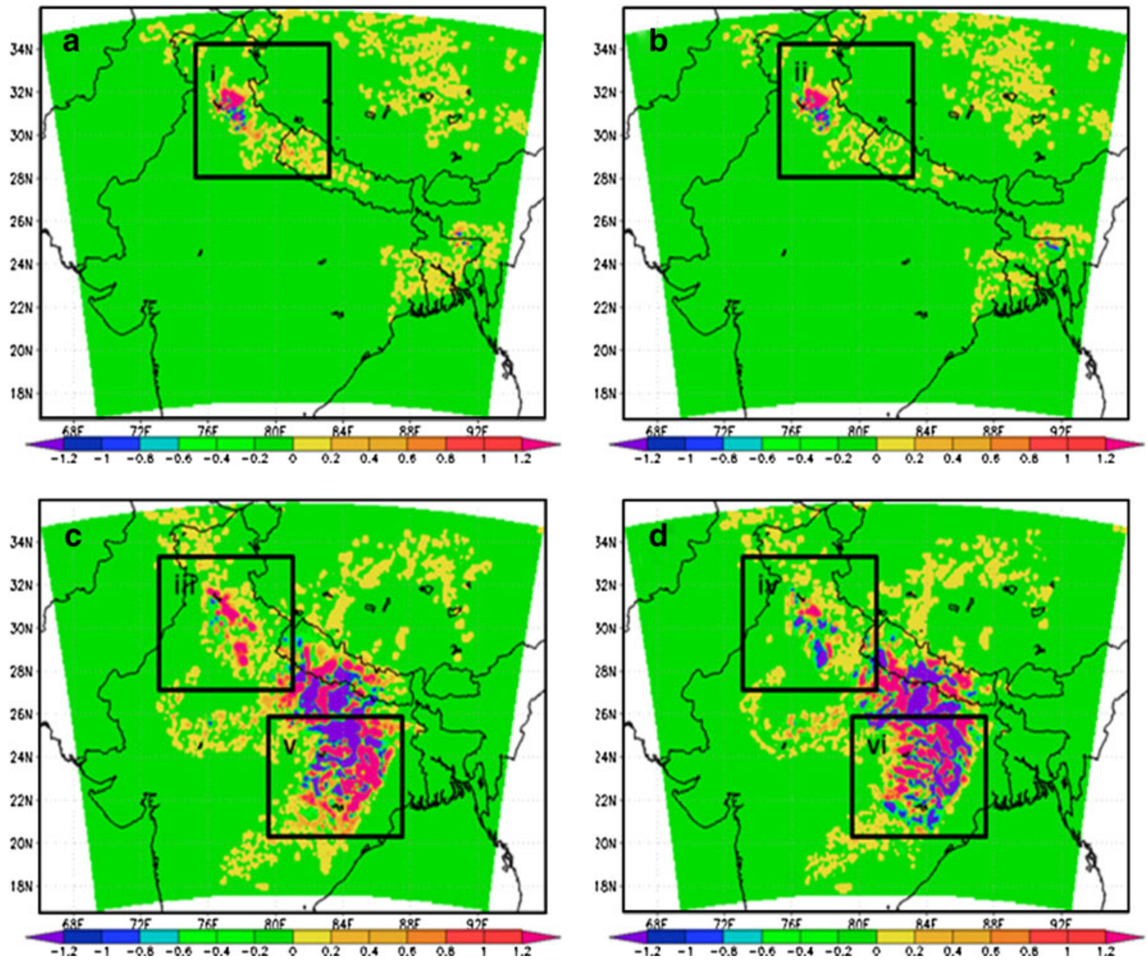

Fig. 6 Differences in 24 h accumulated precipitation (millimeters) up to March 5 1,800 Z: **a** CTRL minus DRY15 and **b** CTRL minus WET15 and up to March 23 1,800 Z: **c** CTRL minus DRY15 and **d** CTRL minus WET15. Close-up regions *i*, *ii* refer to March 5 and regions *iii*, *iv*, *v*, and *vi* refer to March 23

In the vertical, 31 levels were used with the top at 100 hPa and with 13 half-sigma levels below the 0.85 level, decreasing from 1.0 to 0.88 in intervals of 0.01 which roughly corresponded to a vertical resolution of about 90.0 m up to the 0.85 level.

The MM5 was initialized for four periods on March 4 1200 Z, March 11 1200 Z, and March 22 1200 Z, all of 2000, and March 13 1200 Z of 2002 with each experiment running a total of 30 h. Observations show 24, 1.1, 0.1, and 0.8 mm rainfall at three locations (Fig. 5) for these dates, respectively. Recall that the study region is generally extremely dry during this time period. In other words, the scanty rainfall amount is not out of the ordinary. Availability of observed precipitation and final reanalysis data (FNL) were primary determinant of these dates. Both the MM5 and the Noah LSM were initialized with NCEP FNL data at $1\times1°$ horizontal resolution and updated every 6 h (http://dss.ucar.edu/datasets/ds083.2/). Thus, there were four updates available for the 30-h runs for each experiment. Soil moisture data were included in the FNL data at the same four soil levels mentioned previously for the Noah LSM.

The approach to soil moisture sensitivity tests adopted here was previously successfully applied by Quintanar et al. (2008, 2009). Following their lead, three wet (WET) and three dry (DRY) soil moisture experiments were constructed for each precipitation event and over predominantly irrigated areas. In other words, total 28 simulations (four control (CTRL) and 24 sensitivity tests) were completed. DRY runs represented potential SM prior to widespread adoption of irrigation, CTRL simulations represent current soil water status, and WET for further modifications of soil moisture. These sets of simulations were expected to provide a comprehensive view of the impacts of irrigation and soil moisture change on precipitation. For each DRY (WET) experiment, a value of volumetric soil moisture (cubic meters per cubic meter) was subtracted (added) uniformly to the volumetric soil moisture distribution of the CTRL (i.e., for the entire computational domain). The values used were 0.05, 0.10, and 0.15. They will be referred to as DRY05,

