JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D21108, doi:10.1029/2007JD008834, 2007

Impacts of the agricultural Green Revolution–induced land use changes on air temperatures in India

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Received 16 April 2007; revised 29 June 2007; accepted 3 August 2007; published 13 November 2007.

[1] India has one of the most intensive and spatially extensive irrigation systems in the world developed during the1960s under the agricultural Green Revolution (GR). Irrigated landscapes can alter the regional surface energy balance and its associated temperature, humidity, and climate features. The main objective of this study is to determine the impacts of increased irrigation on long-term temperature trends. An analysis of the monthly climatological surface data sets at the regional level over India showed that agriculture and irrigation can substantially reduce the air temperature over different regions during the growing season. The processes associated with agriculture and irrigation-induced feedback are further diagnosed using a column radiation-boundary layer model coupled to a detailed land surface/hydrology scheme, and 3-D simulations using a Regional Atmospheric Modeling System. Both the modeling and observational analysis provide evidence that during the growing season, irrigation and agricultural activity are significantly modulating the surface temperatures over the Indian subcontinent. Therefore irrigation and agricultural impacts, along with land use change, and aerosol feedbacks need to be considered in regional and global modeling studies for climate change assessments.

Citation: Roy, S. S., R. Mahmood, D. Niyogi, M. Lei, S. A. Foster, K. G. Hubbard, E. Douglas, and R. Pielke 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.

1. Introduction

[2] The complex interrelationships between land cover and land use change in the context of variable climatic conditions have been widely investigated [e.g., *Chase et al.*, 2000; *Bounoua et al.*, 2002; *Baidya Roy et al.*, 2003; *McPherson et al.*, 2004; *Feddema et al.*, 2005a]. According to *Houghton* [1990], changes in land uses have contributed to about 25% enhanced levels of greenhouse gases in terms of anthropogenic activities. *Pielke et al.* [2002] concluded that land use change is an important climate policy consideration beyond the radiative effects of greenhouse gases. The majority of studies in the last century have focused on the effects of deforestation and denudation of natural landscapes and associated impacts on the surrounding environment [*Brown et al.*, 1991; *Flint and Richards*, 1991]. Some of the findings from these studies are related to greater temperature variations, decreased proportions of soil retention of carbon, and increased levels of pollution and changes in precipitation pattern [*Houghton*, 1994; *Kauppi et al.*, 1992; *Pielke et al.*, 2002, 2007a].

[3] However, in recent years awareness about the impact of changes in agricultural land use in terms of cropping practices and irrigation on the resulting local weather conditions has substantially increased [*Stohlgren et al.*, 1998; *Foley et al.*, 2005; *Douglas et al.*, 2006, 2007; *Pielke et al.*, 2007b]. One such study by *Ramankutty and Foley* [1999] systematically focused on changes in land use patterns over the last three centuries from 1700 to 1992. They used a combination of historical land use data and satellite imagery to monitor the changes in cropland acreage over different time periods. This study found, globally, significant conversion of forest lands to croplands since the year 1700. A primary example of this trend is the northwestern (NW) Indo-Gangetic Plain of the Indian subcontinent which extends eastward along the foothills of the Himalaya in north-central (NC) India; here the gradual intensification of cropland has been replacing forests/woodlands since 1940. This regional expansion of agricultural cropland has been even greater since 1947 because of independent India's rising population and its subsequent increased demand for agricultural products.

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0148-0227/07/2007JD008834$09.00

[4] Another significant development in India's land use history is the so-called Green Revolution (GR) that has substantially changed the NW and NC Indian landscape. The GR started in 1965 with the introduction of improved varieties of seeds, fertilizers, and an intricate canal/irrigation network throughout NW India which made the region less dependent on precipitation. The benefits of the GR were concentrated initially in NW and NC India where the Indo-Gangetic river system ensured adequate water supply. In 1960, a total of approximately 1.9 million hectares with high yields of wheat, rice, and other grains in several varieties rapidly increased after the introduction of irrigation to 15.4 million hectares by 1970 and 43.1 million hectares in 1980. Thus the region saw a 20-fold expansion of irrigated land use over a 20-a period. Since 1980, the land use change has largely stabilized in these regions (Green Revolution in India, http://www.indianchild.com/green_revolution_india.htm, accessed on 1 May 2006).

[5] The main agricultural seasons in India are kharif (June to September), rabi (November to May), and zaid (March to June). Moreover, the peak rabi and zaid growing seasons are from February through April, and March through May, respectively. These periods coincide with the maximum vegetative growth and associated higher crop water requirements. During the kharif season, the summer monsoon rainfall meets most of the irrigation needs.. However, during the rabi and zaid seasons, regional agriculture fully depends on irrigation. Wheat is one of the primary crops grown during the rabi season, and oilseeds and other types of cash crops are planted during the zaid season, the driest of the three growing periods. The relatively greater availability of adequate water resources during these drier periods has likely modulated the land-atmosphere interaction in the region.

[6] The climatological impacts of the GR in NW and NC India have not been fully studied. Given the large-scale changes in land use resultant from the GR agricultural intensification in NW and NC India, the key objective of this paper is to determine the impacts of the introduction of irrigation to the following three components of this regions' climatology: (1) the observed long-term monthly maximum and minimum temperatures, (2) diurnal temperature range (DTR), and (3) average temperatures at the seasonal timescale. The main causative process resulting from the introduction of extensive irrigation is the greater availability of water for evaporation/transpiration (ET) leading to increased partitioning of energy into latent heat [*Mahmood et al.*, 2004; *Douglas et al.*, 2007]. As a result, we hypothesize that an overall cooling trend in the long-term surface temperatures might be occurring. In the present study we have focused on the impact of land use changes associated with the GR on the long-term temperatures in NW and NC India, where the impact is generally considered greatest (Figure 1). In the 1960s, the GR was viewed as a critical socioeconomic force for transforming the lives of millions of people in India. Over the subsequent years of the introduction of irrigation to this region, this model of agrarian transformation has also been adopted in other parts of the world.

[7] In order to understand the processes contributing to irrigation impact on the surface temperatures over the NW and NC India, and inductively the implications of comprehensive irrigation and its impact in other areas where it is practiced, this study applied a coupled boundary layer-land surface model with detailed hydrology and vegetation response [*Gottschalk et al.*, 2000; *Niyogi et al.*, 2004]. The model was applied to understand the processes contributing to irrigation impact on the surface temperatures over the NW and NC India. The present study provides a unique opportunity to assess the impacts of GR-driven extensive agricultural intensification/land use change and irrigation on regional temperature within the monsoon domain based on observed data in the NW and NC India.

2. Background Studies

[8] The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR), as well as the Fourth Assessment for Policy Makers, revealed the relatively poor understanding of the impact of land use changes on the long-term trends shown in environmental variables. This knowledge gap was reemphasized by *Pielke et al.* [2002] and *Pielke et al.* [2007a], who recommended an original approach to the quantification of changes in vegetation cover as this impacts energy partitioning at different spatial scales of the climate system. Their study also indicated a need for comparative climatological investigations and suggested contrasting the impacts of land use change on remote, local, and regional climate.

