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# Diagnosis of Local Land–Atmosphere Feedbacks in India

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ABSTRACT

Following the convective triggering potential (CTP)–humidity index ($HI_{low}$) framework by Findell and Eltahir, the sensitivity of atmospheric convection to soil moisture conditions is studied for India. Using the same slab model as Findell and Eltahir, atmospheric conditions in which the land surface state affects convective precipitation are determined. For India, CTP–$HI_{low}$ thresholds for land surface–atmosphere feedbacks are shown to be slightly different than for the United States.

Using atmospheric sounding data from 1975 to 2009, the seasonal and spatial variations in feedback strength have been assessed. The patterns of feedback strengths thus obtained have been analyzed in relation to the monsoon timing. During the monsoon season, atmospheric conditions where soil moisture positively influences precipitation are present about 25% of the time. During onset and retreat of the monsoon, the south and east of India show more potential for feedbacks than the north. These feedbacks suggest that large-scale irrigation in the south and east may increase local precipitation.

To test this, precipitation data (from 1960 to 2004) for the period about three weeks just before the monsoon onset date have been studied. A positive trend in the precipitation just before the monsoon onset is found for irrigated stations. It is shown that for irrigated stations, the trend in the precipitation just before the monsoon onset is positive for the period 1960–2004. For nonirrigated stations, there is no such upward trend in this period. The precipitation trend for irrigated areas might be due to a positive trend in the extent of irrigated areas, with land–atmosphere feedbacks inducing increased precipitation.

## 1. Introduction

The interaction between the land surface and atmosphere has multiple pathways, which include the coupled water and energy cycles. Different feedbacks can occur when land and atmosphere interact (Brubaker and Entekhabi 1996; Eltahir 1998). Understanding these feedbacks is important to explain past climatic changes and improve seasonal weather forecasts and assessments of the impact of land use scenarios on climate.

Positive feedbacks occur when a given land surface state enhances itself in magnitude or persistence. For example, a wet surface can induce precipitation, whereas a dry surface cannot. In case of a wet land surface, evaporation is not limited by available soil moisture, and latent heat is released into the atmosphere. This moisture flux increases the specific humidity of the atmospheric boundary layer (ABL). If this moisture rises to layers of conditional instability, latent heat release can result in convective precipitation, increasing soil wetness. By contrast, a dry land surface limits evaporation by moisture availability. The smaller moisture flux is insufficient to induce convection and no precipitation occurs, so the land surface stays dry.

Negative feedbacks occur when dry surfaces lead to precipitation and wet surfaces inhibit the formation of rain. This can occur when a potential instability is present above the ABL top. The larger sensible heat flux from dry surfaces leads to a larger ABL growth. The ABL may entrain the stable layer, reach the unstable air above, and trigger convection, whereas no convection would occur with wet surface conditions.

Feedbacks between land and atmosphere are hard to measure directly in manipulative experiments because it is usually not feasible to make fully controlled changes to the land surface state. An approach is to simulate the influence of the land surface using models. At the global scale, Koster et al. (2004, 2006) intercompared GCMs to determine the sensitivity of temperature and precipitation to the land surface state. They found hotspots of the coupling of soil moisture to precipitation for boreal

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summer [June–August (JJA)] in West Africa, the Midwest of the United States, and India. Guo et al. (2006) analyzed the model runs of Koster et al. (2006) and concluded that the hotspots of coupling were located on transition zones between dry and wet climates. In wet climates, soil moisture is plentiful and evaporation is controlled by atmospheric demand. In dry climates, the typical variations in evaporation are too small to affect precipitation. Between these extremes, evaporation is large enough to influence precipitation, but the magnitude still depends on soil moisture.

Another approach is analysis of the correlation between soil moisture, evaporation, and moisture recycling ratios. Dirmeyer et al. (2009) and Dirmeyer and Brubaker (2007) did this globally, while others focused on regional analyses (Bisselink and Dolman 2008; Findell and Eltahir 1997).

On a local scale, De Ridder (1997) studied the theoretical relationship between land surface and convective precipitation and found that the potential for convective precipitation increased with evaporative fraction, except in very dry conditions. Based on this work, Findell and Eltahir (2003a, hereafter referred to as FE2003a) used a slab model to determine the relative influences of surface and entrainment fluxes on convective precipitation. They found that under certain atmospheric conditions, the soil moisture conditions can trigger or prevent precipitation, while under other conditions the land surface condition was irrelevant. For the United States, they created a framework to classify atmospheric conditions from which feedbacks can be diagnosed without the need to perform model runs.

In this study, we focus on India, one of the hotspot coupling regions identified by Koster et al. (2006). India has a number of distinct seasons. During January to May, the predominant flow is from the north, bringing dry and cool conditions. By May the land surface has been heated by increased solar radiation, which causes rising air masses over land. These draw in moist oceanic air, which brings the summer monsoon rains that provide the majority of annual precipitation (Barry and Chorley 2003). These monsoon rains last until September–October, after which the cool season starts. Feedbacks are expected for the onset and retreat periods because they resemble the transition zones between dry and wet climates of Guo et al. (2006). Moreover, India is an interesting case to study land–atmosphere feedbacks because of the large-scale modification of the land surface. India has become one of the most heavily irrigated areas in the world (Siebert et al. 2005) owing to rising population and demand for agricultural products.

GCMs have been used to study the influence of soil moisture on the Indian monsoon. Webster et al. (1998) noted that soil moisture characteristics are important in determining monsoon structure. Meehl (1994a,b) modified surface conditions and found a correlation between a stronger Indian summer monsoon and the land–sea temperature contrast, but also between wet soil conditions and Indian summer monsoon precipitation. Douville et al. (2001) note that rainfall increases over northern India as a consequence of wetter surface conditions but, as the land–sea contrast decreases, the increased water recycling is balanced by a decreased moisture convergence.

Dirmeyer et al. (2009) found increased moisture recycling ratios during the onset and, especially, the retreating phases of monsoons. For India, the correlations between soil moisture state, evaporation, soil moisture memory, and moisture recycling ratios were all positive during March–May (MAM) and September–October (SON). During SON soil moisture memory was the highest, about 20 days (the time the autocorrelation of soil moisture was above the 99% confidence level). These positive correlations indicate the possibility of land–atmosphere feedbacks but do not exclude other processes such as vegetation changes and interaction.

On a smaller scale, Lohar and Pal (1995) used a 2D model and observed decreased sea breezes as a result of irrigation for southwest Bengal. The smaller sea breeze reduced low-level moisture supply making the net effect of irrigation on precipitation negative. Lee et al. (2009) related remotely sensed increasing trends in premonsoon irrigation to decreasing trends in monsoon precipitation for 1982–2003. They hypothesized that the decreased land–sea contrast is the cause of this relationship.

In the present study, we apply the FE2003a method of determining local land–atmosphere feedbacks with two main goals:

- Test whether the approach of FE2003a and Findell and Eltahir (2003b, hereafter referred to as FE2003B) can be applied to India, and what possible adaptations of their framework need to be done.
- Determine what feedbacks (from soil moisture to convective precipitation) can be expected for India, how they vary spatially and how they relate to monsoon onset and retreat, and whether more precipitation is found in irrigated areas with positive feedbacks.

Three hypotheses are put forward. 1) The convective triggering potential (CTP)–humidity index (HI) framework can be used for India, so the potential for feedbacks can be determined quickly for long periods without the need to perform model simulations. 2) Soil moisture influences precipitation during the monsoon onset and retreat because these are the periods in the year that resemble the transition zones between wet and dry climates (Guo et al. 2006; Dirmeyer et al. 2009). 3) Precipitation is sensitive to large-scale irrigation in these periods.

The structure of this paper is as follows. In section 2, the framework developed in FE2003a that is used to assess the feedbacks is introduced, while section 3 presents the approach to determine the feedbacks and the data used. Section 4 will show how this framework can be used for India, after which the relation between feedbacks and monsoon will be discussed in section 5. Sections 6 and 7 present the discussion and conclusions.

## 2. CTP–$HI_{low}$ framework

To determine the effect of soil moisture on precipitation, this study uses the CTP–$HI_{low}$ framework proposed by FE2003a. Based on two atmospheric indicators (CTP and $HI_{low}$), this framework predicts whether the land surface has an influence on the occurrence of convective precipitation. More precisely, it assesses the sensitivity of the atmosphere, in terms of a convective potential and moisture content, to variations in energy partitioning at the land surface.

FE2003a hypothesized that certain atmospheric conditions favor rainfall over wet soils while other conditions favor rain over dry soils. To test this, they forced a slab model with atmospheric sounding data from the summers of 1997–99 from Illinois (station ILX). The model was run once with wet soil moisture conditions (85%) and once with dry soil moisture conditions (15%), which resulted in three groups of soundings:

(i) atmospherically controlled cases (no difference between wet and dry soil),
(ii) positive feedback cases (precipitation on wet soil, no precipitation on dry soil), and
(iii) negative feedback cases (no precipitation on wet soil, precipitation on dry soil)

They found the atmospheric layer between 950 and 700 hPa to be critical in triggering convection. Two indicators of stability and humidity, convective triggering potential (CTP) and humidity index in the lower level of the atmosphere ($HI_{low}$), were developed into a framework to diagnose the land surface influence.