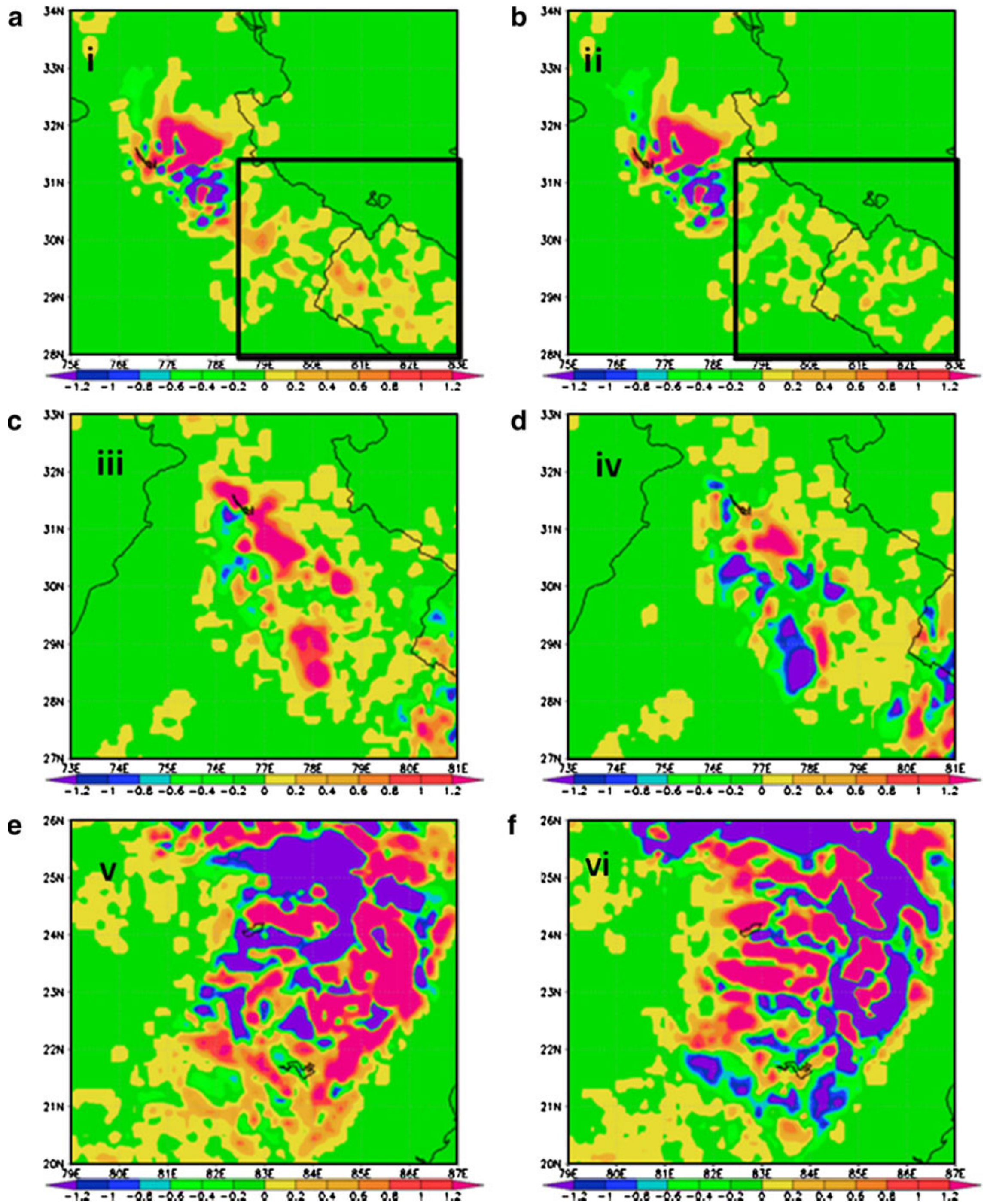

Fig. 7 Same as Fig. 6 but for close-up regions as shown in Fig. 6

DRY10, and DRY15 and WET05, WET10, and WET15 in the following discussions. With these changes, the horizontal gradients of soil moisture were kept the same for all simulations. This also reduced the possibility of the development of spurious mesoscale circulations within the domain (Ookouchi et al. 1984).

In these sensitivity tests, soil moisture was perturbed only at the initial time and allowed to evolve over the simulation period. Moreover, for the model integration period (which was relatively short), the signature in soil moisture perturbation was persistent over time and domain average sense. It needs to be noted that damping time scales of soil moisture perturbations have been studied by Liu and Avissar (1999) with a simplified model akin to that used in Biosphere–Atmosphere Transfer Scheme (Dickinson et al. 1993). They found four timescales were associated with soil