[9] Previous studies have examined the impact of irrigation on near surface air temperatures in order to better understand the role of soil moisture on the general temperatures at different spatial scales. One of the earlier studies showing differences in temperatures between irrigated and nonirrigated areas was conducted by *Idso et al.* [1981]. They found a temperature difference of about 12 K between irrigated and nonirrigated alfalfa fields. Similarly, a temperature difference of nearly 10 K between irrigated and non irrigated land uses was reported by *Segal et al.* [1989] in eastern Colorado. Other studies showing a similar relationship between soil moisture and current temperatures, and following monthly temperatures, include *Walsh et al.* [1985] and *Williams* [1992]. Recently, *Mahmood et al.* [2004] examined the long-term monthly maximum, minimum, and average temperatures for several irrigated and nonirrigated stations in Nebraska. The results of the study indicate a clearly decreasing trend in the mean maximum and average temperatures for the irrigated sites, with an increasing trend observed for the nonirrigated sites. The physical reasoning that supports this difference is that irrigated areas are becoming cooler because of partitioning of the incoming solar radiative flux into increased latent energy flux as a result of increased levels of soil moisture. The role of soil moisture on daily temperatures has been analyzed under different geographical conditions. *Hogg et al.* [2000] found a cooling trend in deciduous forests of interior western Canada during summer as a result of increased latent heat flux. *Fitzjarrald et al.* [2001] identified a decreasing trend in the mean temperatures during the spring season in the eastern US. The main explanation for the aforementioned findings stems from a variety of energy balance studies that identify a feedback cycle in which changes in land surface, such as increased soil moisture availability (as from excess rain or irrigation), can lead to changes in the surface Bowen

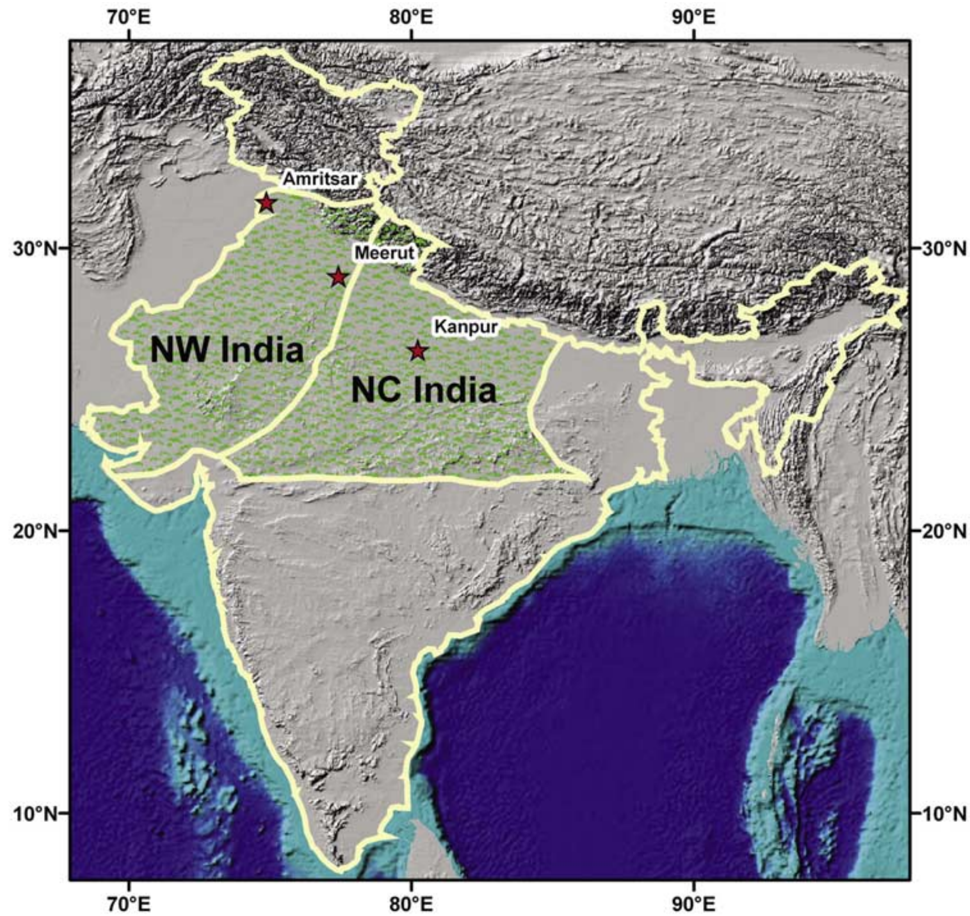

Figure 1. Boundary of the NW (northwestern) and NC (north-central) regions of the Indian Regional Monthly Surface Air Temperature data set developed by IITM, delineated by shaded areas. The star symbols on the map represent locations for which land surface boundary layer model runs were conducted.

ratio due to increased latent energy flux, evaporative cooling and generally lowered air temperatures [*Stull*, 1988; *Niyogi et al.*, 1999].

[10] The results of the above empirical studies have also been supported by modeling studies including *Mahmood and Hubbard* [2002, 2003], who used a soil moisture-energy balance model for three types of land uses in Nebraska representing spatially wet-to-dry conditions. The results of these studies identified the modification in rates of evapotranspiration (ET) and near surface soil moisture content due to the changes in land use. *Kueppers et al.* [2007] reported the modeling results of irrigation's cooling effect on near surface air temperatures in California, referring to it as the Irrigation Cooling Effect (ICE).

[11] *Chase et al.* [2000] also found similar results from model simulation which indicated changes in latent and sensible heat flux at the local and regional scales, which might not be detectable at the global level. Recently, the modification of the summer monsoon has been attributed to land cover changes, modification of the surface energy balance, and the subsequent cooling over Asia [*Feddema et al.*, 2005a]. Overall, the role of the local geographical setting has been found to be critical to a better understanding of the physical processes contributing to overall temperature trends [*Niyogi et al.*, 2002; *Mahmood et al.*, 2004; *Feddema et al.*, 2005a, 2005b]. Although extensive literature exists for the North American continent, a relative absence of any detailed analysis investigating the impacts of land use changes on near surface climate in other parts of the world, including India, is available. One exception is a modeling study by *Douglas et al.* [2006] who reported a 7% increase in latent heat fluxes in the wet season (kharif) and a 55% increase in the dry season (rabi), from a preagricultural and contemporary land cover. Two thirds of these increases were attributed to irrigation. A follow-up numerical study [*Douglas et al.*, 2007] showed decreases in sensible heat flux of 100 W m^{-2} or more due to irrigation in northwestern India. Douglas et al. also found that intensive irrigation in the northwest and along the southeast coast has suppressed the air temperature by 1 to 2 K and has increased the water vapor content by more than 1 g/kg in the lowest atmospheric layer (68 m). In this context, the present study investigates the impacts of the widespread adoption of irrigation on near surface air temperatures in NW and NC India. Since the land use change is associated with the GR, this assessment provides

an opportunity to evaluate the GR's impacts, and will add to the general understanding of the impacts of land use change in other regions of the globe.