### a. Convective triggering potential

The CTP has a similar definition as the convective available potential energy (CAPE), but the integration bounds are different:

$$\mathrm{CTP} = \int_{P_{\mathrm{surf}}-100\mathrm{hPa}}^{P_{\mathrm{surf}}-300\mathrm{hPa}} g\left(\frac{\mathrm{Tv}_{\mathrm{parcel}} - \mathrm{Tv}_{\mathrm{env}}}{\mathrm{Tv}_{\mathrm{env}}}\right) dz. \qquad (1)$$

Here $\mathrm{Tv}_{\mathrm{parcel}}$ is the virtual temperature of a parcel that is lifted moist adiabatically from the level 100 hPa above the surface, while $\mathrm{Tv}_{\mathrm{env}}$ is the temperature of the observed profile. CTP (in J $kg^{-1}$) measures the buoyancy of rising air originating from the temperature difference with its environment. Positive values indicate (conditional) instability between 100 and 300 hPa above the surface. When the ABL reaches this height, energy is available to start deep convection. The values of 100 and 300 hPa above the surface represent the layer that can just be reached by the daytime ABL. Because surface conditions affect the ABL growth, they control whether or not this critical region is reached.

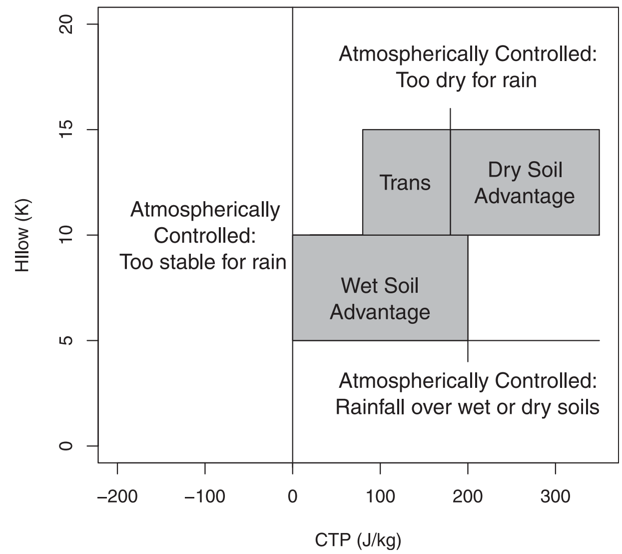


FIG. 1. CTP–$HI_{low}$ framework, regions in which wet soils and dry soils promote precipitation, as well as transition regions (in which the outcome is unsure), are shaded. Figure from FE2003a.

### b. Humidity index

The humidity index in the lower level of the atmosphere ($HI_{low}$) is based on the humidity index by Lytinska et al. (1976), which is designed to determine the possibility of rain for an atmospheric profile. This humidity index is defined as the sum of the dewpoint depressions at 500, 700, and 850 hPa. FE2003a defined $HI_{low}$ as

$$HI_{low} = (T_{950} - T_{d,950}) + (T_{850} - T_{d,850}) \qquad (2)$$

in which $T$ is the temperature and $T_d$ the dewpoint temperature. For high humidities $HI_{low} < 5$ K, while values of $HI_{low} > 20$ K indicate low humidity. Lytinska et al. (1976) found a threshold for precipitation of HI as a three-level humidity index) <30 K, whereas FE2003a found $HI_{low}$ a two-level humidity index <15 K as a precipitation threshold.

### c. Framework for land surface influence

Figure 1 illustrates the CTP–$HI_{low}$ framework, including the original thresholds for feedbacks. FE2003a found the groups of soundings for which the model resulted in a positive feedback to have CTP = 0–200 J $kg^{-1}$ and $HI_{low}$ = 5–10 K. For the negative feedbacks, they found CTP > 200 J $kg^{-1}$ and $HI_{low}$ = 10–15 K, while the atmospherically controlled cases lay outside these bounds; cases with $HI_{low} < 5$ had precipitation for dry and wet soils, whereas cases with $HI_{low} > 15$ showed no convection over either soil condition. Between CTP = 80–200 J $kg^{-1}$ and $HI_{low}$ = 10–15 K, a transition zone was defined in which any outcome was possible. Since the defined framework is based on slab model results, it has a local viewpoint with a limited number of processes taken into account. Omitted processes that are potentially relevant for land–atmosphere interactions include the effects of orography, wind shear, and synoptic systems that affect atmospheric conditions after collection of the early-morning data.

## 3. Methods and data

Our study proceeds along the following steps.

(i) Test the framework applicability for India, using a slab model with a limited sounding dataset (methods in 3a, results in section 4).
(ii) Use the optimized framework to classify a much larger sounding dataset, and analyze the results for India's different seasons (methods in 3b, results in sections 5a–d).
(iii) Test whether large-scale irrigation affects premonsoon rainfall in India (methods in 3c, results in section 5e).

### *a. Framework validation*

The CTP–$HI_{low}$ framework, developed by FE2003a (section 2), was based on measurements from locations in the United States. To test whether this framework is valid in India, the slab model used by FE2003a was slightly modified and forced with atmospheric soundings from India. The slab model simulations are repeated for India because early morning CTP values are higher than in the United States (up to 500 J $kg^{-1}$ for India but up to 350 J $kg^{-1}$ for Illinois) and incoming shortwave radiation is higher for India than for the United States.

FE2003a used the slab model developed by Kim and Entekhabi (1998a) to investigate the coupled exchange of water, heat, and momentum between the land surface and atmosphere. The main assumptions of the model physics and boundary conditions are

- perfect mixing of the ABL,
- a cloud-free ABL,
- no change in overlying air masses during the simulation, and
- constant soil moisture during the simulation.

Kim and Entekhabi (1998a) assumed constant potential temperature and moisture lapse rates above the mixed layer. FE2003a modified the model to acquire the lapse rates from the early morning sounding measurement so that entrainment is determined by observed lapse rates of potential temperature and specific humidity.

Apart from determining the entrainment, the sounding is used to initialize the model at sunrise. After simulation of the daily ABL evolution, three outcomes are possible: no convection, shallow clouds, and deep convection. No convection occurs when the ABL height does not reach the level of free convection (LFC). Shallow, nonprecipitating clouds are assumed to form when the ABL height reaches the LFC, but at the same time the depth of convection (DOC) stays below 5 km, or CAPE below 400 J $kg^{-1}$. Deep convection with precipitation is assumed to occur when the LFC is reached and CAPE > 400 J $kg^{-1}$ and DOC > 5 km.

FE2003a compared slab model results to data from the Flatland ABL Experiment field campaign in Illinois (Angevine et al. 1998). This showed varying correspondence between model and measurement (Findell 2001), but the model was not optimized to fit these observations because it was used as an analytical tool. The model used in the present study determines incoming solar radiation based on the day of year and the geographic location of the atmospheric sounding. This differs from FE2003a, who took the radiative forcing constant for the entire boreal summer season. For further explanation of the model, the reader is referred to Kim and Entekhabi (1998a), Kim and Entekhabi (1998b), Findell (2001), and FE2003a.

For each sounding, a dry and wet soil run (15% and 85% soil moisture) were compared to determine what kind of feedback occurs. This resulted in four possible feedback classes (as in FE2003a, see section 2): positive feedback, negative feedback, atmospheric controlled (rain), and atmospheric controlled (dry). For each of these classes, the statistics of the maximum modeled ABL depth as well as an average sounding are calculated to test the appropriateness of the height intervals chosen for computing CTP and $HI_{low}$. Next, we determine the mean and standard deviations of CTP and $HI_{low}$ for the positive and negative feedback model outcomes to check the separation of these groups in CTP–$HI_{low}$ phase space. For the same reason, the classification success/fail rate using the original FE2003a thresholds is determined and optimized classification thresholds for India are determined. To check for intraregional variation in optimal CTP and $HI_{low}$ thresholds the same analysis is also done per station.

### *b. Feedback classification*

After the validity of the framework for India has been tested and its parameters adapted where appropriate, the potential influence of the land surface on precipitation is predicted for different periods and regions.

To determine which kind of feedback dominates for a given period in the annual cycle, CTP and $HI_{low}$ values are calculated from a much larger set of soundings. Based on these values, the framework is used to classify the feedback potential of all soundings. The obtained classification only presents the possibility of land surface influence on precipitation since no models are actually run to determine the differences between atmospheric conditions with a dry and wet soil.

The resulting classification data are then analyzed along a number of lines. First, for three stations representative of Indian geographic extremes, average monthly values of CTP and $HI_{low}$ are computed to illustrate its annual dynamics. Next, frequencies of occurrence for positive or negative feedbacks are computed for various periods (from a fortnight up to two months) preceding the climatological monsoon onset date in a particular year, during the monsoon and after the monsoon cessation date. The actual onset and retreat dates for each year are computed from the all-India Monsoon Index (IMI, see next section). These frequencies are determined over all of India and per station. Finally, from the latter spatial patterns in feedback, frequencies for these periods are plotted and interpolated on a map.

