A Numerical Study of the Hydrometeorological Dryline in Northwest India During the Monsoon

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Abstract

This objective of this study is to elucidate the processes that govern the space-time persistence of the hydrometeorological dryline in Northwest India. The working hypothesis is that orographic forcing and land-atmosphere interactions via soil moisture and vegetation processes lock the hydrometeorological line to the Aravalli range and the Thar Desert (a.k.a. the Great Indian Desert). For this purpose, simulations of active and break phases of the 2001 monsoon season were conducted using a mesoscale model (MM5). During the active phases of the monsoon, southeasterly depressions from the Bay of Bengal propagate over northern India, maintaining sustained convergence of moist available energy east of the Aravalli range, leading to increased rainfall and cloudiness patterns consistent with deep convective activity. Drier air originating from the Arabian Sea in the Western Indian Ocean is constrained to the west. During monsoon break phases, moisture convergence from the Bay of Bengal to the Northern India Convergence Zone (NICZ) decreases dramatically, weakening regional circulations east of the Aravalli range. This allows ventilation of the central portion of the NICZ through penetration of westerly dry air, leading to reduced rainfall, lower soil wetness, decrease of latent heat fluxes, and finally lower CAPE and humidity in the lower troposphere. Whereas the inland propagation of monsoon depressions from the Bay of Bengal triggers the onset (demise) of active and break periods, the sustainability of either regime requires strong feedbacks between humidity and stability in the lower troposphere and the surface energy balance: negative in the case of monsoon breaks, positive in the case of active periods. This study shows that, albeit relatively modest (<600 m average elevation), the Aravalli provides sufficient lift (upwind) and descend (downwind) to organize the spatial distribution of updrafts westward (active phase) and eastward (break phase) of the topographic divide in such a way that low level updrafts are nearly suppressed over the Thar Desert. Sensitivity experiments with modified soil and vegetation cover show that daytime latent heat fluxes (and evapotranspiration) play an important role in the spatial organization of CAPE and in triggering light rainfall processes in the semi-arid regions of northwest India, whereas the occurrence of heavy rainfall to the east of the Aravalli range is controlled by large-scale monsoon dynamics.

1. Introduction

From the early study of Shukla and Mintz (1982), a large number of observational and numerical studies of land-atmosphere interactions...
have sought to illuminate the relationship between the terrestrial energy budget, and in particular soil moisture and terrestrial evapotranspiration controls on surface fluxes, and precipitation regimes at local, regional and global scales (e.g., Ookoucki et al. 1984; Lanici et al. 1987; Pan and Mahrt 1987; Wetzel 1990; Atlas et al. 1993; Pielke et al. 1998, among many others). Two modeling studies using GCMs (Global Climate Models) are especially relevant for the Indian subcontinent in the context of this work. Sud et al. (1995) found that increases in evapotranspiration and/or land-surface roughness over the Indian subcontinent were conducive to an increase in local rainfall. In a recent study to identify regions of the Earth where precipitation is affected by soil moisture anomalies during the Northern Hemisphere summer, Koster et al. (2004) used a large number of multi-model GCM ensembles to derive an area-averaged global diagnostic of land-atmosphere coupling strength in JJA (June-July-August). Their results point to the NICZ (Northern India Convergence Zone) as one of the “hot-spot” regions where such coupling is stronger, and thus a region where a predictive cause-effect-feedback relationship between soil moisture storage (or surface wetness) and precipitation is expected.

Analysis of the climatology of cloudiness and convective activity over the Indian subcontinent suggests the existence of a persistent discontinuity aligned with the Aravalli range that separates the Northern India Convergence Zone (NICZ) to the east from the dry climate of the Thar Desert to the west, thus effectively establishing a hydrometeorological dryline (Barros et al. 2004, Figs. 1a–b). The location and extent of this boundary exhibit a pattern of westward excursions and retreats consistent with the space-time characteristics of convective systems during the active and break phases of the monsoon. Observational studies indicate that cumulative monsoon rainfall east of the Aravalli range in Northern India is three times higher on average than in the regions to the west often afflicted by major drought (i.e., the Thar Desert; COLA 2003). Whereas the inland propagation of monsoon depressions off the Bay of Bengal trigger the onset (demise) of active and break periods, the sustainability of either regime requires strong feedbacks between humidity and stability in the lower troposphere and the surface energy balance (Webster et al. 1998, Fig. 2). These mechanisms of ocean-land-atmosphere interactions (dry processes in the case of monsoon breaks, wet processes in the case of active periods) introduce persistence (and spatial stationarity) at the time-scales relevant for monsoon weather over land.