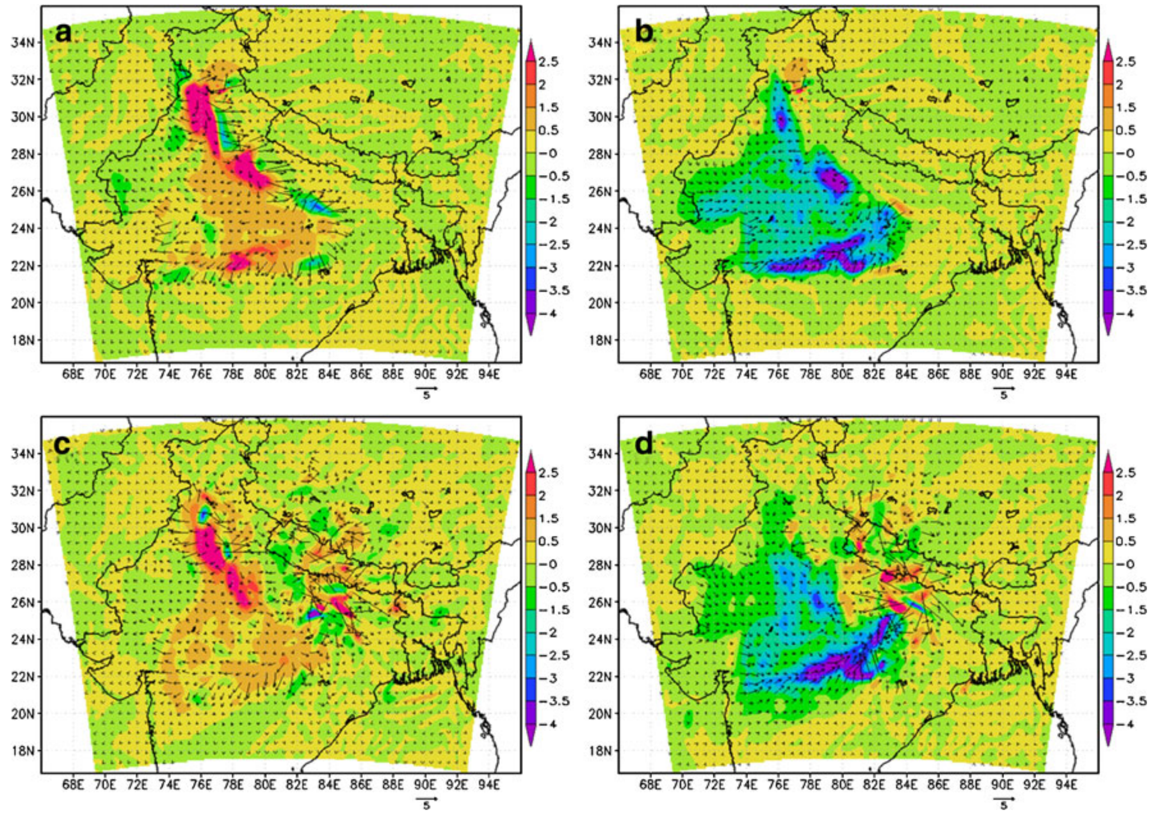

Fig. 8 Differences in equivalent potential temperature (kelvin) and the wind field (meters per second) at 975 mb and at 1,200 Z for March 5: **a** CTRL minus DRY15 and **b** CTRL minus WET15 and for March 23: **c** CTRL minus DRY15 and **d** CTRL minus WET15

moisture perturbations, namely seasonal, monthly, weekly, and daily. Soil moisture perturbations that persist on a daily time scale and interact with day-to-day synoptic systems are the focus of this study.

The discussion here primarily focuses on the cases of March 5 and 23. Figure 6a–d shows changes in precipitation under DRY15 and WET15 conditions on March 5, 2000 (24 mm) and March 23, 2000 (0.1 mm). Both dry and wet simulations show precipitation around Ludhiana on March 5, 2000 (Fig. 6a, b). However, under DRY15, precipitation declined immediate east of Ludhiana, while the difference between CTRL and WET15 was diminished (thus, increase in precipitation). A more enhanced version of Fig. 6a, b is shown in Fig. 7a-i, b-ii which verifies these model responses. In fact, one area within Fig. 7b-ii shows greater precipitation for WET15 compared to CTRL.

For March 23, WET15 shows precipitation south of Ludhiana and over irrigated areas, while relatively larger amounts of precipitation were simulated east of irrigated areas (Fig. 6c, d). Figure 7c-iii, d-iv shows general decrease and increase in precipitation under DRY15 and WET15, respectively, compared to CTRL. They also show changes in general location of the precipitation and more widespread and increased precipitation under CTRL-WET15. In addition, we suspect that the mismatch between actual and modeled location of precipitation is potentially related to accuracy of the land use land cover data (Niyogi 2008, personal communication) and model uncertainty. It is also noted that the impacts of LULCC and soil moisture modifications could be found in regions away from the location of maximum change (e.g., Chase et al. 2000; Sen et al. 2004).

Nonetheless, results of this study suggest that the model satisfactorily explained the mechanisms of precipitation changes. Here, we particularly focus on equivalent potential temperature (also known as moist static energy, θ_e), wind, and energy partitioning. Our previous studies suggest that these variables explain precipitation changes due to soil moisture modifications well (Quintanar et al. 2008, 2009). Figure 8a–d shows change in θ_e with dryer and wet soils. Pielke (2001) and others (Findell and Eltahir 1997; Quintanar et al. 2008) have suggested that θ_e is capable explaining the development of convective events and precipitation. Figure 8b, d shows increased θ_e and changes in horizontal wind for 975 mb under WET15 conditions for March 5 and 23. On the other hand, DRY15 indicates lowering of θ_e and potentially inhibiting development of convection and rainfall (Fig. 8a, c). In addition, the cross-section analysis for the central region of irrigated land use (Fig. 9a–d) shows that there were increases in lower

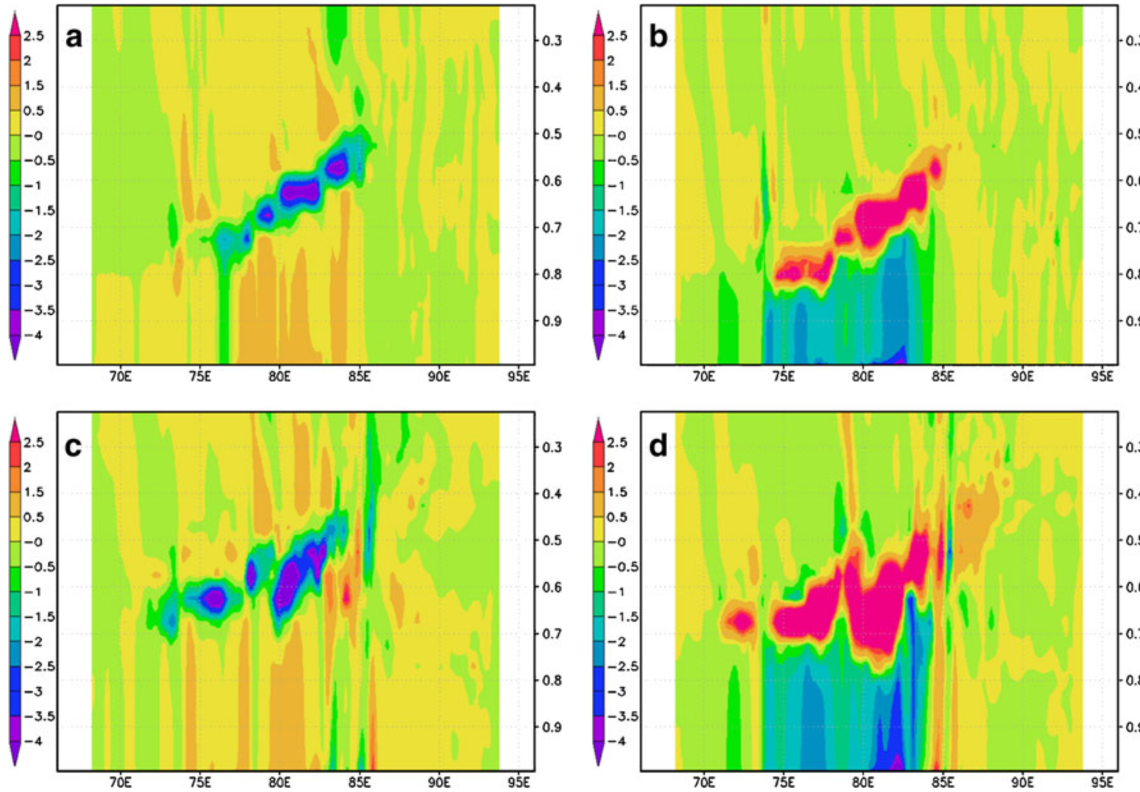

Fig. 9 Differences in equivalent potential temperature (kelvin) as a function of the model's terrain-following vertical coordinates and longitude at latitude 24 N and at 1,200 Z for March 5: **a** CTRL minus DRY15 and **b** CTRL minus WET15 and for March 23: **c** CTRL minus DRY15 and **d** CTRL minus WET15