### c. Determination of premonsoon irrigation influence

After we have established when and where the land surface is *potentially* important, it remains to be seen whether an actual soil moisture anomaly really does affect actual precipitation. Precipitation data of the sensitive periods will be analyzed to see if there is any difference in precipitation between irrigated (more than 25% of the 0.08 degree grid cell equipped for irrigation) and nonirrigated (less than 25% of the 0.08 degree grid cell equipped for irrigation) sites. As will be shown in section 5, the potential for positive feedbacks is maximal in a one-month period before the monsoon onset. Then, a wet land surface is expected to increase precipitation. We assume that anomalously early rain may be enhanced by positive feedback. However, we must distinguish between anomalously early rain due to large-scale circulation changes and that due to local feedbacks. We determine the former from the wind-field-based IMI and the latter from actual rainfall itself. Figure 2 shows a schematic overview of the procedure used. Next, we describe the procedure in more detail.

For each station, the climatological monsoon precipitation onset (marked $t_{MS,pc}$ in Fig. 2) is assumed to be the average date when the cumulative precipitation climate has reached 15% of the total average annual precipitation. For the period 1960–2004, this corresponds to the onset date as suggested by O'Hare (1997).

The climatological monsoon circulation onset (marked $t_{MS,ic}$) is determined by the average date that the sign change of the 10-day moving average of the IMI changes from negative to positive. IMI is defined (Wang and Fan 1999) by the 850-hPa zonal wind averaged over (5°–15°N, 40°–80°E) minus that averaged over (20°–30°N, 60°–90°E). This meridional shear of zonal winds depicts the intensity of the Indian monsoon trough and associated southwesterly monsoon. During the summer monsoon wind patterns, the IMI is positive, while it is negative during the rest of the year. Climatologically, the IMI becomes positive by end May. To determine the anomalous large-scale circulation effects on the monsoon onset date, the anomaly of the IMI in the current year ($t_{MS,ia}$) is calculated: $t_{MS,ic} - t_{MS,ia}$. The difference (marked 2 in Fig. 2) is subtracted from the climatological monsoon precipitation start ($t_{MS,pc}$). The resulting date is assumed to be the start of the monsoon season, corrected for anomalies in the large-scale circulation (marked 3 in Fig. 2).

Then, the climatologically average period sensitive to feedbacks preceding the monsoon onset date is defined as the difference between the date $t_{FB}$ in which the 10-day moving average fraction of positive feedback situations is larger than 0.2 and the climatological monsoon precipitation onset $t_{MS,pc}$; that is, the period between markers 3 and 4 in Fig. 2. This period is different for each station. The fraction threshold of 0.2 is based on the classification by FE2003B, who use this threshold to classify stations as subject to predominantly positive feedbacks.

Then we determine the precipitation anomaly due to feedback ($P_{FB}$ in mm) in the period before the monsoon onset (shaded area in Fig. 2) as

$$p_{FB} = \int_{t_{FB}}^{t_{MA,p}} P_{year} - P_{climate} \tag{3}$$

in which $t_{MA,p} = t_{MS,pc} - (t_{MS,ic} - t_{MS,ia})$ is the monsoon onset date corrected for the large-scale circulation. This resulting premonsoon precipitation anomaly is determined for all stations for each year from 1960 to 2004. Differences in trends in $P_{FB}$ between irrigated and nonirrigated stations then confirms our hypothesis that positive feedbacks over irrigated areas may enhance rainfall.

### d. Data

The data used in this study are from radiosondes launched at 0000 UTC (0500–0700 local time) from 62 meteorological stations in India during the period 1975–2009 and were acquired from the university of Wyoming

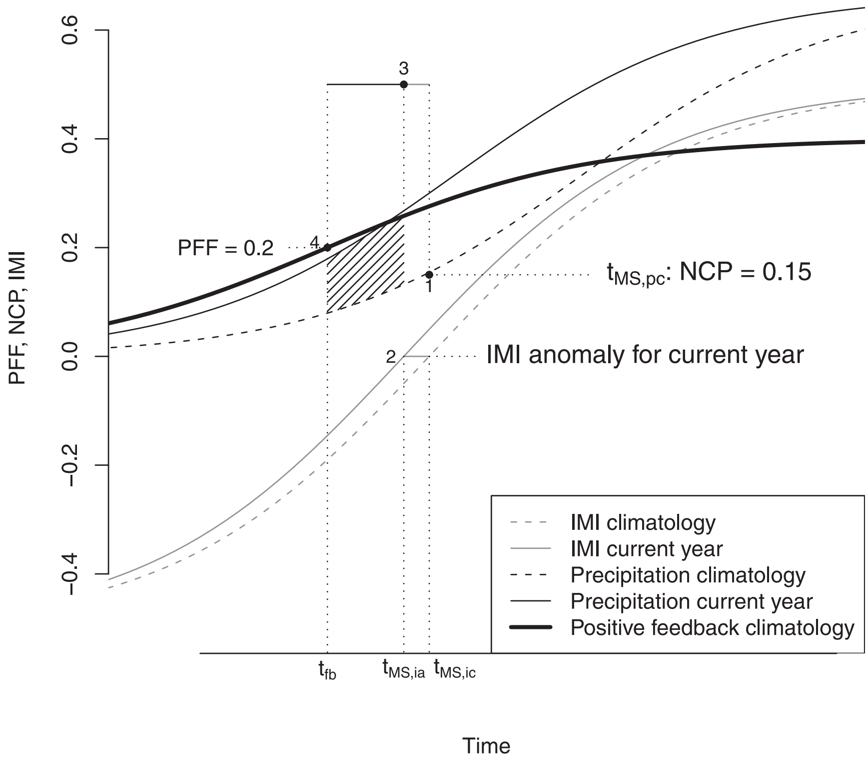


FIG. 2. Schematic of the premonsoon onset period over which the precipitation anomaly is calculated. The positive feedback fraction (PFF), normalized (by yearly total) cumulative precipitation (NCP), and the Indian monsoon index (IMI) are plotted against time. The climatological start of the monsoon season based on precipitation ($t_{MS,pc}$), the climatological start of the monsoon season based on IMI ($t_{MS,ic}$), and the start of the monsoon season in the current year based on the IMI ($t_{MS,pa}$) are indicated; $t_{FB}$ is the start of the feedback period before the monsoon onset. (Curves do not reflect actual data.)

(available online at http://weather.uwyo.edu/upperair/sounding.html). The differences in local time for the early morning soundings will not have a big influence on the analysis because the ABL is unlikely to have reached the levels at which CTP or $HI_{low}$ are evaluated (pressure level > 950 hPa).

The data are used for two purposes: a small subset of these data to force the slab model to test the framework and a much larger subset to determine a climatology of potential feedback situations. For both purposes, the sounding data are filtered on a number of vertical levels. For the model-forcing data, soundings with less than 20 vertical levels in the lower 400 hPa are filtered out, resulting in 4024 suitable soundings from 29 stations. The filtering for the data to determine the climatology was less strict—radiosondes with at least 10 levels below the 600-hPa level are selected. However, stations that had less than 1000 usable soundings for this period were not taken into account. This selection resulted in 30 stations with an average of 6500 soundings per station (195 000 soundings in total, see Fig. 3 for stations).

The Aphrodite 0.25 degree gridded dataset (Yatagai et al. 2009) is used as precipitation data. The precipitation values of the grid cell in which a station is located were aggregated into daily precipitation time series for each station for the period 1960–2004. Furthermore, the global map of irrigated areas (Siebert et al. 2005) is used to determine the fraction of the area suitable for irrigation of the 0.08 degree grid cell in which each station is located.

To determine the yearly anomaly in monsoon onset, the all-India Monsoon Index (Wang and Fan 1999) is calculated from daily National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996) for 1960–2004.

## 4. Performance of the CTP–$HI_{low}$ framework for India

This section tests framework performance for India, based on the results of the slab model runs with soundings from Indian stations. The distribution of CTP and

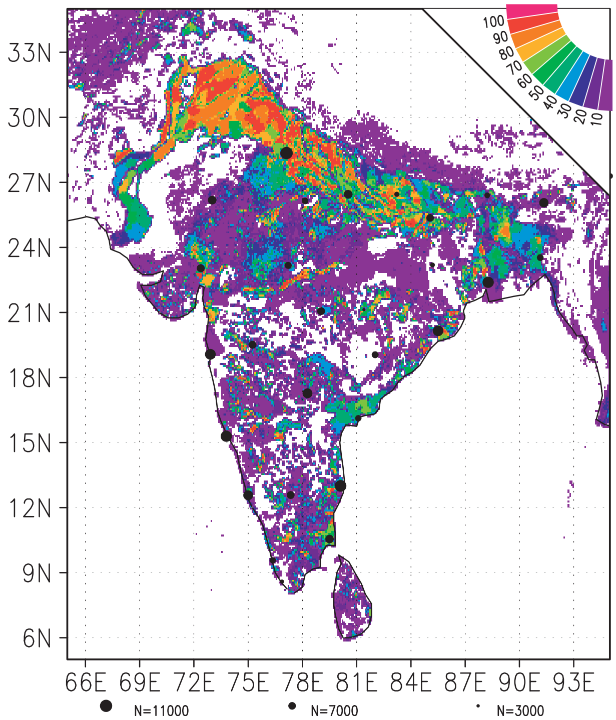


FIG. 3. Distribution of sounding stations used to determine the atmospheric conditions for feedbacks, shading shows the fraction of irrigation (Siebert et al. 2005). The size of the markers indicates the number of soundings available.