3. Methodology

3.1. Data Sources and Analytical Approach

[12] This study uses the data set of the regional monthly maximum and minimum temperature time series compiled by the Indian Institute of Tropical Meteorology (IITM) Indian Monthly Surface Air Temperature (updated 18 January 2006), created from an all-India network of 121 stations in seven homogenous land regions across the subcontinent. This data set initially covered the time period from 1901 to 1990 and was later extended to 2003 with data obtained from Indian Daily Weather Reports. The demarcation of the seven homogenous regions was based on similarities in geographical, topographical, and climatological features. In order to develop a more realistic temperature data set onto the selected network of 121 stations, the climatological normals of monthly mean maximum and minimum temperatures during 1951–1980 for 388 geographically well-distributed stations were obtained from the *India Meteorological Department* [1999]. The available station data were converted into a monthly anomaly time series for the entire time period extending from 1901 to 2003, with respect to individual station normal values. Next, the station level monthly temperature anomaly values were interpolated into a 0.5° by 0.5° grid for the entire period. Then the climatological normals (1951 to 1980) of temperatures for the 388 stations were interpolated onto the same grid that resulted in a high-resolution grid point temperature climatology for the entire subcontinent. Finally, the regional level temperature series were computed using the averages of the constituent grid point data in the different regions. Detailed methodology regarding the construction of this data set is available from *Kothawale and Rupa Kumar* [2005]. Other useful references for the data set include *Pant and Rupa Kumar* [1997] and *Rupa Kumar et al.* [1994]. Given the main objective of determining the impacts of increased irrigation on long-term temperature trends, the present analysis is limited to the last 50 a from 1947 to 2003 for the NW and NC region of the Indian subcontinent (Figure 1). The NW region includes the states of Punjab and Haryana, two states that benefited most from the GR, and also parts of the states of Uttaranchal and Rajasthan. The NC region consists of most of Uttar Pradesh and parts of Madhya Pradesh, Jharkhand, Bihar, and Orissa.

[13] In order to detect the differences in near surface air temperatures, this study completed an analysis of temperatures for individual months for the pre-GR and the post-GR periods. In this investigation, the pre-GR period spans from 1947 through 1964, while the post-GR period covers 1980 through 2003. The transitional period from 1965 through 1979 was excluded from the analysis, in order to accurately describe the impact of GR on temperatures. The overall long-term trend assessment was also conducted using linear trend analysis for the rabi and the zaid seasons. As noted above, these seasons represent the periods of maximum irrigation application. A trend analysis was also conducted separately for the peak growing season in order to more exactly determine the atmospheric effects of irrigation.

3.2. Land Surface–Boundary Layer Model

[14] We perform two types of model analyses. The first involves sensitivity using a 1-D coupled land-atmospheric boundary layer model. The second modeling analysis is performed using a 3-D Regional Atmospheric Modeling System [*Pielke et al.*, 1992].

[15] The 1-D model consists of a subsurface, transition, surface, and a mixed layer continuum model. The model can develop clouds as a function of the initial profiles as well as the atmospheric thermodynamics and thus modify the radiation reaching the surface. Surface and the boundary layer responses are parameterized using the surface layer similarity and the mixed layer theory. It also accounts for mosaic vegetation cover, which was considered uniform for this case of crop cover. The soil moisture response is adopted by a detailed water balance, and the impact to the atmosphere is regulated by a surface moisture availability term which controls the plant response and humidity and temperature changes. The model follows detailed eddy diffusivity and boundary layer formulations using well-tested techniques, having been extensively tested for both midlatitude and tropical conditions. The vegetation is represented following *Taconet et al.* [1986] and *Carlson and Lynn* [1991] for multiple vegetation and land surface interactions for the canopy, the bare ground, the nonleaf part of the canopy, and the interaction of the vegetation with the canopy boundary layer. The model is able to estimate partial canopy resistance as a function of leaf area index and can compute different roughness regimes for canopy separation [*Niyogi and Raman*, 1997]. The model utilizes a default wind profile for a single column representative of the region [*Douglas et al.*, 2006]. The observations focused on soil moistures measured at three different locations: Amritsar (31.64°N, 74.87°E) in northwest India, Meerut, (29.01°N, 77.42°E), and Kanpur (26.4°N, 80.23°E) in north central India. The model was run twice for each of the three locations, once with irrigation and once for water-stressed soils. These runs were completed assuming average March conditions for each location. The vegetation was represented by a leaf area index of 5, with a 95% fractional vegetation cover, which is typical of the fully grown crop canopy. The soil type was assigned as sandy clay loam, and the crop was assumed at its peak greenness with a crop height of 1.5 m and a width of 0.15 m. The deep soil temperature was prescribed on the basis of soil climatology and was 24.6°C for Amritsar, 26°C for Meerut, and 28.6°C for Kanpur. All other values in the model were set to default values typical for the month of March over India [*Douglas et al.*, 2006; *Alapaty et al.*, 2001].

[16] The 1-D model studies were further analyzed using a fully coupled 3-D modeling study which used the Regional Atmospheric Modeling System (RAMS). We adopted a domain with 30 km grid spacing, with 46 × 42 grids covering an area of 1380 km x 1260 km with the domain center located at 28°N, 78°E (Figure 2). In the vertical, 35 stretched sigma levels were employed with a stretching factor of 1.15 up to a1500 m spacing level. All vertical grid spacing above this height were maintained at a constant 1500 m. The model's initial conditions were prescribed using the 1° National Center for Environmental Prediction-Global Data Analysis System (NCEP GDAS). The lateral boundary conditions followed *Klemp and*

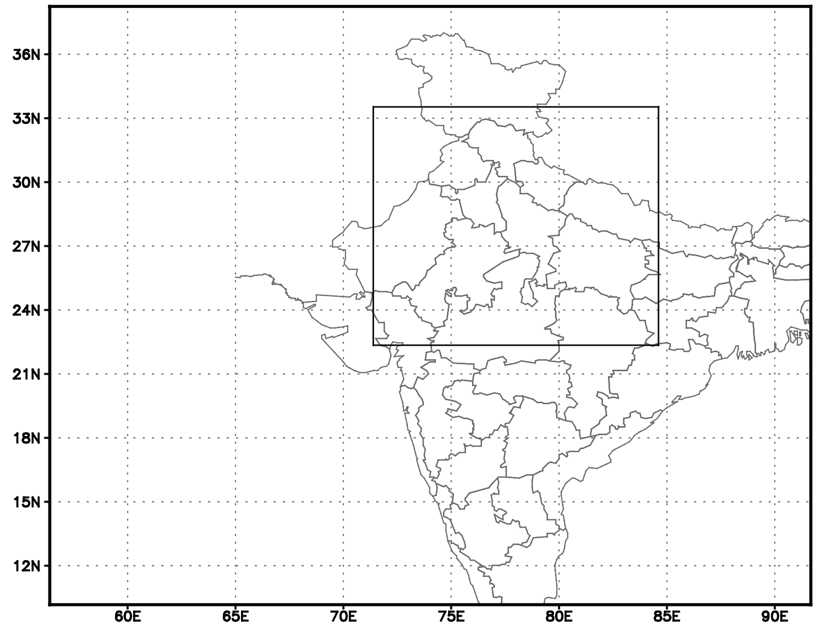

Figure 2. Simulation domain used in the Regional Atmospheric Modeling System for the irrigation experiment, shown by the box over north central India.