atmospheric θ_e compared to CTRL for both March 5 and 23 events under WET15 conditions. Also found was a diminished difference in θ_e to the east and west of the irrigated region, while DRY15 shows much lower θ_e compared to CTRL for the irrigated region. Overall, these results are consistent with previous findings from similar studies (e.g., Quintanar et al. 2008, 2009).

Lower atmospheric energy partitioning plays an important role in convection and precipitation development (e.g., Raddatz and Cummine 2003; Numaguti 1999). Analysis of simulated data suggests increase (decrease) in latent (sensible) energy flux for the irrigated area (Fig. 10a–d) for March 5 and 23. On March 5 (0700 Z) under DRY15 and WET15 conditions, latent heat fluxes were 22 and 216 Wm^{-2}, respectively (Fig. 10a). On March 23, these values were 24 and 219 Wm^{-2} for DRY15 and WET15 conditions, respectively. For March 5, sensible heat fluxes (0700 Z) for DRY15 and WET15 were 398 and 198 Wm^{-2}, respectively. On March 23, these fluxes were 434 and 225 Wm^{-2}, respectively. Figure 11a–f clearly shows increasing and decreasing sensible heat flux with drying and wetting of soils over the irrigated regions, respectively. On the other hand, latent heat flux decreased and increased with drying and wetting of soils, respectively (Fig. 12a–f). In summary, it is evident that the increased latent energy flux due to irrigation has increased and created a condition for enhanced rainfall. Further discussion of the impacts of these flux changes is provided in the next section.

4 Discussion and final remarks

In the present study, we have investigated the GR-related expansion of irrigation and its impacts on the long-term precipitation in northwestern India. We have analyzed the trends and averages of precipitation for the pre- and post-GR. We acknowledge that one of the limitations of the current study includes the absence of larger number of observed daily precipitation data from various stations which could lead us to conduct additional simulations. In the future, we hope to overcome this issue. The main findings of the study are summarized below:

1. Meteorological subdivisions/regions of northwestern India experienced both decreasing and increasing *trends* in precipitation during the post-GR period. It was suggested that increasing trends were linked to the post-GR increases in precipitation. The declining trends were lower during the post-GR period in comparison to the pre-GR period. It is noted that the lower negative

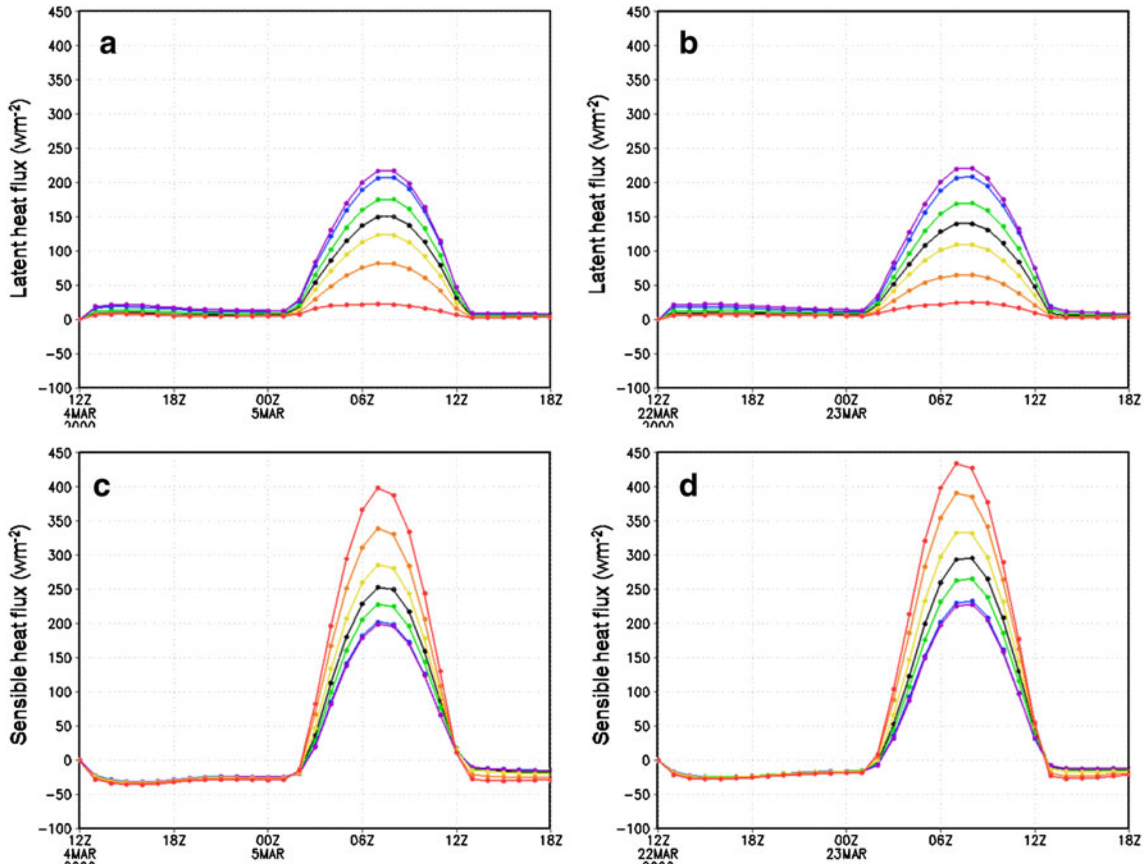

Fig. 10 Area (shown in yellow in Fig. 4) average latent heat fluxes for **a** March 5 and **b** March 23 and sensible heat fluxes for **c** March 5 and **d** March 23. CTRL (*black*), DRY05 (*yellow*), DRY10 (*orange*), DRY15 (*red*), WET05 (*green*), WET10 (*blue*), and WET15 (*violet*)

trends were caused by increasing precipitation during the post-GR period.