$HI_{low}$ values for the model outcomes will be compared to the thresholds for feedbacks found by FE2003a. Furthermore, we will quantify the predictive capacity of the framework. Thresholds for feedbacks will be changed to optimize this predictive capacity.

For 81% of the soundings the slab model simulations diagnosed an atmospherically controlled situation. However, in 19% of the simulations surface conditions determined the occurrence of convection.

The average atmospheric profiles of different model outcomes are shown in Fig. 4. The positive feedback and atmospherically controlled wet cases have higher specific humidity in the lowest 100 hPa than the negative feedback and atmospherically controlled dry cases. Between 900 and 850 hPa, the moisture profiles of the positive and negative feedback model outcomes are different as well. The positive feedback cases show a decline of specific humidity, whereas the negative feedback cases show increased moisture content from 900 to 850 hPa. Above 850 hPa, the positive, negative, and dry profiles show similar specific humidities. Moisture differences between the model outcomes are maximal at the levels at which $HI_{low}$ is evaluated (950 and 850 hPa). Moisture measures based on the dewpoint depression evaluated at various levels were tested, but were unable to distinguish better between the model outcome categories. Therefore, $HI_{low}$ is considered to be an adequate measure.

The mean potential temperature profiles of the model outcomes (Fig. 4) show an approximately constant slope for the atmospherically controlled wet and positive feedback cases. The negative feedback and atmospherically controlled dry cases show lower potential temperature lapse rates between 1000 and 900 hPa and higher lapse rates between 900 and 700 hPa. Thus, CTP (evaluated between 900 and 700 hPa) diagnoses the instability at the levels where positive feedback and atmospherically controlled wet outcomes differ from negative feedback and atmospherically controlled dry outcomes.

The surface conditions have an impact on the ABL height, with average maximum simulated heights of 1200 m over wet soils and 2000 m over dry soils (Fig. 5). The difference in ABL height between wet and dry soil runs confirms that the layer between 1 and 2 km above the ground is the one that is susceptible to entrainment by the ABL. Therefore, it was tested whether a modified version of the CTP, with integration bounds of 100 and 200 hPa above the land surface, improved the classification framework. This appeared not to be the case because the majority of the soundings did not have enough observation levels between 1 and 2 km above the surface to calculate the wet adiabat reliably.

Figure 6 shows the CTP–$HI_{low}$ values for cases in which the soil moisture affected the model outcome, the cases with positive or negative soil moisture feedback. In agreement with the results for the United States in FE2003a, positive feedback cases generally occur if CTP $< 250$ J kg$^{-1}$ (mean: 135 J kg$^{-1}$, standard deviation: 120 J kg$^{-1}$), while negative feedbacks cases occur if CTP $> 250$ J kg$^{-1}$ (mean: 276 J kg$^{-1}$, standard deviation: 138 J kg$^{-1}$). However, we find higher $HI_{low}$ values for positive and negative feedbacks than proposed by FE2003a. The bulk of the positive feedback cases have $HI_{low}$ values of up to 13 K (mean: 9.9 K, standard deviation: 3.6 K). The majority of negative feedback cases have $HI_{low}$ values of 10–16 K (mean: 13.8 K, standard deviation: 7.4 K), slightly higher than the thresholds found by FE2003a. This distribution of positive and negative feedbacks (Fig. 6) suggests that different thresholds for feedbacks should be adopted for India. An optimization showed the best prediction of the model results with positive thresholds of CTP = 0–200 J kg$^{-1}$ and $HI_{low}$ = 7–12 K and negative thresholds of CTP $>$ 200 J kg$^{-1}$ and $HI_{low}$ = 11–16 K.

The model runs are also analyzed for the individual stations. For positive feedbacks, the mean values for CTP varied between 108 and 183 J kg$^{-1}$ and for $HI_{low}$ between 8.6 and 11.9 K, whereas for negative feedbacks CTP ranged between 191 and 305 J kg$^{-1}$ and $HI_{low}$ between

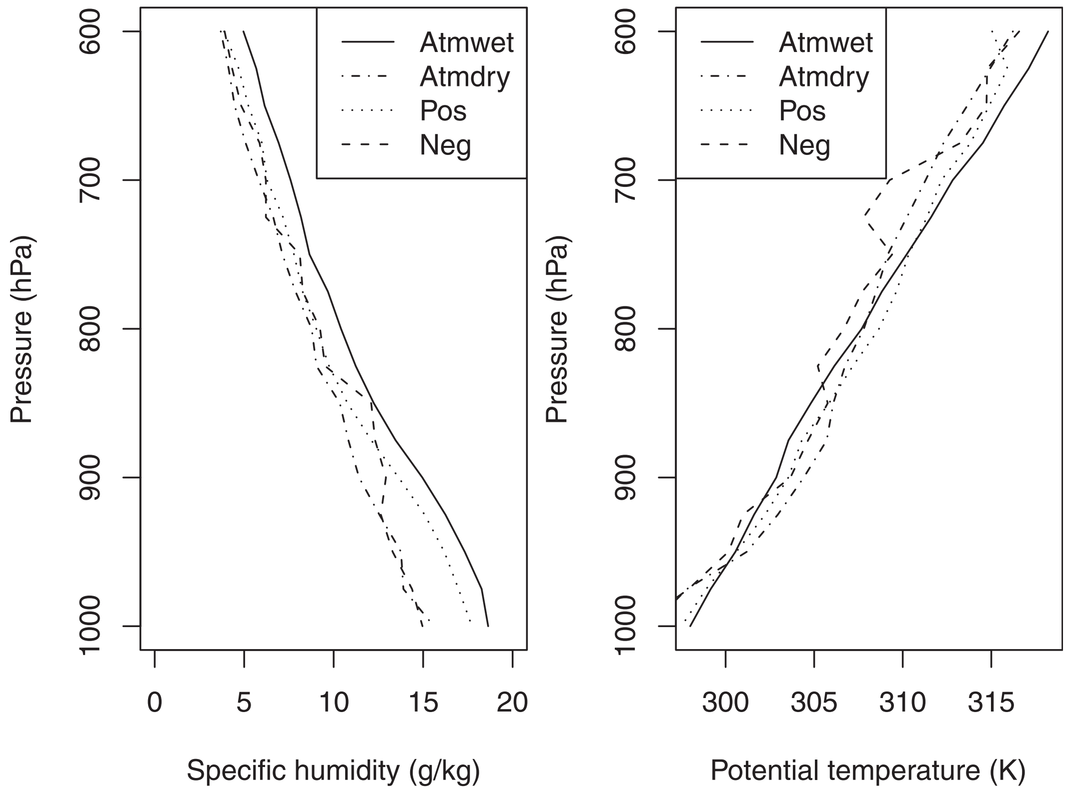


FIG. 4. Mean (measured) specific humidity and potential temperature profiles of the soundings that resulted in the slab model outcome categories: atmospherically controlled wet (Atmwet), atmospherically controlled dry (Atmdry), positive feedback (Pos), and negative feedback (Neg).

10.5 and 16.1 K. No relationship was found between the location (for example the north–south gradient) of a station and the mean CTP–$HI_{low}$ values from the slab model results. Therefore, henceforth the CTP and $HI_{low}$ thresholds are assumed to be equally valid for all stations in India.

A cross table of model results versus predictions of the framework (Table 1) shows that about 70% of the soundings is correctly classified (framework diagnosis is the same as slab model outcome) by the framework when using the original FE2003a thresholds. When a particular feedback is modeled for a sounding, the framework diagnoses that same feedback in 47% of the cases for positive feedbacks and in 34% of the cases for negative feedbacks. A positive feedback diagnosed by the framework is only simulated with the model in 30% of the cases; this is 21% for negative feedbacks. When these original (FE2003a) thresholds are used, the occurrence of both positive and negative feedback situations is overestimated. Positive feedbacks are diagnosed in 20% of the cases by the framework while only in 13% of the cases by the model. For negative feedbacks, these figures are 8.6% for the framework and 5.4% for the model.

With the new thresholds, 76% of the soundings are correctly classified. The relevant cross table (Table 2) shows that 49% of the positive feedback model outcomes are classified as such by the framework, while 41% of the situations classified as positive feedback are modeled as such. For the negative feedback these figures are 34% and 23%. Using the new thresholds, the fraction of feedback cases is better estimated. The framework predicts 15% of the cases to have a positive feedback (13% in the model) and 7.7% of the cases to have a negative feedback (5.4% in the model).