Wilhelmson [1978] and were updated every 6 h using analysis nudging. The radiation processes were parameterized following *Chen and Cotton* [1983] with an update every 1200s. Surface energy balance was calculated in the LEAF2 model [*Walko et al.*, 2000] and had nine soil layers. A similar modeling setup has been applied in a number of irrigation-related studies [e.g., *Mahmood et al.*, 2004; *Adegoke et al.*, 2007]. A 1-week period from 13 to 19 March 2006 was selected. This period generally coincided with the green-up phase of the growing season. The period was also selected as the region had little to no synoptic activity with relatively clear skies, and the surface-boundary layer feedback was expected to be a prominent forcing on the mesoscale processes. Two experiments were performed, a control run assuming no irrigation, and an ''irrigation'' run in which all the cropland within the domain was assumed to be irrigated. Note that, even though we chose a 7-d period because of computational limitations, irrigation was a daily event over the domain during the growing period, and the potential impacts could be extrapolated for the entire growing season. In the simulation we assumed the top 12 cm of soil (top 3 soil layers in the model), reached their field capacity because of irrigation, which was initiated once a day at 1000 LT. This idealized experiment was developed for further illustrating the significant influence irrigation can exert on regional surface temperatures.

4. Results

4.1. NW India

[17] The present analysis is limited to the rabi (November to May) and zaid (March to June) growing seasons. Overall, November to June is the driest period of the year, when irrigation is most intense in order to meet crop growth requirements. The long-term trend in the seasonal mean maximum (−0.04°C per decade) and minimum temperatures (−0.05°C per decade) has been negative (cooling) for the zaid season (Table 1). Compared to seasonal maximum temperatures, minimum temperatures show a slightly greater decline (Table 1). During the rabi season, the trends were almost neutral to slightly positive, with almost no

Table 1. Decadal Trends in Seasonal Surface Air Temperature Data From 1947 to 2003 Over NW India[a]

Variables	Growing Season: Rabi (Nov–May)	Peak Growing Season: Rabi (Feb–Apr)
Maximum temperature, °C	0.0008	**−0.02**
Minimum temperature, °C	0.02	0.01
Average temperature, °C	0.01	**−0.003**
Diurnal temperature range, °C	0.01	0.006
Variables	Growing Season: Zaid (Mar–Jun)	Peak Growing Season: Zaid (Mar–May)
Maximum temperature, °C	**−0.04**	**−0.03**
Minimum temperature, °C	**−0.054**	**−0.03**
Average temperature, °C	**−0.049**	**−0.03**
Diurnal temperature range, °C	**−0.018**	**−0.03**

[a]Bold numbers indicate cooling (none of the trends are statistically significant by themselves as is stated also in the text).

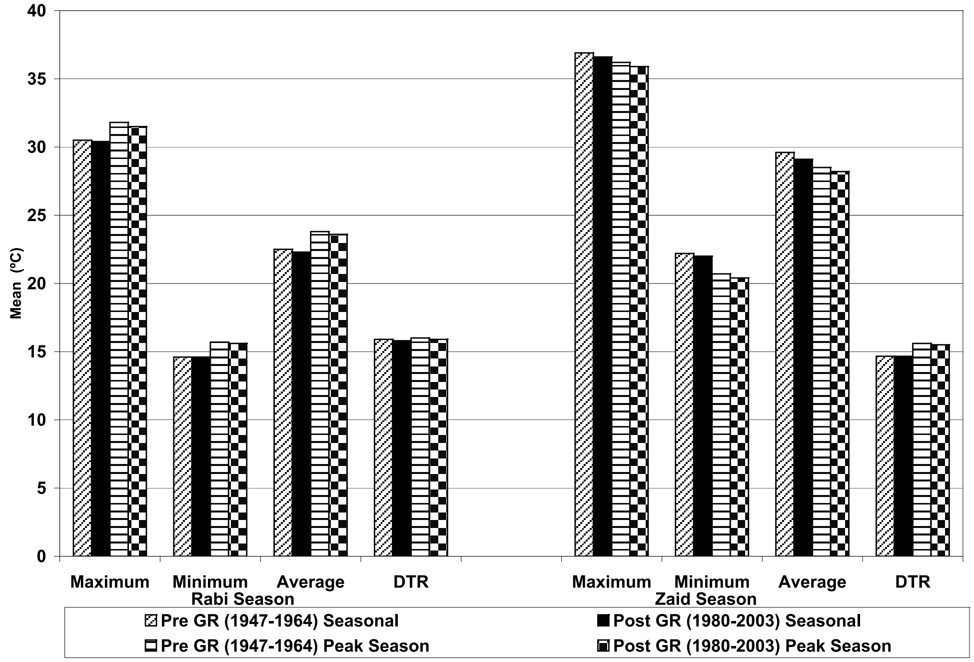

Figure 3. Mean growing season and peak growing season temperatures during pre-GR (1947–1964) and post-GR (1980–2003) time periods for NW India.

trend observed in the maximum temperatures. The linear trends were also calculated for the seasonal average temperatures and diurnal temperature range (DTR). The DTR was reduced and average temperatures showed decreasing trends (cooling) during the zaid season, while for the rabi season the trends were nearly neutral to slightly positive. The decreasing trend during the zaid season was slightly greater for average temperatures (−0.05°C per decade) than that of the DTR (−0.02°C per decade).

[18] In order to specifically isolate the impact of irrigation on the partitioning of the energy budget, we further investigated the peak growing season temperatures for the two cropping seasons. The peak growing period for the rabi season was limited to February through April, while for the zaid, it was March through May, when crops experienced peak water requirements. The trends were negative (cooling) at −0.03°C per decade for the peak zaid season mean maximum, mean minimum, mean, and mean DTR. In contrast, during the peak rabi season only the maximum temperatures showed a decline (−0.02°C per decade) (Table 1). The declining trends can be attributed to the increased availability of soil moisture from greater inputs of irrigation. The impact of soil moisture on the surface atmosphere energy budget was relatively greater during the zaid season. The reduction in DTR for both seasonal and peak seasonal periods can be attributed to evaporative cooling as suggested by *Dai et al.* [1999].

[19] In order to detect the differences in temperatures between the pre-GR and post-GR period, we divided the study period into two parts with the pre-Green Revolution period extending from 1947 to 1964, and the post-Green Revolution period extending from 1980 to 2003. The mean growing season and peak growing season maximum and minimum temperatures, DTR, and average temperatures were calculated for the pre-GR and post-GR periods. The results indicate a lower maximum and average temperature and DTR during both growing seasons and peak growing season months of the rabi and zaid seasons (Figure 3). For example, it was found that the mean peak growing season maximum temperature for the rabi crop was 31.7°C and 31.4°C during the pre- and post-GR periods, respectively. Moreover, the mean peak growing season DTR was 16°C and 15.8°C during the pre- and post-GR period, respectively. In other words, 0.34°C and 0.18°C cooling and decline had occurred for the mean growing season maximum temperature and DTR, respectively, during the post-GR period. For the zaid crop, the mean growing season maximum temperature was 36.2 and 35.9°C during the pre- and post-GR period, respectively. In addition, the mean growing season DTR was 15.56°C and 15.5°C during the pre- and post-GR period, respectively. Hence, for the zaid season, 0.3°C and 0.06°C declines occurred for maximum temperature and DTR, respectively, during the post-GR period.