2. The results clearly suggest higher growing season average precipitation during post-GR period for all but one region within northwest India. The highest increases were observed in Punjab and Haryana.
3. The results indicate statistically significant differences between pre- and post-GR precipitation for both the peak and entire growing seasons for most of the areas.
4. Applications of the MM5 model also suggest enhancement of precipitation under irrigation (and thus increased soil moisture). The change in precipitation was accompanied by increased latent energy flux, θ_e, and changes in the wind field.

Our results are entirely in line with the findings of Sen Roy et al. (2007), which clearly showed that irrigation and enhanced soil moisture has lowered near-surface temperatures during the post-GR period (Fig. 4; Sen Roy et al. 2007). The study also showed an increase in atmospheric moisture content and latent heat flux. Sen Roy et al. (2007) found up to 100% and 20% increase in moisture flux and specific humidity, respectively, over irrigated areas in northern India during the dry seasons. Hence, an increase in local and regional precipitation due to the introduction of intense irrigation is not surprising.

Previously, Betts and Ball (1995) and Betts et al. (1996) provided explanations of the processes likely responsible for precipitation under enhanced soil moisture status. We suggest that similar processes were responsible for the increased precipitation in northwestern India. It was reported in these studies that soils with higher moisture content result in a shallower boundary layer and thus concentration of larger amounts of moisture and heat fluxes within a thin layer of air. This leads to further convective instability. Schär et al. (1999) also noted that high soil moisture content caused a lowering of the level of free convection, and hence, convective instability could be released. Those authors found that the net radiation would increase under moist soils leading to increased moist entropy in planetary boundary layer. Like Schär et al. (1999), the authors of the present study suggest that all of these processes under enhanced soil moisture due to irrigation caused an increase in precipitation during post-GR period in northwestern India.

Barnston and Schickendanz (1984) reported an increase in irrigation-induced precipitation in the Texas Panhandle.

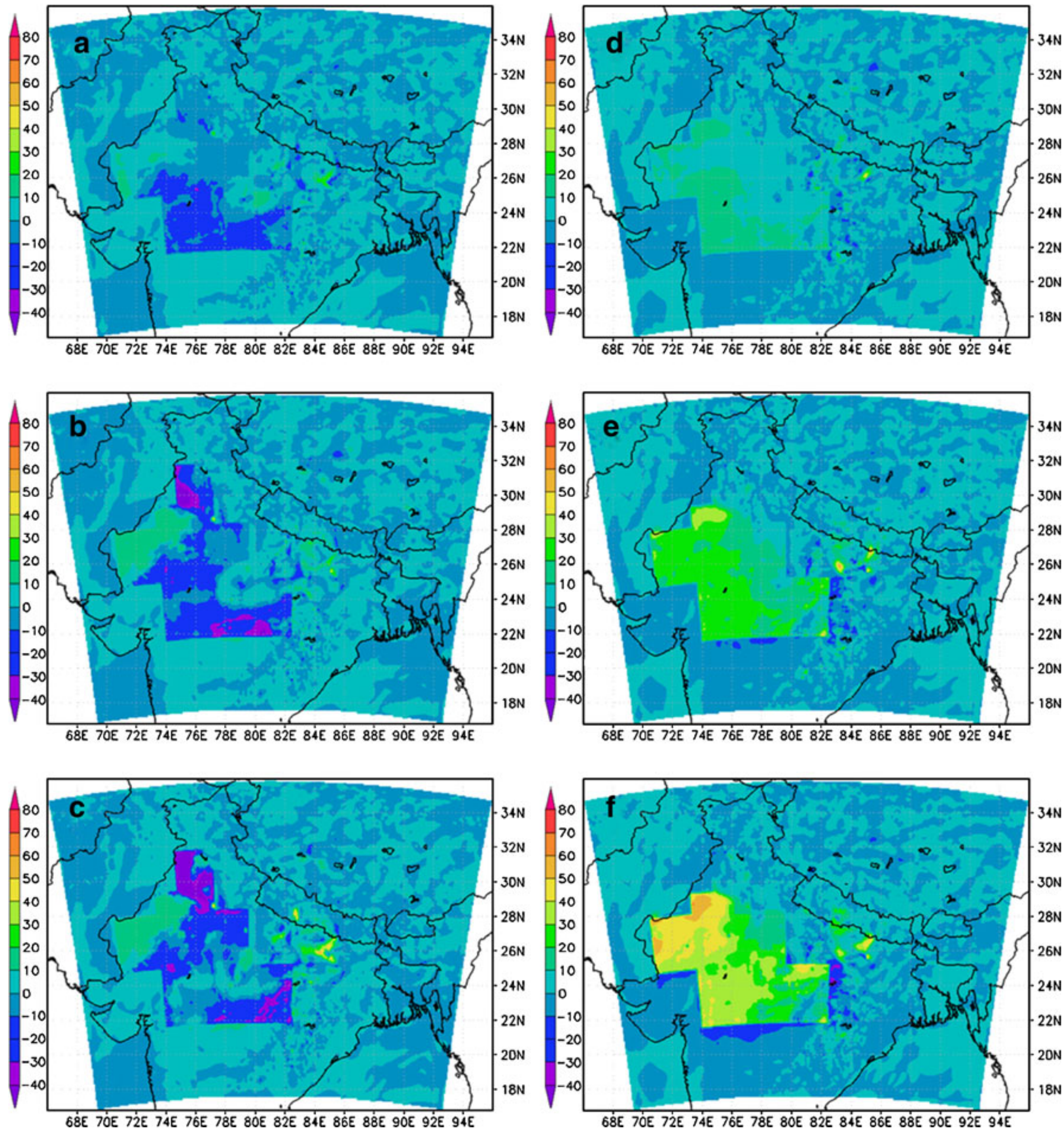

Fig. 11 March 23, sensible heat flux differences (watts per square meter): **a** CTRL minus DRY05, **b** CTRL minus DRY10, **c** CTRL minus DRY15, **d** CTRL minus WET05, **d** CTRL minus WET10, and **e** CTRL minus WET15

Mahmood and Hubbard (2002) demonstrated that there could be 36% increase in evapotranspiration in the Northern Great Plains due to conversion of natural grassland to irrigated agriculture. Recently, Mahmood et al. (2008) have found up to a 2.17°C increase in dew point temperature over irrigated areas of the Northern Great Plains. A series of studies set in the Canadian Prairies clearly suggested increases in convective activity due to conversion of natural grassland to farming (Hensiak et al. 2004; Raddatz 2003, 2007; Raddatz and Cummine 2003). These authors have noted that changes in evaporative fluxes and its impacts on development of boundary layer played a key role. The authors of the present study suggest that similar changes in land surface conditions resulted in an increase of precipitation in northwestern India during post-GR period.