An earlier study of land-atmosphere interactions in the southern Great Plains during summertime rainfall using a mesoscale model (MM5) showed that land surface heterogeneity determines the dynamic range of land-atmosphere interactions regionally (Barros and Hwu 2002). Further, these interactions are closely linked to atmospheric stability in the lower troposphere, and a feedback mechanism that reinforces the persistence of moist and dry processes, until significant changes in the large-scale environment take place. Because of the stationary characteristics of land-use and land-cover east and west of the Aravalli range, and because synoptic scale conditions are dominated by the westerly air masses from the Arabian Sea in the west and by easterly systems from the Bay of Bengal in the east, the convective activity barrier along the Aravalli is in fact a quasi-stationary hydrometeorological dryline. In this study, we intend to investigate the importance of land cover and soil type in the formation and persistence of the dryline and its behavior during monsoon onset and break phases in northwest India.

Past studies (e.g., Grasso 2000; Peckham and Wicker 2000) that investigated drylines in the western high plains of the United States suggested that horizontal soil moisture gradients as well as topographic complexity and lower-tropospheric winds are all factors in the dynamical evolution of the dryline and in triggering the generation of mesoscale convective systems. Whether the dryline mechanisms and regional impact associated with the South Asia Monsoon resemble those in the Central United States needs to be investigated. Besides the differences in physiographic and climate settings, one significant difference between the two drylines is the remarkable spatial stationarity of the northern India hydrometeorological dryline that remains aligned with the Aravalli range over the entire duration of the monsoon season.
The role of the dryline in organizing the spatial distribution of convective activity and consequently precipitation was studied in detail by Peckham and Wicker (2000), who concluded that moist air parcels from near the surface are captured by the dryline updrafts resulting in higher mid-tropospheric relative humidity, subsequently increasing the likelihood of convective storm initiation in the western Great Plains. This suggests a possible explanation for the confinement of convective activity along the eastern slopes of the Aravalli and against the Hindu Kush mountains, if it can be demonstrated that dryline updrafts are organized in such way that reach their maximum intensity and impact in the redistribution of low-level moisture at those specific locations.

In this study, we will examine the physical dynamics and thermodynamics of the dryline with a focus on the spatial organization of vertical velocity fields and low-level moisture distribution during the monsoon. We will investigate the sensitivity of terrestrial controls of latent and sensible heat exchange and low troposphere stability to land use and soil type, and whether and how that reinforces the dominant weather regime via feedback mechanisms. Ultimately, one of our goals is to elucidate the role of landform and land-cover in the intra-seasonal spatial variability of the monsoon in northern India. The specific goals in this study are to: (1) investigate land singularities/discontinuities that control convective activity and rainfall in association with the stationary dryline during the onset and break phases of the monsoon; and (2) understand how soil type and land cover have an impact on land-atmosphere interactions in terms of the spatial and temporal variations of the dryline. We investigate our hypothesis using the Penn State/NCAR MM5 coupled to land surface model at 30 and 10 km resolution over the Indian subcontinent. The sensitivity experiments will examine the differences in the vertical thermodynamic structure resulting from the changes of land use and soil type. The numerical model and experimental design, as well as a general description of the spatial structure and temporal evolution of the monsoon onset and break phases in 2001 are presented in Section 2. The evaluation of simulation results by intercomparison against observations and satellite imagery as well as the results from sensitivity studies are presented in Section 3. Section 4 presents the conclusions and discussion.