[20] These results are in agreement with findings of previous modeling and observed data-based studies indicating a cooling trend in daily maximum temperatures, leading to further reductions in DTRs over major agricultural areas of the USA [*Bonan*, 1997; *Mahmood et al.*, 2004]. The analysis suggests a 0.19°C and 0.27°C decrease of average temperatures for the rabi and zaid seasons, respectively, during the post-GR period. Declines in both the mean maximum and mean minimum temperatures in the post-GR period have resulted in this lowering of average temperatures.

[21] We further examined the monthly average temperatures before and after the GR in order to specifically identify the period of maximum impact. Figure 4 shows the monthly average maximum and minimum temperatures

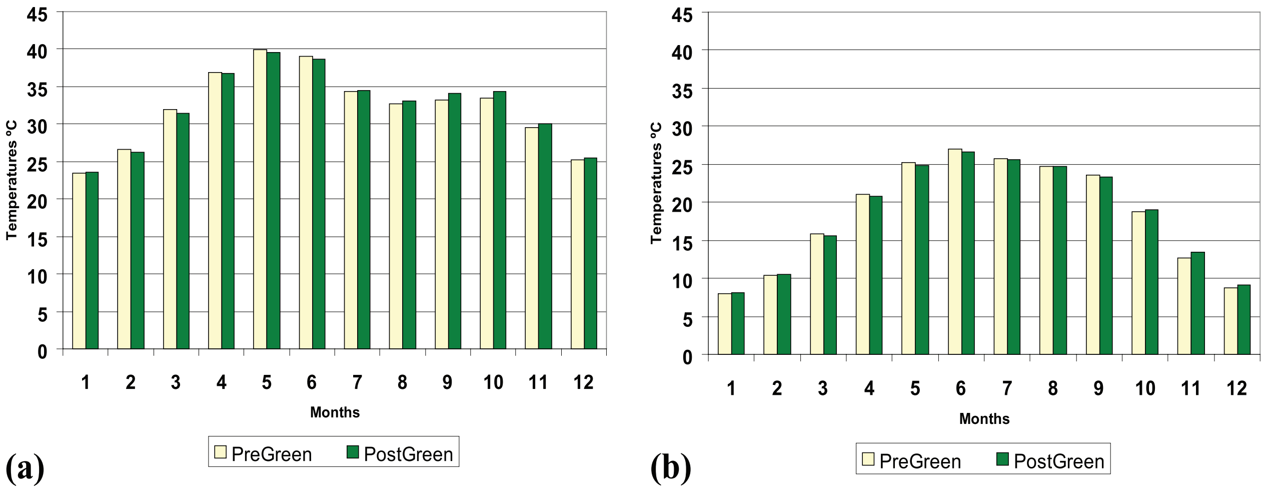

Figure 4. Comparative analysis of average monthly temperatures for NW India during pre-GR and post-GR time periods. (a) Maximum temperatures and (b) minimum temperatures.

for the pre-GR and post-GR periods. The results evidence that, overall, the months of February, March, April, May, and June show lower average monthly maximum temperatures during the post-GR period. Further analysis reveals that the mean maximum growing season temperatures were 0.29, 0.51, 0.07, 0.38, and 0.28°C lower for the months of February, March, April, May, and June, respectively, during the post-GR period. Minimum temperatures for the entire period extending from March to June showed lower monthly averages for the post-GR period.

[22] Statistical tests were performed to determine the significance of differences in means between the pre- and post-GR periods. The tests include a student's t-test, bootstrapping, and robust statistics (20%-trimmed mean approach). Even though the results are not statistically significant at a 05 confidence level, the lowering of temperatures are physically consistent with the theoretical understanding of the relationship between soil moisture, energy partitioning, and the Bowen ratio. Findings are also consistent with results from the Great Plains and other modeling studies [e.g., *Mahmood et al.*, 2004; *Cai and Kalnay*, 2004; *Adegoke et al.*, 2003; *Baidya Roy et al.*, 2003; *Zhao and Pitman*, 2002; *Eastman et al.*, 2001]. For additional verification, we also conducted a coupled land-atmosphere model simulation to determine the physical relationship between land use and temperature in NW India. The results are presented in a following section.

4.2. NC India

[23] Although the impacts of the GR are most pronounced in NW India, its benefits have gradually spread over most of the Gangetic basin. As evident from Table 2, the long-term seasonal and peak growing season temperatures also experienced a cooling trend in the NC region. The rates of decline were greater during the zaid season, with the highest negative trend in the case of seasonal minimum temperature at −0.12°C per decade, followed by −0.07 per decade for seasonal maximum temperature (Table 2). The rates of cooling for maximum and minimum temperatures in general were also greater than those observed in the NW India temperature rates. However, in the case of the DTR, the trends were positive, as the −0.002°C rate of decline in minimum temperatures was slightly greater than that of the −0.004°C maximum temperature during the peak growing season.

[24] The temperatures calculated for the pre-GR and post-GR periods during the seasonal and peak growing months demonstrated changes similar to those found in the case of NW India (Figure 5). In most cases, the post-GR temperatures were lower, except for the DTR which showed either

Table 2. Decadal Trends in Seasonal Surface Air Temperature Data From 1947 to 2003 Over NC India[a]

Variables	Growing Season: Rabi (Nov–May)	Peak Growing Season: Rabi (Feb–Apr)
Maximum temperature, °C	**−0.03**	**−0.02**
Minimum temperature, °C	**−0.02**	**−0.04**
Average temperature, °C	**−0.03**	**−0.04**
Diurnal temperature range, °C	0.01	0.07
Variables	**Growing Season: Zaid (Mar–Jun)**	**Peak Growing System: Zaid (Mar–May)**
Maximum temperature, °C	**−0.07**	**−0.04**
Minimum temperature, °C	**−0.12**	**−0.1**
Average temperature, °C	**−0.09**	**−0.07**
Diurnal temperature range, °C	**−0.02**	0.03

[a]Bold numbers indicate cooling (none of the trends are statistically significant by themselves as is stated also in the text).

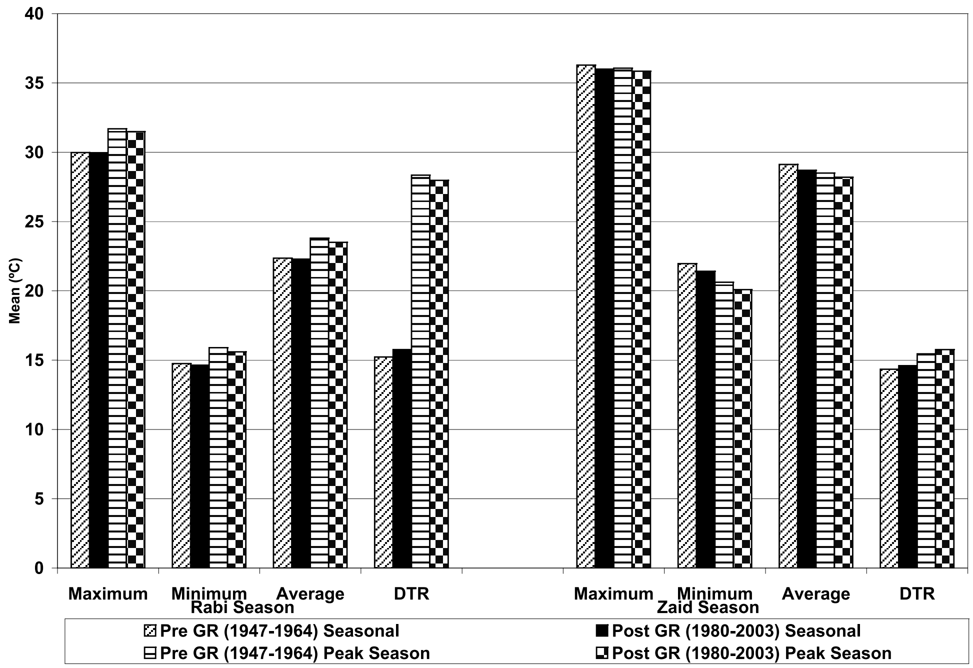

Figure 5. Mean growing season and peak growing season temperatures during pre-GR (1947–1964) and post-GR (1980–2003) time periods for NC India.