The studies by Rabin et al. (1990) and Segal et al. (1995) suggested that various types of cumulus clouds formed along the discontinuity of lowest Bowen ratio, and the timing of cloud development was dependent on land surface soil moisture content. In addition, it has been reported in the literature that if the size of vegetated areas becomes approximately equal to the synoptic scale, then frictional inflow associated with cyclonic disturbances enhances due to increase in surface roughness and results in a significant increase in rainfall (Segal et al. 1988; Chang

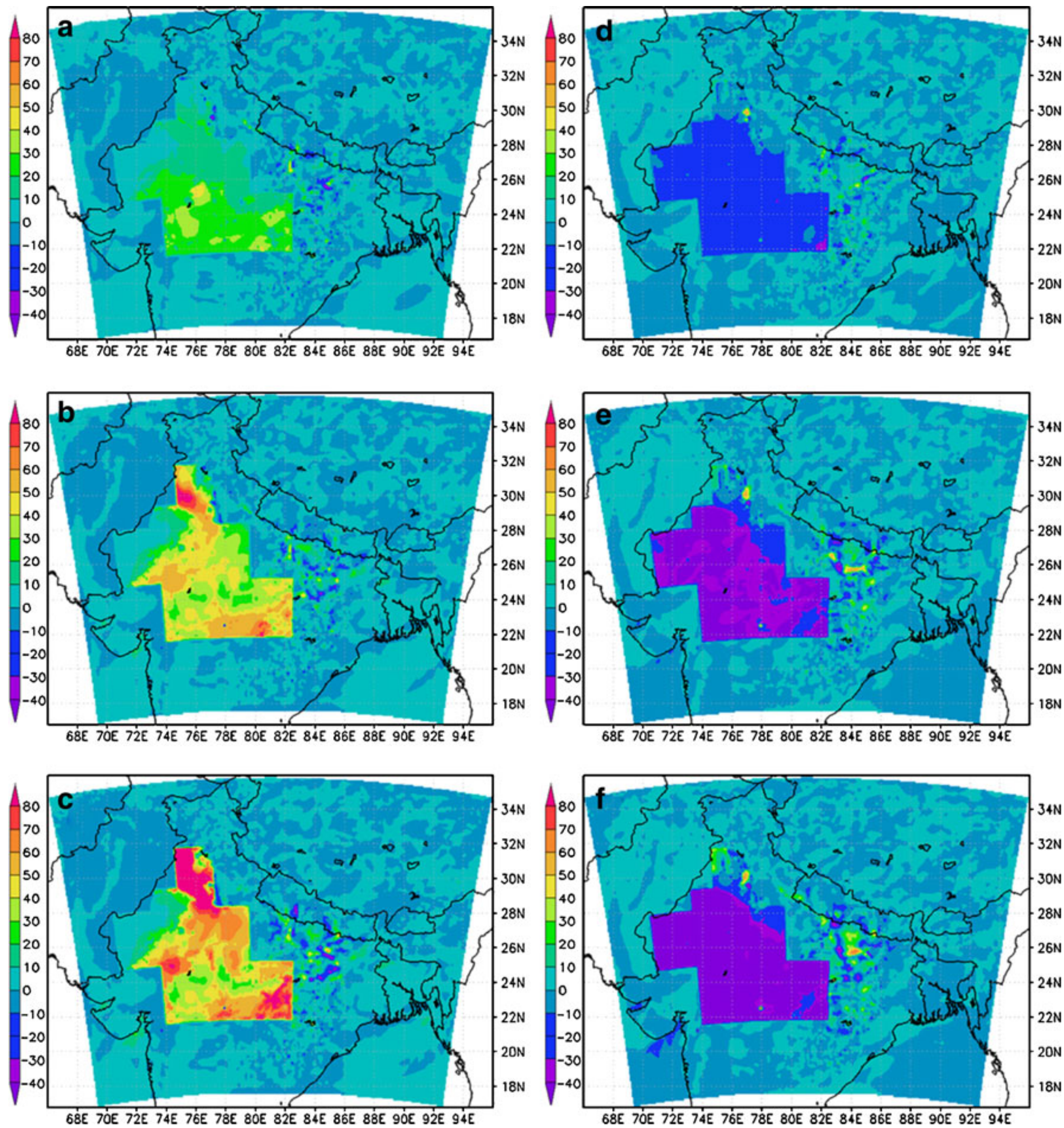

Fig. 12 Same as Fig. 11 but for latent heat flux differences

and Wetzel 1991; Adegoke et al. 2007). We suggest that a similar mechanism could partly be responsible for increased precipitation in irrigated areas of northwestern India during the post-GR period.

Using data from the Oklahoma Mesonet, Basara and Crawford (2002) noted a strong linear relationship between root zone soil moisture and daytime evaporative fraction. Recently, Quintanar et al. (2008) have found that either an increase or decrease of soil moisture affects the evolution of boundary layer and precipitation amount and its timing. They have noted that changes in Bowen ratio, equivalent potential temperature (moist static energy, θ_e), and initiation of strong vertical velocity due to soil moisture changes significantly control precipitation. We suggest that increases in soil moisture due to the adoption of irrigated agriculture has similarly modified the growing season energy balance, planetary boundary layer moisture flux, and thermodynamic properties which led to enhanced seasonal rainfall in northwestern India during the post-GR period.