The model results suggest that the CTP–$HI_{low}$ framework can be used for the Indian continent. It predicts positive feedbacks better than negative feedbacks. Compared to the study for the United Sates (FE2003a), different $HI_{low}$ thresholds have to be used to classify feedbacks. Using these adjusted thresholds, the predictive performance of the framework increases, especially for positive feedback situations. In the remainder of this study, CTP = 0–200 J $kg^{-1}$ and $HI_{low}$ = 7–12 K will be used to classify positive feedbacks, and CTP = 200–500 J $kg^{-1}$ and $HI_{low}$ = 11–16 K for negative feedbacks. Furthermore, the transition zones (Fig. 1) as defined by FE2003a are assumed to be atmospherically controlled and are not considered separately.

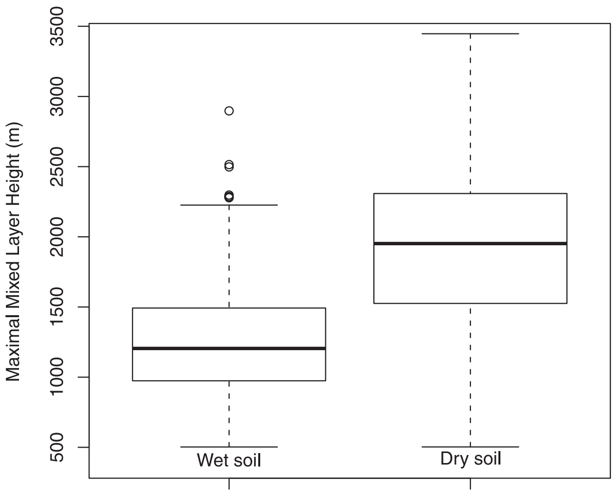


FIG. 5. Standard box plot [with box indicating lower and upper quartiles, bar in box indicating the median, whiskers indicating the range of the data (maximized at 2.5 quartiles of the median), and dots indicating outliers] of the slab model results showing the differences in modeled mixed layer height (m) between the runs with wet and dry soils for model runs in which the soil moisture determined the model outcome.

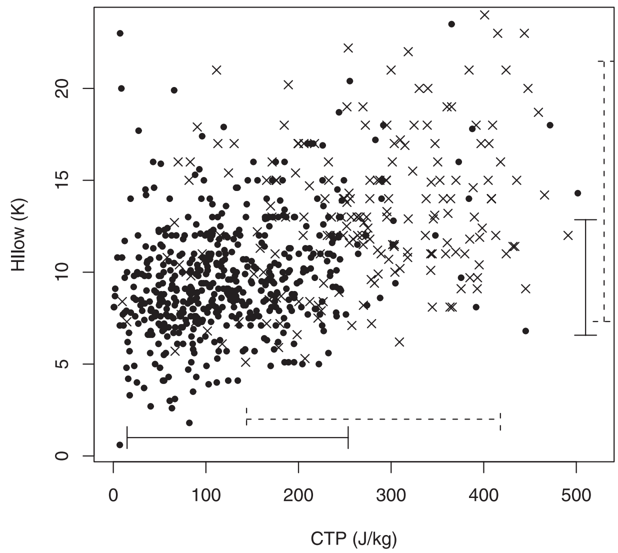


FIG. 6. Slab model results in CTP–$HI_{low}$ framework for India (all stations) showing only the cases with different outcomes for different surface conditions. Dot markers show positive feedbacks (wet soils promote precipitation); cross markers show negative feedbacks (dry soils promote precipitation).

## 5. Land–atmosphere feedbacks and monsoon

In this section, we will determine the prevalence of atmospheric conditions for which feedbacks are expected for India's different seasons. First, we investigate the climatological yearly cycle of feedback potential for different stations. Next, we test how the feedbacks relate to the summer monsoon timing, with special attention paid to the relation with onset and retreat. It must be stressed that, as we use the framework to classify atmospheric situations, this section only discusses chances of feedback occurrence. Finally, we will test whether this feedback potential actually has an effect on precipitation by comparing irrigated and nonirrigated sites.

### a. Seasonal CTP–$HI_{low}$ cycle

India's regions have differing yearly CTP–$HI_{low}$ cycles. Figure 7 shows these cycles for stations in the north (New Delhi, 28.35°N, 77.12°E), south (Thiruvananthapuram, 8.29°N, 76.57°E), and east (Kolkata, 22.39°N, 88.27°E; indicated in Fig. 8C with N, T, and K).

The differences in the yearly cycles of these three stations follow the large-scale differences in climatic regime. New Delhi has a very dry premonsoon season, with $HI_{low} > 20$ from November to June. CTP values increase during this period due to increasing solar radiation and consequent increased surface heating. New Delhi has a monsoon season from July to September, with average $HI_{low}$ = 8–15 K. These months have the most precipitation and the most potential for feedbacks. After the monsoon season, $HI_{low}$ values increase again, and from October to January, less incoming radiation decreases the CTP values again.

Kolkata shows a similar increase in CTP during January–April, but the presence of marine moist air decreases $HI_{low}$ values earlier. The monsoon season starts in June, with $HI_{low} < 7$ K during July–September. After the monsoon season, a similar pattern is found as for New Delhi, with a dry incoming air (increasing $HI_{low}$ values) and subsequent decrease in radiation (lower CTP values). For Kolkata, the period just before and just after the monsoon season has the highest feedback potential.

Thiruvananthapuram has a much moister climate, with smaller seasonal CTP–$HI_{low}$ variation. During the monsoon season (May–October), $HI_{low}$ values are so small that precipitation occurs regardless of land surface. From November to April, $HI_{low}$ values are higher, showing the most potential feedbacks in these months.

### b. Monsoon onset

The contours in Fig. 9 depict the average onset date of the monsoon, varying from the end of May to early July. The upper panels in Fig. 8 show the fraction of positive and negative feedbacks in a period of one month before the climatological monsoon onset (as documented by O'Hare 1997).

The percentage of days with positive feedback varies between 0% and 20% in central and northwest India. South and northeast India/Bangladesh have the largest

TABLE 1. Comparison of feedbacks as determined by the slab model and predicted by the framework, using the same thresholds for feedbacks as FE2003a. Overall, 70% of the soundings are correctly classified. 47% of the modeled positive feedback cases are determined as positive feedback by the framework, while 29% of the cases classified as positive feedback actually are modeled as positive feedback. For negative feedbacks these figures are 34% and 21%, respectively.

| | Framework prediction | | | |
|---|---|---|---|---|
| Model prediction | Positive | Negative | Atmospheric controlled | Total |
| Positive | 244 | 41 | 235 | 520 |
| Negative | 20 | 74 | 123 | 217 |
| Atmospheric controlled | 554 | 231 | 2502 | 3287 |
| Total | 818 | 346 | 2860 | 4024 |

probabilities of feedbacks, with fractions between 20% and 40%. Table 3 shows the percentages of positive, negative, and atmospherically controlled cases for two-week and one-month periods before the monsoon for all stations in India and for the three regions indicated in the contours in Fig. 8 (upper-left panel). With non-atmospherically controlled fractions higher than 30%, the south and northeast have the largest probability for the occurrence of feedbacks. In these regions, the positive feedback situations are much more likely than negative feedback situations.

In the rest of India, the fraction of days with potential for feedbacks is considerable; however, both positive and negative feedbacks occur, so no clear classification can be made.

### c. Monsoon season

The length of the monsoon season (the difference between onset and retreat dates, Fig. 9) varies from about six months in the south to about two months in the north. The middle row in Fig. 8 shows the fraction of positive and negative feedback situations during the monsoon period. For almost all stations, the percentage with positive feedback is 20%–25%, with an average value of 23% for all stations. Negative feedbacks during the monsoon occur only 5% of the time. Atmospherically controlled cases (precipitation regardless of the land surface conditions) are found for 71% of the soundings.

Two stations have a small fraction of feedback situations, Jagdalpur (19.1°N, 82.0°E) and Bangalore (12.5°N, 77.3°E). Both are dominated by atmospherically controlled wet conditions.

### d. Monsoon retreat

During the monsoon retreat, considerable potential for feedbacks is also present. However, the situation in the north of India is quite different from that in the south and east. The northern region has some potential for feedbacks in the two weeks after the monsoon retreat, with positive and negative feedbacks equally likely. Table 4 shows the percentages of positive, negative, and atmospherically controlled cases for a two-week, a one-month, and a two-month period after the monsoon for all stations in India and for the two regions indicated in the contours in Fig. 8 (lower-left panel). Atmospherically controlled situations prevail after about one month after the retreat.

In the south and east, the potential for positive feedbacks after the monsoon retreat is much stronger. In the two months after the monsoon retreat, the feedback situations (of which the majority are positive) represent about 30% of the cases, as shown in Fig. 8, lower panels. The duration of the period during which feedbacks are expected is longer than during the monsoon onset, suggesting that land surface changes can have a larger influence during the retreat period than during the onset period.