2. Description of the model and experimental design

2.1 The model

Numerical simulations were performed using the PSU/NCAR MM5 model (Dudhia 1993; Grell et al. 1994). The planetary boundary layer (PBL) scheme used in this study is the MRF PBL scheme (Hong and Pan 1996). The atmospheric radiation scheme accounts for longwave and shortwave transfers and interactions with the atmosphere, clouds, and the surface (Dudhia 1989). Precipitation is produced from both grid-scale condensation and convection. Grid-scale precipitation is determined from an explicit moisture scheme that includes ice microphysics (Tao et al. 1993). The Kain-Fritsch (Kain and Fritsch 1993) scheme was selected for the cumulus parameterization. Klemp and Durran’s (1983) upper-radiative boundary condition was applied in order to prevent gravity waves from being reflected at the top of the model grid. The atmospheric model is coupled to the Oregon State University/NCEP Eta Land-surface model (Mitchell et al. 2002) which includes 5 soil layers and a canopy layer, and solves the water and energy balance equations at the land surface. For further details on the coupled model, the reader is referred to Chen and Dudhia (2001). A total of 30 unequally spaced layers in the vertical were employed with the lowest model level beginning approximately 20 m above the ground. The 2-domain nested simulations were configured with grid spacing of 30 km (131×131), and 10 km (196×199) horizontal resolutions respectively for domain 1 and domain 2. The top of the atmosphere in the model is located at 50 hPa level. Time steps of 30 and 10 seconds were used in these simulations respectively for domain 1 and domain 2. The 30 km resolution domain encompasses the Indian subcontinent, while the 10 km domain is centered on northwestern India (Fig. 1a). A 5-minute topographic dataset was interpolated to the 30 km and 10 km domain grids (Fig. 1b). The soil type and land cover datasets were obtained from the USGS (Figs. 2a–b).
2.2 Experimental design

The NCEP global analysis data at 1° × 1° resolution was used to initialize the model and to create the boundary conditions every 6 hours for the coarse domain. The first guess fields are enhanced by blending the rawinsonde and surface observational data. In this study, the simulation of the monsoon active phase took place from 11 to 14 June 2001 (ONSET), while the monsoon break phase simulation was selected from 20 to 25 June 2001 (BREAK). Our focus on the 2001 monsoon, and the month of June in particular, stems from our previous work and in particular access to MOHPREX data (Monsoon Himalaya Precipitation Experiment, Barros and Lang 2003). Figures 2c–d illustrate the initial soil moisture conditions in the top 10 cm soil layer for the ONSET and BREAK runs, respectively. The purpose of these simulations is to examine the effect of soil moisture conditions on land-atmosphere interactions, especially with regard to convective activity in northwest India. Note that the ONSET simulation will be treated as a representative case of monsoon meteorology during an active phase. A detailed discussion of the 2001 monsoon season can be found in Barros and Lang (2003). In addition to these two simulations, two other simulations were conducted for alternative land cover and soil type distributions. In the first sensitivity experiment (EXP1), the barren land cover in the Thar Desert was replaced by shrubs. The second sensitivity experiment was conducted by replacing all barren land with shrubs, and using sandy loam as the sole soil type in the region of study (EXP2). The ONSET and EXP1 cases were integrated for 72 hours. The BREAK case is integrated for 120 hours, while the EXP2 is integrated from 11 to 25 June 2001 (i.e., 2 weeks). As a means of validating these simulations, we rely on concurrent hydrometeorological ground-based and satellite observations. Analysis of thermodynamic and dynamic fields will be performed to elucidate the role of land atmosphere interactions in controlling the persistence of the different phases of the monsoon, and whether and how the Thar Desert in northwest India provides a barrier to the westward propagation of convective activity.

3. Results of numerical experiments

3.1 Control simulations

a. Monsoon onset (11–14 June 2001)

The onset of the summer monsoon is characterized by the development of the Somali jet...
over the Arabian Sea and the rapid increase in precipitation over the Indian subcontinent. The 500 hPa isotachs and vertical motion at 1200 UTC on 12 June 2001 indicate that the monsoon depression is well developed, with strong upward motion in the western periphery of the monsoon depression over the Bay of Bengal (Fig. 3a). The surface low-pressure center is about 996 hPa before landfall (not shown). The 850 hPa height field at 0600 UTC 12 June indicates that the monsoon depression was embedded in the monsoon trough (not shown), and steered by the flow near the southern periphery of the high pressure system over the Tibetan Plateau. It is generally accepted that an upper troposphere anticyclone develops associated with the strong surface heating of the Tibetan Plateau (Krishnamurti and Kishtawal 2000; Murakami 1987). Six hours later, the 850 hPa height and wind analysis indicate that the monsoon depression is steered westward by the Tibetan anticyclone, with landfall on the northeast coast of the Indian subcontinent (Fig. 3b). Subsequently, the monsoon depression moved northwestward, and it did not reach the central Himalayas. The low pressure center gradually strengthened as it moved inland after 1200 UTC 12 June 2001 (not shown). Regional Metosat-5 infrared (IR) imagery of the Indian subcontinent illustrates the westward propagation of clouds associated with the monsoon depression away from the Bay of Bengal (Figs. 4a–b). The convective activity is weaker to non-existent on the west side of the Aravalli