no difference or a slight increase. This can be attributed to an equal, and in some cases, greater decline in minimum temperatures. The minimum temperatures at the seasonal level showed greater cooling (0.11°C), compared to the maximum temperatures (0.04°C), resulting in a higher DTR during the post-GR period. The average DTR during the post-GR period was, however, slightly lower than the pre-GR period consistent with previous studies [*Dai et al.*, 1999]. Similar to NW India, NC India also showed greater cooling during the zaid season. For example, our study found a 0.55°C and 0.53°C cooling of minimum temperatures for the entire and peak growing season, respectively. The decline in maximum temperatures was lower compared to the minimum temperatures, which were 0.29°C and 0.22°C at the seasonal and the zaid peak growing season. The average temperatures were lower overall during both the rabi and zaid seasons. A maximum cooling of 0.42°C was observed in the zaid seasonal average temperatures, followed by a 0.3°C maximum cooling during the peak growing periods for both seasons.

[25] In addition, the temperatures during the pre-GR and post-GR periods were analyzed to further focus on the months of greatest cooling (Figure 6). As expected, the overall pattern showed irrigation-induced cooling during the first half of the year, which is also the driest period. The observed cooling was greatest during April, May, and June. For example, during pre-GR period for these months, the mean maximum temperature values were 36.96°C, 39.5°C, and 37.0°C, respectively. These mean temperatures for the post-GR period were 36.9°C, 39.1°C, and 36.4°C, respectively. Hence a 0.01°C, 0.4°C, and 0.53°C cooling has occurred for April, May, and June, respectively. However, as mentioned earlier, this cooling was greater in the case of the minimum temperatures for the months of April, May, and June with values of 0.57, 0.66, 0.67°C, respectively.

5. Model Sensitivity Results

[26] The above results were also verified by coupled 1-D land surface-boundary layer model runs for three sites, located over NW and NC India. These include Amritsar in the NW region, and Kanpur and Meerut in the NC region. The results of the model runs are in agreement with the observations and show a distinct cooling in the near surface air temperatures due to agricultural irrigation. The modeling results reveal the impact of irrigated crop land versus moisture stressed land surface conditions on the diurnal variation of the surface air temperature for the three locations. Typically, the irrigated crop landscape is about 2°C to 3°C cooler during the day (similar to the findings of *Douglas et al.* [2007]) and about 5°C cooler at night. The resulting temperature difference between the two model scenarios is due to the large difference in the evapotranspirative cooling produced by the irrigated crop. The results of model run for Meerut for 15 March 1999 is shown in Figure 7 with and without the irrigated crop consideration. Consistent with past studies for other regions, the irrigated crop surface partitions the available surface radiative flux leading to an enhanced moisture flux through a modified surface latent heat flux as shown in Figure 7a. The day time moisture flux is about 100% higher when the surface cropland is irrigated. The enhanced evaporation/transpiration leads to an altered humidity regime. It is evident in Figure 7b that the irrigated crop leads to about 3 g kg^{-1} or a 20% increase in the boundary layer-specific humidity. Similarly, the air temperatures at 2 m are cooler under the influence of irrigated crops (Figure 7c). The amount of cooling shown in Figure 7 is to

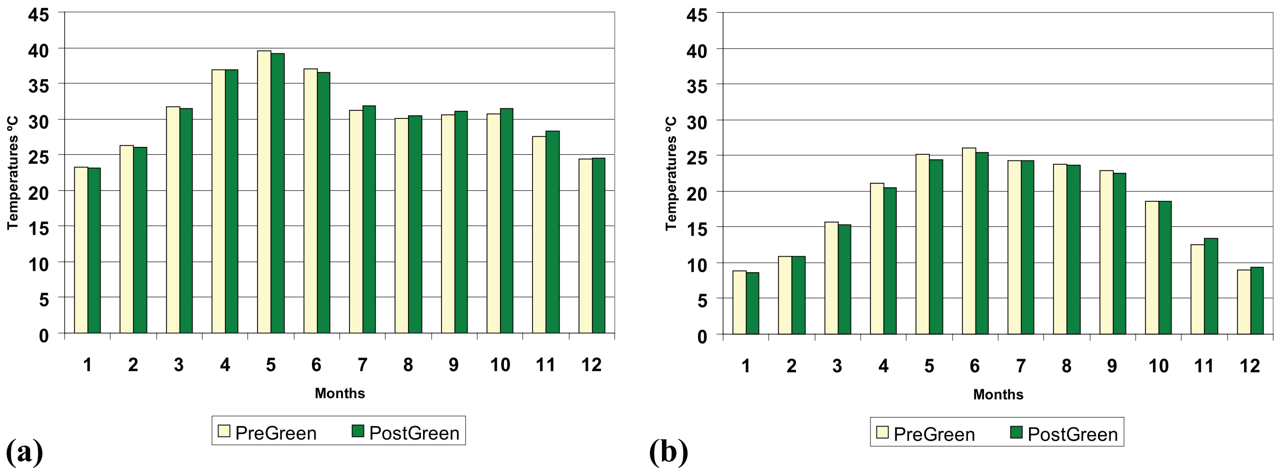

Figure 6. Comparative analysis of average monthly temperatures for NC India during pre-GR and post-GR time periods. (a) Maximum temperatures and (b) minimum temperatures.