Lyons (2002) found that the adoption of farming in Western Australia and related modification in aerodynamic properties of vegetation has resulted in a reduced frequency of convective cloud development. In a sense the current work agrees with the research presented in Lyons (2002). Adegoke et al. (2007) and Carleton et al. (2001) have found, in the midwestern USA, that peak cloud development occurred nearly 2 h earlier over agricultural land uses. Hence, again, this paper suggests that post-GR enhancement of precipitation in northwestern India is linked to land use change and elevated soil moisture content due to irrigation.

Chase et al. (2007) have reported enhanced greenness and lower sensible heat flux during March–May (thus, physically agrees with the present study), lower land–ocean temperature difference, and resultant lowering of July rainfall in India and noted that this was possibly linked to land use change. Kim and Hong (2007) found that an increase in spring-time soil moisture has enhanced seasonal precipitation in East Asia. However, they have also noted that the wet soil resulted in lower temperature contrasts and weakening of the pressure gradient between land and ocean and of the East Asian monsoon circulation. Based on these findings, it is reasonable to suggest that the lowering of dry growing season near-surface temperature (Sen Roy et al. 2007) and enhanced precipitation (reported here) due to irrigation, increase in irrigation-linked soil moisture, and resultant changes in albedo in northwestern India could profoundly impact the strength of subsequent wet summer monsoon and precipitation. These warrant further research. Therefore, we call for additional studies to better understand the impacts of land use change and associated increase in dry season precipitation in northwestern India. In particular, modeling and satellite climate studies could be undertaken to complement the results presented here. Follow-up research activities could examine land use forced dry season climate changes and subsequent wet monsoon precipitation.

Chase et al. (2000) and Sen et al. (2004) have shown that modifications in land use could affect climates of remote areas. It is well-known that the south Asian monsoonal climate is an interactive system and plays a critical role in global atmospheric circulation and re-distribution of mass, momentum, and energy. Thus, new research efforts need to be undertaken to determine remote climatic impacts due to the LULCC caused regional climate change in India.

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References

Adegoke JO, Pielke RA, Carleton AM (2007) Observational and modeling studies of the impact of agriculture-related land use change on climate in the central U.S. Agric For Meteorol 142:203–215

Aligo EA, Gallus WA, Segal M (2007) Summer rainfall forecast spread in an ensemble initialized with different soil moisture analyses. Weather Forecast 22:299–314

Alonge CJ, Mohr KI, Tao W-K (2007) Numerical studies of wet versus dry soil regimes in the West African Sahel. J Hydrometeorol 8:102–116

Anthes RA (1984) Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. J Appl Meteorol 23:541–554

Barlage M, Zeng X (2004) The effects of observed fractional vegetation cover on the land surface climatology of the community land model. J Hydrometeorol 10:823–830

Barnston AG, Schickendanz PT (1984) The effects of irrigation on warm season precipitation in the southern Great Plains. J Clim Appl Meteorol 23:865–888

Basara JB, Crawford KC (2002) Linear relationships between root-zone soil moisture and atmospheric processes in the planetary boundary layer. J Geophys Res 107(D15):4274. doi:10.1029/2001JD000633

Betts AK, Ball JH (1995) The FIFE surface diurnal cycle climate. J Geophys Res 100(25):679–25693

Betts AK, Ball JH, Beljaars ACM, Miller MJ, Viterbo PA (1996) The land surface–atmosphere interaction: a review based on observational and global perspectives. J Geophys Res 101:7209–7225

Carleton AM, Adegoke J, Allard JO, Arnold DL, Travis DJ (2001) Synoptic context of summer season land cover-convective cloud associations for the Midwest US "Corn Belt". Geophys Res Lett 28:1679–1682

Chang JT, Wetzel PJ (1991) Effects of spatial variations of soil moisture and vegetation on the evolution of a prestorm environment: a numerical case study. Mon Weather Rev 119:1368–1390

Chase TN, Pielke RA Sr, Kittel TGF, Nemani RR, Running SW (2000) Simulated impacts of historical land cover changes on global climate in northern winter. Clim Dyn 16:93–105

Chase TN, Lawrence PT, Lee E (2007) Comparisons of the effect of land surface hydrology and deforestation on three Asian Monsoon systems. Workshop on detecting the atmospheric response to the changing face of the Earth: a focus on human-caused regional climate forcings, land-cover/land-use change, and data monitoring. Held on August 27–29, 2007, Boulder, CO. http://kyclim.wku.edu/Boulder.html. Accessed on Apr 2008

Chen F, Dudhia J (2001) Coupling an advanced land surface—hydrology model with the Penn State-NCAR MM5 modeling system. Part I: model implementation and sensitivity. Mon Weather Rev 129:934–958

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Dickinson RE, Henderson-Sellrs A, Kennedy PJ (1993) Biosphere–Atmosphere Transfer Scheme (BATS) version 1E as coupled to the NCAR community climate model. NCAR Tech. Note TN-387. National Center for Atmospheric Research, Boulder, p 72

Dudhia J (1993) A nonhydrostatic version of the Penn State–NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. Mon Weather Rev 121:1493–1513

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The importance of land-cover change in simulating future climates. Science 310:1674–1678

Findell K, Eltahir E (1997) An analysis of the soil moisture–rainfall feedback based on direct observations from Illinois. Water Resour Res 33:725–735

Findell KL, Eltahir EAB (2003) Atmospheric controls on soil moisture-boundary layer interactions: three-dimensional wind effects. J Geophys Res 108:D8,8385. doi:10.1029/2001JD001515

Gallus WA Jr, Segal M (2000) Sensitivity of forecast rainfall in a Texas convective system to soil moisture and convective parameterization. Weather Forecast 5:509–525

Gordon LJ, Steffen W, Jonsson BF, Folke C, Falkenmark M, Johannessen A (2005) Human modifications of global water vapor flows from the land surface. Proc Natl Acad Sci 102:7612–7617

Hensiak JM, Raddatz RL, Lobban S (2004) Local initiation of deep convection on the Canadian Prairie provinces. Boundary-Layer Meteorol 110:455–470

Hong S-Y, Pan H-L (1996) Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon Weather Rev 124:2322–2339

Kain J (2004) The Kain-Fritsch convective parameterization: an update. J Appl Meteorol 43:170–181

Kim J-E, Hong S-Y (2007) Impact of soil moisture anomalies on summer rainfall over East Asia: a regional climate model study. J Clim 20:5732–5743