Fig. 2. (a) Soil type and (b) land cover in the 10 km resolution domain; (c) and (d) are the initial conditions of 10 cm soil moisture from the 10 km resolution domain for active (ONSET) and break (BREAK) phase simulations, respectively.
range, and some convective clouds can be found along the upsslopes of central Himalayas in the late afternoon.

The simulated vertical motion and winds at 500 hPa, and 850 hPa from the 30 km resolution domain on 1200 UTC (18 LST) 12 June are shown in Figs. 5a and 5b, respectively. The results show that the center of the monsoon depression extends up to 500 hPa (Fig. 5a). The center made landfall during that time as shown in the 850 hPa simulated results (Fig. 5b). As the monsoon depression moved further inland, a broad area of upward motion is over the Indian subcontinent consistent with the NCEP reanalysis shown in Figs. 3a and 3b. Furthermore, the Somali jet is partially blocked by the Western Ghats, despite the average terrain height being only about 1000 m. Similar past observational and numerical studies (e.g., Grossman and Durran 1984; Wu et al. 1999) also indicated that the blocking effect could induce deep convection offshore, a feature that is captured in our simulations. Another relevant feature is the region of strong upward
motion along the upslopes of the central Himalayas, which reproduces well-documented features in the literature (Barros and Lang 2003; Lang and Barros 2004; Barros et al. 2006). Finally, the simulated convective activity during the monsoon onset is consistent with the spatial patterns of intense rainfall from the TRMM precipitation radar (PR) observations (see Barros and Lang 2003).

To explore the distribution of deep and shallow clouds, we analyzed the model cloud fractions from 0000 UTC to 1800 UTC 12 June 2001 at 6 hr intervals (Figs. 6a–d). Note that significant convective activity (i.e., deep clouds) occurs on the east side of the Aravalli range at locations consistent with the IR imagery (Figs. 4a–b). Lower level clouds (cloud fraction < 1.0) form in the late afternoon over northwest India (i.e., over the west side of the Aravalli) because of thermally induced shallow convection in this area. The simulated 6-hr accumulated precipitation fields from 0000 UTC to 1800 UTC 12 June 2001 are shown in Figs. 7a–d. From 0000 UTC to 0600 UTC 12 June (Figs. 7a–b), most of rainfall is concentrated on both east and west coasts of the Indian subcontinent associated with the monsoon depression in the east and blocking effects along the Western Ghats in the west (cf. Fig. 5). Light rain (~5 mm/6 hr) occurs in the central part of India, and none is simulated in the upper northwest quadrant. During the following 12 hrs (Figs. 7c–d), the simulated rainfall accumulation decreases along both coasts, and light rain appears in the southern portion of the northwest region, especially on the west side of the Aravalli range in the late afternoon (see Section 3.2). The results suggest the light afternoon rainfall appears linked to increasing low level moisture due to surface latent heating fluxes (evapotranspiration) during the early afternoon and added lifting caused by low level convergence of southeasterly moist air. In other words, the spatial maximum in warm advection can produce upward motion. The role of land-atmosphere interactions as a trigger and catalyst of rainfall processes will be discussed further in Section 3.2, in the context of the sensitivity experiments. Dynamically, a boundary established along the Aravalli range separates dry (west) and wet (east) regions. This boundary behaves like a dryline, but with a broad area of influence and shifts spatially between 72°E and 78°E during daytime.