### e. Influence of irrigation on premonsoon precipitation

The effect of land–atmosphere feedbacks cannot be determined from precipitation records alone since, at

TABLE 2. Comparison of feedbacks as determined by the slab model and predicted by the framework, using the optimized thresholds for feedbacks for the Indian data. Overall, 76% of the soundings are correctly classified; 49% of the modeled positive feedback cases are determined as positive feedback by the framework, while 41% of the cases classified as positive feedback actually are modeled as positive feedback. For negative feedbacks these figures are 34% and 23%, respectively.

| | Framework prediction | | | |
|---|---|---|---|---|
| Model prediction | Positive | Negative | Atmospheric controlled | Total |
| Positive | 254 | 30 | 236 | 520 |
| Negative | 19 | 73 | 125 | 217 |
| Atmospheric controlled | 344 | 209 | 2734 | 3287 |
| Total | 617 | 312 | 3095 | 4024 |

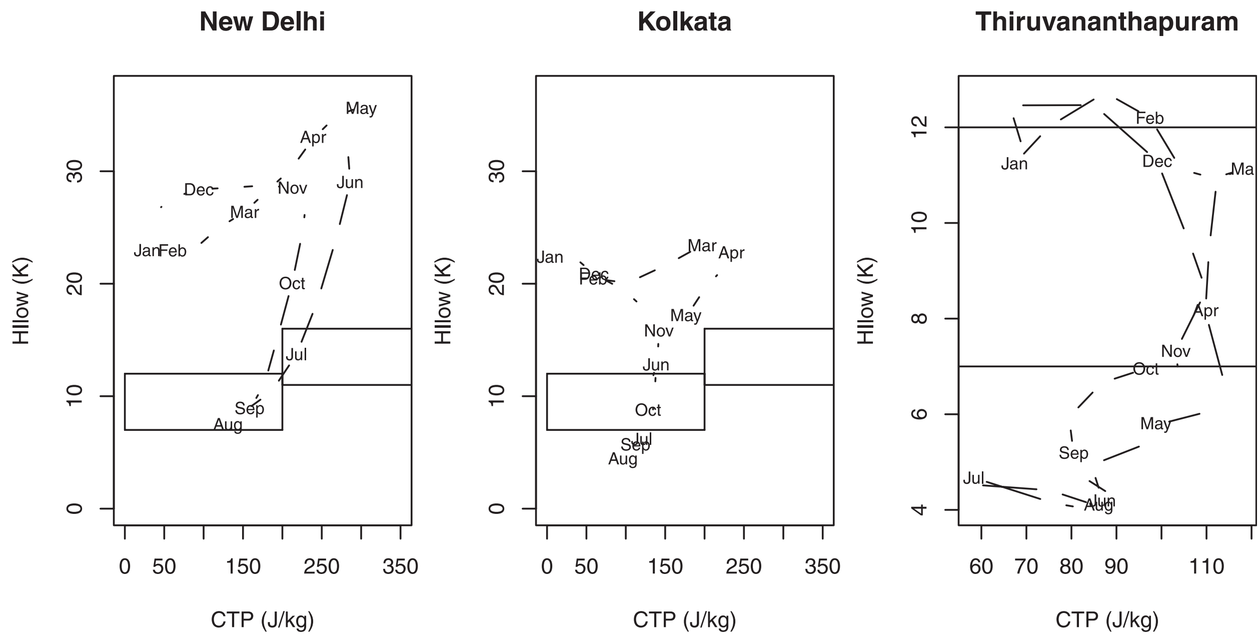


FIG. 7. Average yearly cycle of CTP and $HI_{low}$ values for stations New Delhi, Kolkata, and Thiruvananthapuram, based on the period 1975–2009. The cycle has been smoothed with a 10-day kernel filter. A value is plotted every decade, with the first decade of the month indicated with the month abbreviation. The CTP–$HI_{low}$ regions for which feedbacks are expected are indicated with boxes. Note the different scale for the Thiruvananthapuram plot.

a given moment, only one land surface state is present. However, for India, the irrigation extent has doubled between 1960 and 2004 (see trend in Fig. 10), giving different land surface conditions over time for the same sites. Figure 10 shows the trends in precipitation in the premonsoon period that are sensitive to positive feedbacks (probability of positive feedbacks higher than 0.2) for stations in irrigated regions and in nonirrigated regions (part of 0.08 degree grid cell suitable for irrigation larger/smaller than 25%). The length of this period is different for each station, but on average it is 23 days.

The irrigated stations show an upward trend of 0.7% of the annual precipitation per year in the period considered, whereas the nonirrigated stations show almost no trend. The trend lines of irrigated and nonirrigated stations are different at the 93% confidence level. While the irrigated trend is different from zero at the 93% confidence level, the nonirrigated trend is not statistically different from zero. The upward trend in the irrigated areas results in about 30% more premonsoon rainfall over the 1960–2004 period. This increase in premonsoon precipitation for the irrigated stations corresponds to about 1%–3% of the annual precipitation.

## 6. Discussion

In this study, the importance of local feedbacks from land surface state to convective precipitation has been quantified for India using the existing CTP–$HI_{low}$ framework (FE2003a). It was shown that this framework, which was proposed for the United States, can be applied to India as well. However, some adaptation of the classification thresholds will improve the performance in these tropical conditions. By forcing a slab model with atmospheric soundings from India, feedbacks were found for higher values of $HI_{low}$ then those proposed for the United States.

Using the acquired thresholds for feedbacks, a much larger number of soundings can be efficiently classified without running a model. Overall, the framework predicts 76% of the atmospheric situations correctly. However, two types of errors are made: not all situations that show feedbacks in the model are classified as having a feedback by the framework, and not all situations that are classified as having a feedback show this feedback in the model. For the chosen feedback thresholds for India, the number of cases falling into these error categories are similar. Therefore, the framework does not over- or underestimate the number of cases in which there is a feedback situation.

However, when considering individual soundings classified as having a feedback, the chances of misclassification are significant (about 60% of positive feedback classifications actually are atmospherically controlled and about 50% of the modeled positive feedbacks are not classified as such). The framework classifies about half of the feedbacks that occur in the model. In the original study by FE2003a, the predictive capacity of the

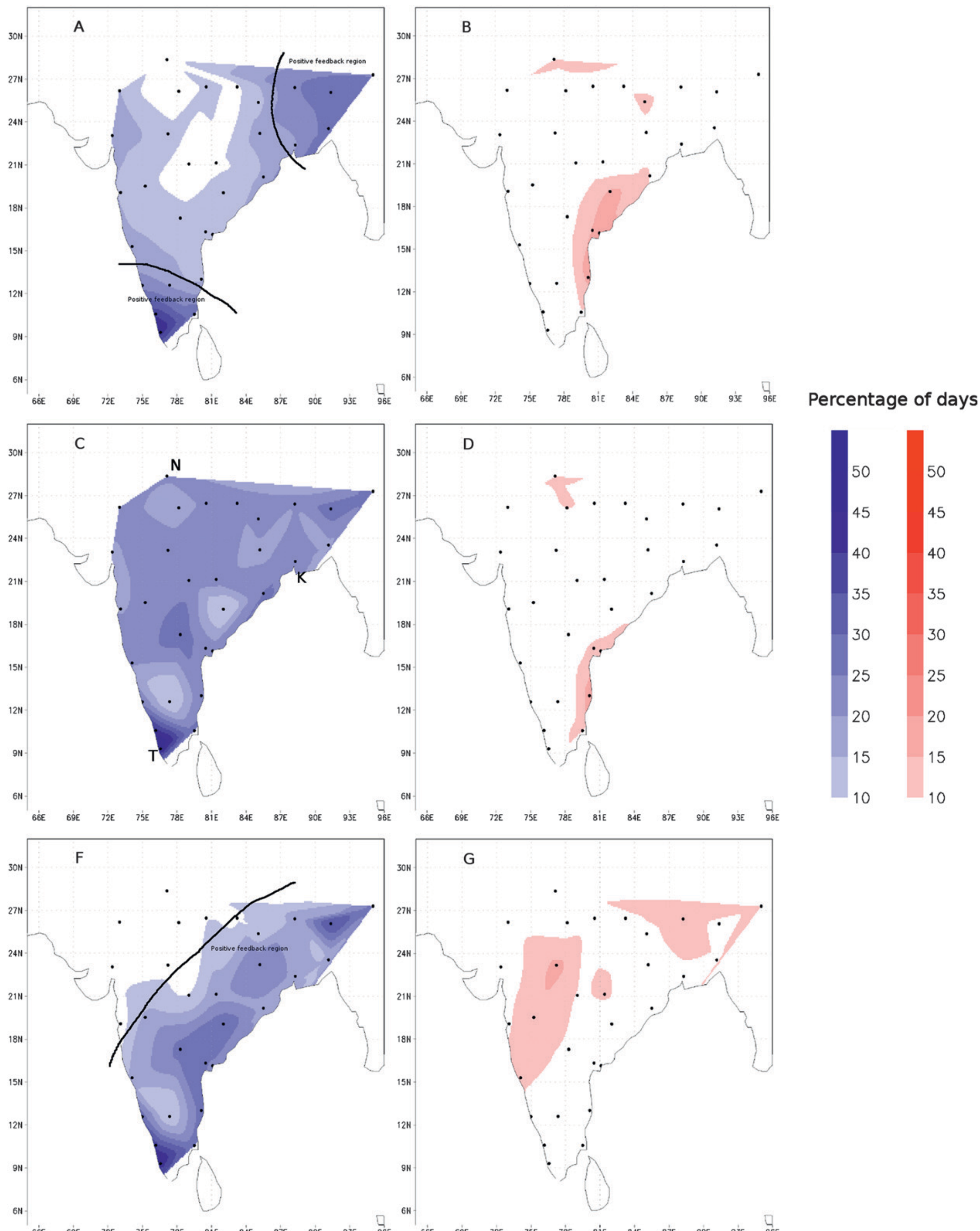


FIG. 8. Interpolation of the percentage of (left) positive and (right) negative feedbacks from one month before the monsoon onset until (top) the onset date, (middle) during the monsoon season, and (bottom) in the two months after the monsoon retreat. Feedbacks are diagnosed by applying the modified CTP–$HI_{low}$ framework to the soundings for all stations. Stations are indicated with black markers. Note that the onset and retreat dates are not the same for all stations, so integration periods are different for all stations in all rows.