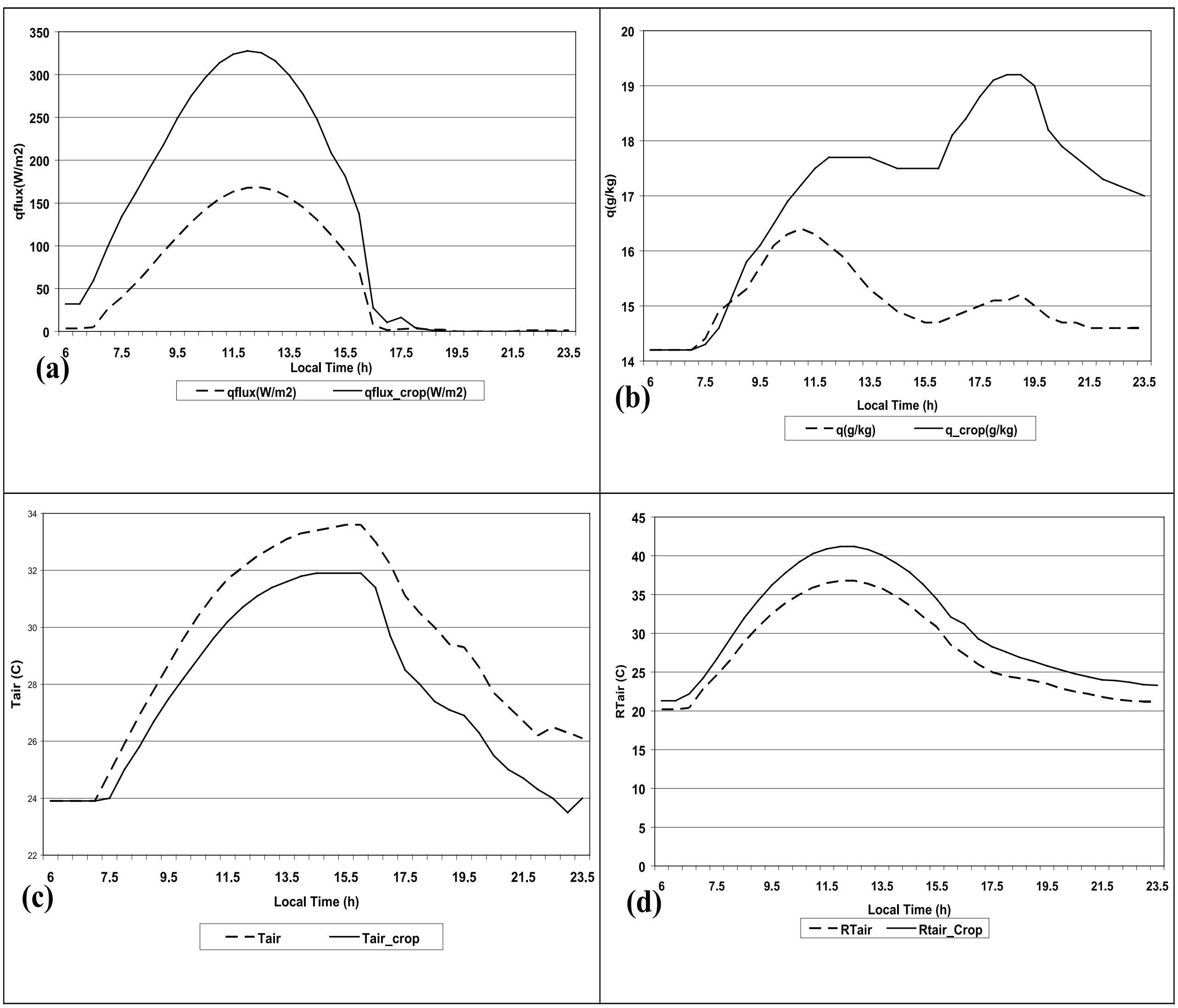

Figure 7. Results of model runs by the Land Surface-Boundary Layer Model for 15 March 1999 in Meerut, (a) latent heat flux (W/m^2), (b) specific humidity (g/kg), (c) air temperature (°C), and (d) radiometric temperature (°C). The suffix "crop" indicates model results for irrigated crop.

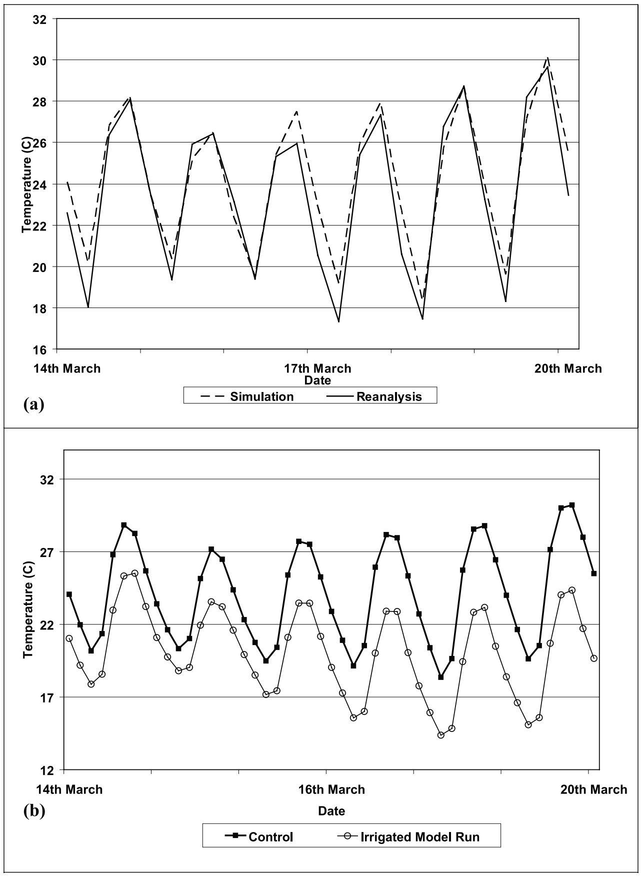

Figure 8. RAMS simulated time series of domain-averaged temperature for (a) control (dashed line) compared to the reanalysis temperature data (solid line) and (b) control (solid line with solid squares) and the irrigated model run (lighter line, open circles).

the order of about 2°C both for the day and nighttime. The impact of the surface changes is dramatically depicted in the radiometric temperature data (such as those sensed by the satellites), and is shown in Figure 7d. For this variable, the difference between the irrigated crops versus default is of the order of 5°C during day and about 2°C during night.

[27] Similar results are obtained in the 3-D RAMS modeling study. Figure 8 shows the temperature time series for the week-long run. With irrigation, the average temperature is reduced by about 5°C. The regional distribution of the averaged temperature differences for the entire simulation, and for day and night, is shown in Figures 9a–9c. Interestingly, in a few locations, particularly in the northeast corner of the domain, the irrigation case shows a slight warming (by 0.5 to 1°C). This can be attributed to the regional feedbacks associated with changes in cloudiness and humidity in the irrigated regions. However, in the majority of the domain, the irrigation case shows an overwhelming cooling response, by as much as 6°C. The cooling is more pronounced during the day time, but continues to be prominent even for the nighttime, typically of the order of 4°C across the domain.