Cross-sections of equivalent potential temperature \( \theta_e \) and vertical motion fields at 10 km resolution (i.e., \( AA' \), from 26.5°N, 70°E to 26.5°N, 78°E, Fig. 1) are shown in Figs. 8a–b. At 1200 UTC 11 June (Fig. 8a; 1800 LST 11 June), a capping inversion in association with an unstable layer (i.e., \( \partial \theta_e / \partial z < 0 \)) is located around 3 km above the surface on the east side of the Aravalli range. Strong low-level flows were simulated during this time (Fig. 8a), leading to the establishment of a convergence zone west of the Aravalli range consistent with the
location of the light rainfall in Fig. 7c. A noteworthy feature is that a rotor developed in the west as shown in Fig. 8a. This rotor is in part due to the daytime heating from the Thar Desert. The strength of low-level flows as well as upward motion weakened gradually in the subsequent 6-hour period and at nighttime (Figs. 8b and 8c). The depth of the daytime inversion layer (~4 km) is related to the spatial distribution of Bowen ratios, in that deeper convective boundary layers are associated with larger daytime Bowen ratios as previously discussed.
Sun and Ogura (1979), Segal and Arritt (1992), and Ziegler et al. (1995). At the end of the morning in the following day, by 0600 UTC (1200 LST) 12 June, the strength of low-level flows increases again, and the inversion layer was about 4 km above the surface (Fig. 8d). In the near surface layer, southeasterly moist air with relatively high $\theta_e$ moves in and environmental conditions prone to vigorous convective activity in northwest India develop as indicated by upward motion at this time (Fig. 8d). However, cells with strong upward motion develop at higher altitudes in the troposphere above the Thar Desert (between 200 and 400 km in
the distance axis of AA'), whereas they develop much closer to the surface westward of the 200 km line on the distance axis for cross-section AA on the west side, and eastward of the Aravalli range on the other side. This behavior is consistent with the leeside ('rain-shadow') location of the Thar Desert with respect to easterly winds impinging on the Aravalli range. The spatial organization of light rainfall around the southern tip of the Aravalli is associated with low level convergence of moist air from the Arabian Sea and locally enhanced convection via land-atmosphere interactions, whereas heavier rainfall associated with strong convection and easterly moisture advection is kept at the edge of the dryline region consistent with observations of cloud top temperatures estimated from IR (infrared) imagery and lightning activity (see Fig. 4 in Barros et al. 2004).

The latent and sensible heat fluxes in northwest India exhibit a pronounced diurnal cycle. The diurnal cycle of the surface sensible and latent heat fluxes between 0300 UTC (0900 LST) and 0900 UTC (1500 LST) 12 June 2001 at 3 hr intervals is shown in Figs. 9a–f. Overall, the
Fig. 9. Surface sensible heat fluxes (a), (c), and (e) and latent heat fluxes (b), (d) and (f) from 0300 UTC (0900 LST) to 0900 UTC (1500 LST) on 12 June 2001 with 3 hr intervals. [ONSET simulation].
sensible heat fluxes increase during the day, whereas the latent heat exchange is nearly shut down due to surface dryness (low soil moisture and low evapotranspiration) in the desert (cf. Fig. 7). The spatial variability of the surface energy budget on model grid cells across the Indian subcontinent indicates two physical controls on the relative contribution of latent and sensible heat fluxes: (1) the antecedent rainfall regime, and (2) the role of vegetation in determining the evolution of the boundary layer via evapotranspiration to the east. Furthermore, these results suggest that the amplitude of the diurnal cycle of surface energy fluxes is also linked to land surface characteristics (i.e., soil type and land cover) as demonstrated by the spatial distributions of surface sensible and latent heat fluxes in this region, including the alignment and confinement of convective activity at the edge of dry and wet regimes (compare patterns in Figs. 9a–f and Figs. 4a–b).

b. Monsoon break phase (20–25 June 2001)