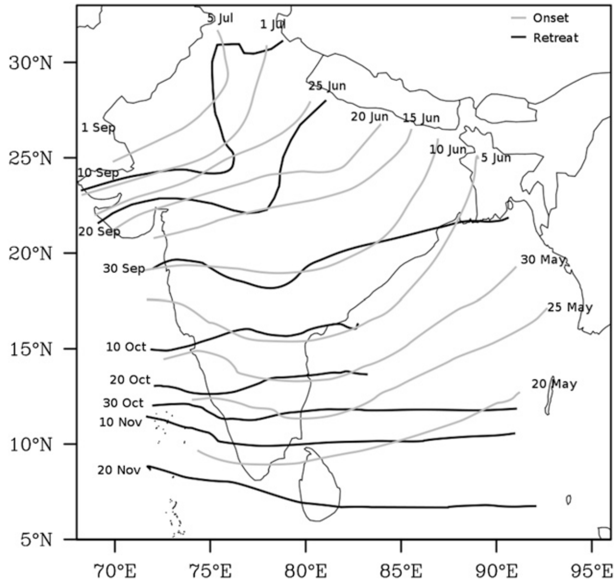


FIG. 9. Average climatological monsoon onset and retreat dates after O'Hare (1997). There is a north–south gradient in the monsoon length, with longer monsoon seasons in the south than in the north.

framework is not quantified, so it is unknown whether the framework performs differently for India than for the United States. However, it is shown that by using different thresholds for feedbacks for different regions, the prediction error is reduced. Therefore, for new regions where the framework is to be applied, models should be used to reassess the feedback thresholds. Alternatively, given enough computing resources one might skip the classification and use the model only to evaluate the soundings.

Apart from optimizing the framework thresholds, alternative measures have been used to classify the soundings. However, changing the levels and ranges at which CTP and $HI_{low}$ are evaluated did not improve the framework predictions. Moreover, the slab model was also run with soil moisture between 15% and 85% of the maximum soil moisture. However, no significant relation was found between the soil moisture percentage at which the model result changed from precipitation to no precipitation or vice versa and CTP or $HI_{low}$.

In our approach, a simple model that might lack important processes is used to determine land–atmosphere feedbacks. Advection, orography, and flows that originate from land surface heterogeneity are not included in our simple model. These processes are important for the feedbacks that are considered here, but are not taken into account. To test the effect of those processes on land–atmosphere feedbacks, a 3D atmospheric model should be used.

TABLE 3. Feedback expectations for a two-week and a one-month period before the monsoon onset for soundings from all stations in different regions in India (see Fig. 8, upper-left panel, for the delineation of these regions).

| Period | | All India | South | North–east | Rest of India |
|---|---|---|---|---|---|
| Two weeks | Atm | 73.0 | 66.7 | 69.2 | 74.8 |
| | Pos | 18.5 | 28.0 | 23.8 | 15.9 |
| | Neg | 8.5 | 5.3 | 7.0 | 9.3 |
| One month | Atm | 75.7 | 67.6 | 68.4 | 78.2 |
| | Pos | 17.0 | 27.6 | 23.7 | 14.3 |
| | Neg | 7.3 | 4.8 | 7.9 | 7.5 |

Application of the framework showed that there is significant potential for local positive feedbacks from the land surface state to convective precipitation; the opposite negative feedbacks are less predominant. This means that wet surface conditions can enhance local precipitation. The potential for these local feedbacks varies both spatially and seasonally for India.

The yearly CTP–$HI_{low}$ cycle shows the signature of the monsoon dynamics. From about a month before the onset of the monsoon, India's south and east and Bangladesh show a potential for positive feedbacks. $HI_{low}$ values are in the positive feedback range in these areas due to advected moisture from the nearby ocean, while CTP values are positive because of increased insolation. Thus, areas with wet surface conditions favor convection and can trigger premonsoon convective rains. In the remainder of India, $HI_{low}$ values are slightly higher and positive and negative feedbacks occur in equal ratios (see Table 3).

During the monsoon season, the probability of positive feedbacks is high throughout India. Feedbacks during the monsoon period might be important in regions that receive the majority of precipitation from convective

TABLE 4. Feedback expectations for a two-week, a one-month, and a two-month period after the monsoon retreat for soundings from all stations in different regions in India (see Fig. 8, lower-left panel, for a delineation of these regions).

| Period | | All India | North | South and east |
|---|---|---|---|---|
| Two weeks | Atm | 67.9 | 72.8 | 64.6 |
| | Pos | 21.9 | 14.8 | 26.7 |
| | Neg | 10.2 | 12.4 | 8.7 |
| One month | Atm | 71.0 | 77.7 | 66.3 |
| | Pos | 19.5 | 10.9 | 25.5 |
| | Neg | 9.5 | 11.4 | 8.2 |
| Two months | Atm | 75.8 | 83.5 | 70.6 |
| | Pos | 16.6 | 8.1 | 22.4 |
| | Neg | 7.6 | 8.4 | 7.0 |

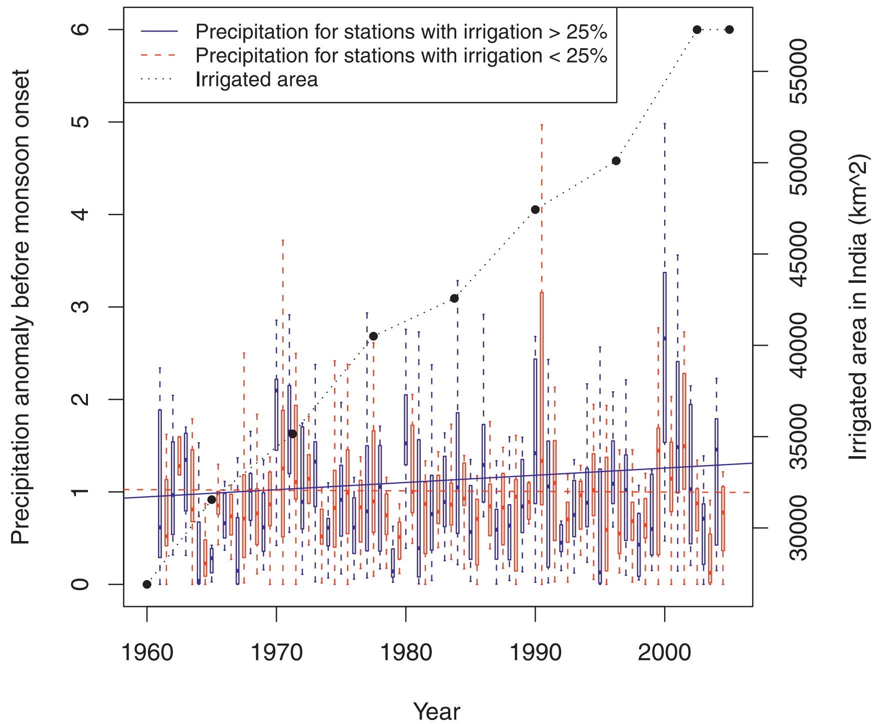


FIG. 10. Relative deviation from the 1960–2004 precipitation mean in the period with positive feedbacks before the monsoon onset for irrigated (blue) and nonirrigated (red) sites from 1960 to 2004. The period before the monsoon onset is different for each site but constant in time. The irrigated sites show an upward trend (0.0077 ± 0.0042 of yearly precipitation, this trend is significant from zero at the 93% confidence level), while the nonirrigated do not (−0.0006 ± 0.0033 of yearly precipitation). Total irrigated area in India (Siebert et al. 2005) is plotted on the right axis.

storms. These regions are found in the rain shadow of mountain ranges and during monsoon breaks (periods of up to two weeks during which the prevailing monsoon flow pattern stops; O'Hare 1997).

During the period two months after the monsoon retreat, atmospheric situations where positive and negative feedbacks can be expected are present in about the same quantities in north India. During that same period, positive feedbacks can be expected in a region extending from the south, through a strip along the Bengal coast, to the east.

When the summer monsoon has completely retreated, dry atmospherically controlled situations start prevailing, with no convection regardless of surface conditions. These conditions persist throughout the winter months (January–March) during which the land surface conditions are not expected to trigger rainfall.