Koster RD, Dirmeyer PA, Zhichang G, Bonan G, Chan E, Cox P, Gordon CT, Kanae S, Kowalczyk E, Lawrence D, Liu P, Lu C-H, Malyshev S, McAvaney B, Mitchell K, Mocko D, Oki T, Oleson K, Pitman A, Sud YC, Taylor CM, Verseghy D, Vasic R, Xue Y, Yamada T (2004) Regions of strong coupling between soil moisture and precipitation. Science 305:1138–1140

Lanicci JM, Carlson TN, Warner TT (1987) Sensitivity of the Great Plains severe storm environment to soil-moisture distribution. Mon Weather Rev 115:2660–2673

Liu Y, Avissar R (1999) A study of persistence in the land-atmosphere system with a fourth-order analytical model. J Clim 12:2154–2168

Lyons TJ (2002) Clouds prefer native vegetation. Meteorol Atmos Phys 80:131–140

Mahmood R, Hubbard KG (2002) Anthropogenic land-use change in North American tall-grass transition and modification of near surface hydrologic cycle. Clim Res 21:83–90

Mahmood R, Hubbard KG, Leeper D, Foster SA (2008) Increase in near-surface atmospheric moisture content due to land use changes: evidence from the observed dewpoint temperature data. Mon Weather Rev 136:1554–1561

Mahmood R, Pielke RA Sr, Hubbard KG, Niyogi D, Bonan G, Lawrence P, Baker B, McNider R, McAlpine C, Etter A, Gameda S, Qian B, Carleton A, Beltran-Przekurat A, Chase T, Quintanar AI, Adegoke JO, Vezhapparambu S, Conner G, Asefi S, Sertel E, Legates DR, Wu Y, Hale R, Frauenfeld ON, Watts A, Shepherd M, Mitra C, Anantharaj VG, Fall S, Lund R, Nordfelt A, Blanken P, Du J, Chang H-I, Leeper R, Nair US, Dobler S, Deo R, Syktus J (2010) Impacts of land use land cover change on climate and future research priorities. Bull Am Meteorol Soc 91:37–46

Narisma GT, Pitman AJ (2003) The impact of 200 years of land cover change on the Australian near-surface climate. J Hydrometeorol 4:424–436

Numaguti A (1999) Origins and recycling processes of precipitating water over the Eurasian continent: experiments using an atmospheric general circulation model. J Geophys Res 104:1957–1972

Ookouchi Y, Segal M, Kessler RC, Pielke RA (1984) Evaluation of soil moisture effects on the generation and modification of mesoscale circulations. Mon Weather Rev 112:2281–2292

Pal JS, Eltahir EAB (2001) Pathways relating soil moisture conditions to future summer rainfall within a model of the land–atmosphere system. J Clim 14:1227–1242

Pant GB, Rupa Kumar K (1997) Climates of South Asia. Wiley, Hoboken, p 320

Parthasarathy B, Munot AA, Kothawale DR (1995) All India monthly and seasonal rainfall series: 1871–1993. Theor Appl Climatol 49:217–224

Pielke RA (2001) Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convection rainfall. Rev Geophys 39:151–177

Pielke RA, Adegoke J, Beltran-Przekurat A, Hiemstra CA, Lin J, Nair US, Niyogi D, Nobis TE (2007a) An overview of regional land use and land cover impacts on rainfall. Tellus Ser B 59:587–601

Pielke RA, Adegoke JO, Chase TN, Marshall CH, Matsui T, Niyogi D (2007b) A new paradigm for assessing the role of agriculture in the climate system and in climate change. Agric For Meteorol 142:234–254

Quintanar IA, Mahmood R, Loughrin J, Lovanh NC (2008) A coupled MM5–NOAH land surface model-based assessment of sensitivity of planetary boundary layer variables to anomalous soil moisture conditions. Phys Geogr 29:54–78

Quintanar AI, Mahmood R, Motley MV, Yan J, Loughrin J, Lovanh N (2009) Simulation of boundary layer trajectory dispersion sensitivity to soil moisture conditions: MM5 and Noah-based investigation. Atmos Environ 43:3774–3785

Rabin SM, Stadler S, Wetzel PS, Stensrud DJP, Gregory MDJ (1990) Observational effects of landscape variability on convective clouds. Bull Am Meteorol Soc 71:272–280

Raddatz RL (2003) Agriculture and tornadoes on the Canadian Prairies: potential impact of increasing atmospheric CO2 on summer severe weather. Nat Hazards 290:113–122

Raddatz RL (2007) Evidence for the influence of agriculture on weather and climate through the transformation and management of vegetation: illustrated by examples from the Canadian Prairies. Agric For Meteorol 142:186–202

Raddatz RL, Cummine JD (2003) Inter-annual variability of moisture flux from the prairie agro-ecosystem: impact of crop phenology on the seasonal pattern of tornado days. Boundary-Layer Meteorol 106:283–295

Ramankutty N, Foley J (1999) Estimating historical changes in global land cover: croplands from 1700 to 1992. Glob Biogeochem Cycles 13:997–1027

Schär C, Luthi D, Beyerle U (1999) The soil-precipitation feedback: a process study with a regional climate model. J Clim 12:722–741

Segal M, Arrit RW (1992) Non-classical mesoscale circulations caused by surface sensible heat-flux gradients. Bull Am Meteorol Soc 73:1593–1604

Segal M, Avissar R, McCumber CM, Pielke RA Sr (1988) Evaluation of vegetation effects on the generation and modification of mesoscale circulations. J Atmos Sci 45:2268–2292

Segal M, Arrit RW, Clark C, Rabin R, Brown J (1995) Scaling evaluation of the effect of surface characteristics on potential for deep convection over uniform terrain. Mon Weather Rev 123:383–400

Sen OL, Wang B, Wang Y (2004) Impacts of re-greening the desertified lands in Northwestern China: implications from a regional climate model experiments. J Meteorol Soc Japan 82:1679–1693

Sen Roy S, Mahmood R, Niyogi DDS, Lei M, Foster SA, Hubbard KG, Douglas E, Pielke RA Sr (2007) Impacts of the agricultural Green Revolution induced land use changes on air temperatures in India. J Geophys Res 112:D21108. doi:10.1029/2007JD008834

Sutton C, Hamill TM, Warner TT (2006) Will perturbing soil moisture improve warm-season ensemble forecasts? A proof of concept. Mon Weather Rev 134:3174–3188