Based on a series of satellite images in the monsoon season, we identify a short period of time in the early monsoon season when convective activity is much weaker than during the onset period (e.g. Barros and Lang 2003). The Bay of Bengal outgoing longwave radiation (OLR) Monsoon Break Index indicates a monsoon break in June 2001 at this time (see Vecchi and Harrison 2002). The 500 hPa wind field and upward motion at 1200 UTC (1800 LST) 21 June 2001 show that an anti-cyclonic circulation originating in the Middle East penetrates into the Indian subcontinent (Fig. 10a). The large-scale upward motion is relatively weak in comparison with the active phase (compare with Fig. 3). The 850 hPa height and wind fields show prevalent flow from west and northwest (Fig. 10b) concurrent with the weakening of the regional circulation east of the Aravalli range, thus allowing ventilation of the central portion of the Madhya Pradesh through penetration of westerly flow. Moreover, a near surface shallow cyclonic circulation is present in the central Himalayas at the same time, which is consistent with the observed analysis of TRMM PR reflectivity (not shown). MeteoSat-5 IR imagery in 21 June 2001 is shown in Figs. 11a–b. These IR images display convective clouds located in the southeast portion of the continent, extending from the Bay of Bengal to the central Himalayas from the early morning (Fig. 11a) to the late evening (Fig. 11b). The evolution of these cloud patterns suggests that large-scale ascent occurs predominately in the southeast, whereas convective activity in the
northwest is confined against the slopes of the Hindu Kush Mountains.

The initial soil moisture conditions for the monsoon break simulation are wetter than those for the onset simulation (Fig. 2d), because monsoon activity brought moisture northward during the preceding active phase. The simulated 500 hPa and 850 hPa wind fields and vertical motion at 1200 UTC (1800 LST) 21 June 2001 at 30 km resolution are shown in Figs. 12a and 12b, respectively. Significant upward motion against the Hindu Kush Mountains implies vigorous convective activity in this region. The shallow cyclonic circulation in central Nepal is forced by orographic blocking effects similar to those that lead to local enhancement of monsoon depressions (Barros et al. 2006). The simulated cloudiness fields on 21 June 2001 are shown in Figs. 13a–d expressed in terms of cloud fraction at 6 hr intervals. Deep convection remains well to the east of the Aravalli range and along the east coast. A broad area of low cloud fraction (clear or quasi-clear skies) spreads over the remainder of the Indian subcontinent. The simulated results are consistent with the NCEP reanalysis (Fig. 10) as well as the IR imagery (Fig. 11).

The simulated 6-hr accumulated precipitation fields at 0000 UTC (0600 LST) 21 June show a spiral rainband collocated with the shallow vortex near the central Himalaya (Fig. 14a) and precipitation maxima against the foot-
hills consistent with observations of a nocturnal maximum in the region (see Barros et al. 2004). From 0600 LST to 1200 LST 21 June (Fig. 14b), the rainfall distribution was similar to the previous 6-hr period with most precipitation concentrated in the southwest portion of the subcontinent. Light rainfall was simulated over the northwest and southeast slopes of the Aravalli range. During the following 12 hours, as shown in Figs. 14c–d, light rainfall spread to the central part of the Indian subcontinent. Overall, during the monsoon break phase, the
simulation results show light rainfall (~5 mm/6 hr) ubiquitously distributed in a pattern that follows closely local terrain features (see inset in Fig. 1b), while the remainder of the Indian subcontinent receives considerably less precipitation compared to the onset phase. Again, this is in agreement with the hypothesis that the light rainfall in the northwest results from orographic forcing, and shallow convective activity organized by orography and antecedent soil wetness (higher soil moisture conditions at the end of the prior active phase of the monsoon).
The temporal evolution of the isentropes and the distribution of updrafts around the stationary dryline during the day is shown in Fig. 15 (i.e., AA'; see Fig. 1). Note the dramatic switch in low level flow direction as compared with the onset conditions (Figs. 8a–d). The data show a strong near surface horizontal flow from west to east at 1800 LST 20 June (Fig. 15a) that comes to a halt on the eastern slopes of the Aravalli range to form a strong cell of upward motion (now on the leewind side with respect to incoming westerly flow). The convective boundary layer is relatively shallow with a capping inversion layer around 3 km. Another strong convective cell can be found to the west of the Aravalli range. Subsequently, during the next 6 hours, the convective boundary layer tilts and becomes increasingly slanted from west to east (i.e., 0000 LST 21 June, Fig. 15b) due to spatial differences in low level moisture consistent with the distribution of soil types in northwest India (see Fig. 2). Specifically, greater evaporative cooling near the surface east of the Aravalli range where soil wetness is high trans-
lates into higher (lower) surface latent (sensible) heat fluxes. The near surface winds slow down during the night and the tilting of the inversion layer vanishes by 0600 LST 21 June (Fig. 15c). In response to solar heating, the surface boundary flow strengthens during the daytime due to the presence of a potential (convective) unstable layer \((\frac{\partial \theta}{\partial z} < 0)\) at the outset of the diurnal cycle (Fig. 15d). The formation of a capping inversion is in part due to a cool, elevated mixing layer (e.g., 500 hPa) moving over warmer surface air at lower levels (e.g., 850 hPa). Note that few and weak low-level updrafts between 400 and 600 km on the distance axis of the AA’ cross-section in Fig. 15, a zone that coincides with the leeside of the Aravalli range during the break phase.