6. Discussion and Concluding Remarks

[28] This study investigates the GR-induced large-scale adoption of irrigation and its impacts on the long-term temperatures in NW and NC India. The GR in India has brought about phenomenal growth in food production with the introduction of high-yielding varieties of seeds and the installation of a widespread irrigation network across this region. The results of the analysis broadly conform with the findings of previous studies for other parts of the world which examine the impact of irrigation on surface-atmosphere interactions which affect local level energy budgets [e.g., *Chase et al.*, 2000; *Adegoke et al.*, 2003; *Mahmood and Hubbard*, 2002; *Mahmood et al.*, 2004, 2006; *Feddema*

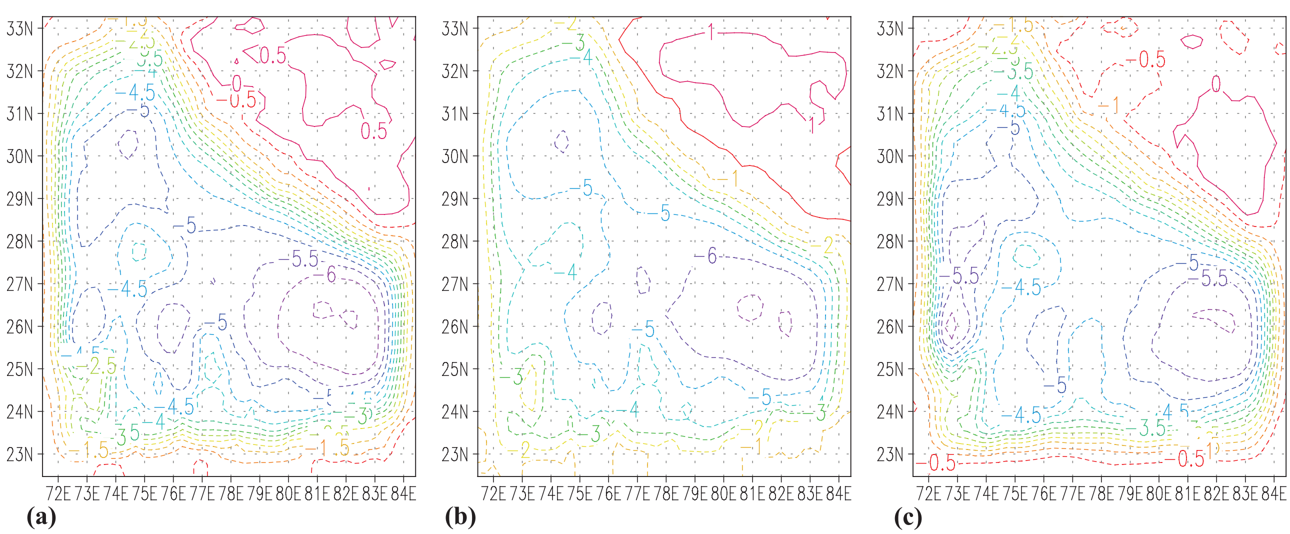

Figure 9. Average difference in the RAMS simulated air temperature (°C) between the control (no irrigation) and irrigation run: (a) average difference for the entire simulation, (b) during the day time throughout the simulation period, and (c) during the nighttime throughout the simulation period.

et al., 2005a, 2005b; *Douglas et al.*, 2006, 2007]. The main findings of the study are as follows:

[29] 1. The overall seasonal trends during the rabi season in NC India suggest a cooling, while NW India showed predominantly neutral to slightly positive trends (Tables 1 and 2). The trend in maximum temperatures during the peak growing season was negative for both regions. These results are in agreement with previous findings by *Mearns et al.* [1995], *Dai et al.* [1999], *Kalnay and Cai* [2003] attributing them to increased surface ET rates.

[30] 2. In the case of the zaid season, the overall trends were negative for both the seasonal and peak growing season months for both NW and NC India (Tables 1 and 2). This is the driest period of the year, when the impact of irrigation on temperature can be detected most clearly. The negative trends were relatively greater at the seasonal level than the peak season months. These findings are in agreement with the findings of an earlier study examining the trends in seasonal maximum and minimum temperatures, and DTR, by *Roy and Balling* [2005], who also reported a declining trend over NW India.

[31] 3. The comparative analysis of averages of DTR, maximum, minimum, and mean temperatures, revealed lower averages for the post-GR period for both the rabi and zaid seasons (Figures 2 and 4). The differences between the pre-GR and post-GR periods were generally similar for the entire growing season as well as the peak growing season. Lower averages during the post-GR period were also observed in the case of individual monthly mean temperatures (Figures 3 and 5).

[32] 4. In the case of NC India, both the rabi and zaid season showed a stronger decline during the peak growing season months. However, because of an equal or greater decline in minimum temperatures, a slightly positive or neutral trend occurred in the DTRs' long-term trends.

[33] 5. The above results were also validated by the simulations from a coupled land-atmosphere model run carried out for three locations within the two study regions and a 3-D modeling study using the Regional Atmospheric Modeling System. The irrigated areas showed a 3°C to 4°C daytime cooling (Figures 7 and 8).

[34] Lower average maximum temperatures and a reduction in the DTR during the post-GR period is possibly as a result of the greater availability of soil moisture as suggested from previous empirical and modeling studies conducted in other parts of the world [*Cao et al.*, 1992; *Mearns et al.*, 1995]. Also, for the Indian region, the role of atmospheric aerosols leading to warming or cooling of the lower atmosphere needs to be considered [*Ramanathan et al.*, 2005]. We conducted one sensitivity experiment with the RAMS model setup with doubled optical depth representative of the aerosol rich air over NW India following *Niyogi et al.* [2007a, 2007b]. Results indicate the aerosol induced cooling could be about half of that due to irrigation. We obtained cooling over the region which is of the order of less than 1°C (range: 0.3–2.1°C; average: 0.9). While the effect of irrigation from our results is much larger, i.e., order of 2°C (range: 0.4–4.3°C; average: 2.3°C). These values need to be treated with caution as the aerosol issue is complex and can cause both warming and cooling depending on the single scattering albedo and aerosol speciation [*Menon et al.*, 2002]. *Niyogi et al.* [2007a] reviewed the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depths and the Aerosol Robotics Network (AERONET) optical depth data over Kanpur, India. Their results indicate that the aerosol plumes are transitory with optical depths ranging around 0.5 for majority of the period and going in excess of 2 for few occasions. Thus the impact of aerosols can be an important, but variable, forcing that can increase or decrease the surface temperatures. On the other hand, irrigation activity is nearly permanent feature of the growing season. As a result of which, the irrigation effect on surface temperature can be consistently considered as one of cooling.

[35] The present study generally found cooling of growing season minimum temperatures. These results are somewhat analogous to the findings from various locations in the Great Plains [*Mahmood et al.*, 2004, 2006] which report both the cooling and warming of growing season mean minimum temperatures at irrigated locations. Thus we suggest that the cooling trends for mean minimum growing season temperatures in irrigated areas indicate that complex surface-atmosphere interactions are occurring in these regions. The lack of significant changes in monsoon activity during the two selected time periods [*Pant and Rupa Kumar*, 1997] also supports these results.

[36] On the basis of the above findings, it can be concluded that because of the introduction of widespread irrigation measures in NW and NC India, the potential exists for the cooling of maximum temperatures and a reduction in the DTR during the earlier part of the year, primarily from March to May. We suspect that the signal could have been improved if station level data were available rather than regional data. Also, inclusion of the arid Rajasthan desert in the regional data may have diluted the overall signal. Future studies that examine station level data may reveal much stronger irrigation-related signals in long-term temperatures. Thus inclusion of land use/cover changes particularly those due to agricultural intensification can improve regional climate assessment for climate change conditions.

[37] **Acknowledgments.** This work has been partially supported by NASA grants NAG5-11370 and NNG04GL61G, NASA-THP NNG04GI84G (J. Entin), NASA-IDS NNG04GL61G (J. Entin and G. Gutman), NASA LULCC Program (G. Gutman), NSF-ATM 0233780 (S. Nelson), and the Purdue Asian Initiative Grant. The data were obtained from the Indian Institute of Tropical Meteorology and are greatly appreciated.

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