These results are in agreement with the positive correlations among soil moisture, recycling ratio, and evaporation for MAM and SON reported by Dirmeyer et al. (2009). As in the present study, Dirmeyer et al. concluded that soil moisture is important during the monsoon onset and retreat phases, although their integration period of three months is quite large in comparison with onset and retreat. During the monsoon season, we find the same land–atmosphere coupling patterns as Koster et al. (2004), but additional sensitive regions are found in east and south India and Bangladesh. We plan further research using reanalysis data to get a better spatial and temporal feedback description and to compare this with other diagnostics (recycling ratios, correlation between soil moisture and precipitation, etc.).

Although we find positive local feedbacks for large parts of India in the monsoon season, the reduction of the land–sea contrast can affect the large-scale monsoon flow and act as a large-scale negative feedback, as suggested by Lee et al. (2009). Regional-scale atmospheric models could assess the relative importance of local- and large-scale feedbacks.

Determining the actual importance of land–atmosphere feedbacks from precipitation data alone is complicated. The signals from both large-scale processes and local feedbacks are present in the data. Moreover, when relating the potential for feedbacks to the monsoon onset, local feedbacks may already have influenced the precipitation data from which the onset date is determined. The determination of monsoon onset date by the large-scale wind pattern (IMI) can at least partly circumvent this problem.

In the period before the monsoon onset, surface conditions are mostly dry. Therefore, large-scale irrigation is expected to influence precipitation just before the monsoon onset. Since there has been an increase in irrigation in India during the entire twentieth century, the premonsoon precipitation is expected to have increased in irrigated areas. This is confirmed in Fig. 10, which shows the difference in trends of premonsoon precipitation between irrigated and nonirrigated areas. In the 1961–2004 period, there has been an increase in premonsoon precipitation in irrigated areas that corresponds to 1%–3% of annual precipitation. This is a modest amount compared with the total annual precipitation, but it is significant in a period of small precipitation amounts and may be important, for example, for crop germination.

Further examination of precipitation data could determine how well the trends in premonsoon precipitation follow the irrigation trends as well as the influence of irrigation during the monsoon and postmonsoon season.

## 7. Conclusions

This study applied the CTP–$HI_{low}$ framework to India to determine the influence of land surface on convective precipitation. The framework can be applied to India, but $HI_{low}$ thresholds to determine cases with feedbacks were higher than in the original study for the United States. With the new thresholds for feedbacks applied to atmospheric situations in India's climatology, the periods around the monsoon season and the monsoon season itself showed the largest percentages (of up to 40%) of days with potential for local feedbacks.

Using the framework improves the feedback potential prediction about 30%–40%, compared to a classification without prior knowledge. However, for a significant fraction of the soundings the classification is incorrect. Efforts to make the framework more physically realistic, for example, by limiting the integration of definitions of CTP and $HI_{low}$ to the simulated ABL depth, did not improve this classification. There seems to be a limit to the predictive capacity of a framework with only two indicators; however, the advantage of the framework is that large time series can be analyzed quickly.

The feedback potential follows Indian monsoon dynamics. During January–April, the atmosphere is too dry for the land surface to induce precipitation. However, in the period before the monsoon onset, positive feedbacks are found in the south and east. During the monsoon season, all of India has atmospheric conditions in which a wet land surface can trigger precipitation more than 20% of the time. After the monsoon retreat, a region extending from the south to the east shows these atmospheric conditions more than 20% of the time.

The effect of these feedbacks just before the monsoon onset was tested by comparing the extent of large-scale irrigation with the premonsoon precipitation. Irrigated areas show an increasing premonsoon precipitation trend, while nonirrigated areas lack this trend. This suggests that irrigation increases precipitation in these periods. This precipitation increase corresponds to about 3% of the annual precipitation; however, falling in the month before the monsoon onset, it may represent a significant contribution to water resources.

We conclude that the CTP–$HI_{low}$ framework is a good method to efficiently determine the potential for local land–atmosphere feedbacks. Periods and regions where feedbacks are potentially important can be determined easily. Because of the limitations in the framework, a three-dimensional model that takes into account more processes should be used to study the land atmosphere feedbacks in more detail. This is beyond the scope of the present paper and is a subject of further study.

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REFERENCES

Angevine, W. M., A. W. Grimsdell, L. M. Hartten, and A. C. Delany, 1998: The Flatland boundary layer experiments. *Bull. Amer. Meteor. Soc.,* **79,** 419–431.

Barry, R. G., and R. J. Chorley, 2003: *Atmosphere, Weather, and Climate*. 8th ed. Routledge, 421 pp.

Bisselink, B., and A. J. Dolman, 2008: Precipitation recycling: Moisture sources over Europe using ERA-40 data. *J. Hydrometeor.,* **9,** 1073–1083.

Brubaker, K. L., and D. Entekhabi, 1996: Analysis of feedback mechanisms in land–atmosphere interaction. *Water Resour. Res.,* **32,** 1343–1357.

De Ridder, K., 1997: Land surface processes and the potential for convective precipitation. *J. Geophys. Res.,* **102,** 30 085–30 090.

Dirmeyer, P. A., and K. L. Brubaker, 2007: Characterization of the global hydrologic cycle from a back-trajectory analysis of atmospheric water vapor. *J. Hydrometeor.,* **8,** 20–37.

——, C. A. Schlosser, and K. L. Brubaker, 2009: Precipitation, recycling, and land memory: An integrated analysis. *J. Hydrometeor.,* **10,** 278–288.

Douville, H., F. Chauvin, and H. Broqua, 2001: Influence of soil moisture on the Asian and African monsoons. Part I: Mean monsoon and daily precipitation. *J. Climate,* **14,** 2381–2403.

Eltahir, E. A. B., 1998: A soil moisture–rainfall feedback mechanism 1. Theory and observations. *Water Resour. Res.,* **34,** 765–776.

Findell, K. L., 2001: Atmospheric controls on soil moisture-boundary layer interactions. Ph.D. Thesis, Massachusetts Institute of Technology, 172 pp.

——, and E. A. B. Eltahir, 1997: An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois. *Water Resour. Res.,* **33,** 725–735.

——, and ——, 2003a: Atmospheric controls on soil moisture–boundary layer interactions. Part I: Framework development. *J. Hydrometeor.,* **4,** 552–569.

——, and ——, 2003b: Atmospheric controls on soil moisture–boundary layer interactions. Part II: Feedbacks within the continental United States. *J. Hydrometeor.,* **4,** 570–583.

Guo, Z., and Coauthors, 2006: GLACE: The global land–atmosphere coupling experiment. Part II: Analysis. *J. Hydrometeor.,* **7,** 611–625.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kim, C. P., and D. Entekhabi, 1998a: Feedbacks in the land-surface and mixed-layer energy budgets. *Bound.-Layer Meteor.,* **88,** 1–21.

——, and ——, 1998b: Impact of soil heterogeneity in a mixed-layer model of the planetary boundary layer. *Hydrol. Sci. J.,* **43,** 633–658.

Koster, R. D., and Coauthors, 2004: Regions of strong coupling between soil moisture and precipitation. *Science,* **305,** 1138–1140.

——, and Coauthors, 2006: GLACE: The global land–atmosphere coupling experiment. Part I: Overview. *J. Hydrometeor.,* **7,** 590–610.

Lee, E., T. N. Chase, B. Rajagopalan, R. G. Barry, T. W. Biggs, and P. J. Lawrence, 2009: Effects of irrigation and vegetation activity on early Indian summer monsoon variability. *Int. J. Climatol.,* **29,** 573–581.

Lohar, D., and B. Pal, 1995: The effect of irrigation on premonsoon season precipitation over south west Bengal, India. *J. Climate,* **8,** 2567–2570.

Lytinska, Z., J. Parfiniewicz, and H. Pinkowski, 1976: The prediction of air mass thunderstorms and hails. *Proc. WMO Symp. on the Interpretation of Broad-Scale NWP Products for Local Forecasting Purposes,* Warsaw, Poland, WMO, 128–130.

Meehl, G. A., 1994a: Coupled land–ocean–atmosphere processes and South Asian monsoon variability. *Science,* **266,** 263–267.

——, 1994b: Influence of the land surface in the Asian summer monsoon: External conditions versus internal feedbacks. *J. Climate,* **7,** 1033–1049.

O'Hare, G., 1997: The Indian monsoon. Part 2: The rains. *Geography,* **82,** 335–352.

Siebert, S., P. Döll, J. Hoogeveen, J. Faures, K. Frenken, and S. Feick, 2005: Development and validation of the global map of irrigation areas. *Hydrol. Earth Syst. Sci.,* **9,** 535–547.

Wang, B., and Z. Fan, 1999: Choice of South Asian summer monsoon indices. *Bull. Amer. Meteor. Soc.,* **80,** 629–638.

Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.,* **103,** 14 451–14 510.

Yatagai, A., O. Arakawa, K. Kamiguchi, H. Kawamoto, M. I. Nodzu, and A. Hamada, 2009: A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *SOLA,* **5,** 137–140.