This simulation further provides evidence that deep convective activity always occurs against the eastern foothills of Aravalli range (i.e., the quasi-stationary dryline) consistent with the area of most lightning activity and colder cloud tops (e.g., Barros et al. 2004). Overall, the coupled model simulation results are in agreement with observations, and the results from the break phase simulation suggest orographic (upwind versus leewind orientation) and near surface wetness increased after monsoon onset (soil moisture and evapotranspiration) on the spatial organization of regional rainfall during the break phase of the monsoon.

3.2 Sensitivity analysis

The first sensitivity experiment (EXP1) was conducted using the same initial conditions as the active phase (i.e., monsoon onset), but the land cover over the Thar Desert region (i.e., bare soil) was replaced by shrubs. EXP1 results are not presented here because the results are very similar to the ONSET case with a small increase in rainfall amounts (5–10 mm) but no change in rainfall patterns (figure not shown). Nevertheless, the results are important in that they demonstrate that changes in surface energy budget and land-atmosphere interactions at short time-scales do not modify the dominant weather regime during the active phase. The implication of this result is that weather is controlled by synoptic scale disturbances and large-scale monsoon dynamics at this time, whereas land-atmosphere interactions play a lesser, though not negligible role. The second sensitivity experiment (EXP2) was carried out for two successive (back-to-back) phases of the monsoon (i.e., 11 to 25 June 2001). The land cover and soil type were changed over a large area that includes the Thar Desert and extends to the foothills of the Himalayas in northwest India. Figures 16a–b show the new soil type and land cover in northwest India, respectively. The soil type was replaced by sandy loam (Fig. 16a), and land cover was replaced by shrub/grassland (Fig. 16b). The hypothesis is that evapotranspiration could be enhanced as a result of the change of the soil and land cover distributions. The EXP2 simulation is a long-duration experiment (i.e., 2 weeks) that encompasses active and break phases, and thus the results can be compared against both the ONSET and BREAK control cases. The results
from EXP2 show widespread occurrence of light rain (~5 mm/6 hr) in the upper northwest quadrant during the afternoon (not shown). Although the precipitation is higher over northwest India during the night, the 6-hourly accumulated rainfall fields from the EXP2 case indicate that rainfall in northwest India is consistent with the ONSET control case study in particular.

In order to document the evolving vertical structure of simulated convective activity and \( \theta e \) over northwestern India in the EXP2 case, Fig. 17 shows the cross section (AA', Fig. 1a) from west (70°E, 26.5°N) to east (78°E, 26.5°N). Convective activity in northwest India at 1800 LST 11 June (Fig. 17a) is explained by the low-level convergence of easterly and westerly flows. The gradient of \( \theta e \) indicates that a warmer air mass penetrated from west at lower levels, while the depth of the convective boundary layer was around 3 km at this time. The easterly flow weakened at nighttime (Fig. 17b), whereas the warm westerly flow and increased surface sensible heat fluxes provide localized lifting to the capped inversion boundary layer as suggested by the potential temperature (\( \theta e \))
gradients. By 0600 LST 12 June (Fig. 17c), convective activity increases significantly on both sides of the dryline region. This can be explained by vertical differential advection which causes the moist convective boundary layer air to flow out from beneath the lid, leading to rapid destabilization and development of convection (Schaefer 1986). Dry convection prevails on the west side of the Aravalli range because of low (high) surface latent (sensible) heat fluxes and dry soils (low upper soil moisture levels, not shown). The capping inversion is lower (~3 km) in the afternoon (Fig. 17d), and elevated convection is mainly realized by the release of potential instability through the capping inversion. A substantial difference between these results and the onset control results is patent in the strength and intensity of daytime low level winds and subsidence over the Thar Desert (200–400 km in the distance axis of AA’).

A comparison of the time evolution of the surface sensible and latent heat fluxes, ground temperature, and top soil moisture (upper 10 cm) for the ONSET and EXP2 simulations is shown in Fig. 18 at a randomly selected point in the Thar Desert (73°E, 25°N). The amplitude of the diurnal cycle of surface sensible heat flux in the EXP2 is slightly lower than in the ONSET case (Fig. 18a). This result suggests that
the dominant control of land-atmosphere interactions, and the surface energy budget in particular, is exercised by vegetation (land cover) (Fig. 18b). Because latent heat fluxes are always small in northwest India (e.g., Fig. 9), a small change toward higher daytime latent heat fluxes by increasing the vegetated surface area in EXP2 can enable the simulated changes in convective activity (Fig. 17). Although the ground temperature does not vary significantly (Fig. 18c), the top 10 cm soil moisture storage in the EXP2 drops rapidly as shown in Fig. 18d concurrent with the increase of latent heat flux.

Another interesting way to explore the results of EXP2 is to assess the spatial patterns of convective available potential energy (CAPE) during the active and break phases of the monsoon. Figure 19 shows the evolution of CAPE from 1800 LST 12 June and 0000 LST 13 June during the monsoon onset period. The areas with highest simulated CAPE (~600 to 800 J kg\(^{-1}\)) are in the Indian Subcontinent as well as on the foothills of the Himalayas in the late afternoon of 12 June (Fig. 19a) as the monsoon trough and monsoon depression are moving in the northwest direction (cf. Fig. 5). By 0000 LST 13 June (Fig. 19b), the CAPE distribution has not changed significantly. Very low CAPE was simulated in northwest India around the Thar Desert during the active phase as expected (see Fig. 7). This contrasts with CAPE simulated during the monsoon break (>1200 J kg\(^{-1}\)) that extends westward of the Indian subcontinent as shown at 1200 LST (Fig. 20a) and 1800 LST (Fig. 20b) on June 20. During the remainder of the break phase, the diurnal amplitude of CAPE continues to decrease with the march of the monsoon break phase as the landscape dries, reflecting negative feedbacks of land-atmosphere interactions on rainfall as discussed earlier.

In general, the diurnal cycle of convective activity and \(\theta_e\) as well as surface sensible and latent heat fluxes for ONSET and EXP2 are similar. The experimental changes of land cover and soil type impact the diurnal cycle of rainfall via surface heat fluxes and affect late-afternoon convection in the east, but have small impact west of the Aravalli range and do not affect the hydrometeorological dryline, or the temporal succession of the active and break phases of the monsoon. Their role is better described as one of providing sufficient additional potential instability to the local PBL (planetary boundary layer) to trigger shallow convection and fuel light rainfall processes.

4. Conclusion and remarks

This paper describes a series of control simulations and idealized experiments to investigate the physical mechanisms underpinning the hydrometeorological dryline in Northwest India. This includes orographic forcing along the Aravalli range, as well as the participation
of land-atmosphere interactions in the meso-scale rainfall regime. This study expands upon Barros et al. (2004) and Webster et al. (1998) on the role of land-atmosphere interactions on the thermodynamic evolution of the atmosphere in northwest India during the active and break phases of the monsoon. The dryline is the region at the interface of dry (west) and rainy (east) weather regimes along the Aravalli range. The strength and eastward penetration of westerly flow at 850 hPa and northwesterly flow at 500 hPa control the temporal succession of dry and wet hydrometeorological regimes. Despite very different physiographic and climatic settings, the role of vertical mixing processes is similar in the case of the Central Plains and the NW India drylines. In the case of the latter, the strong gradient of soil moisture in the Thar Desert controls the near-surface moisture supply, whereas the Aravalli provides orographic forcing (upwind and downwind flows) to explain the spatial oscillations between the active and break phases of the monsoon. Heavy precipitation and convective activity remain to the eastside of the dryline in good agreement with observations (Barros and Lang 2003; Barros et al. 2004). The break phase simulation provides another scenario that shows the variation of boundary layer processes in terms of surface wetness. The initialization of soil moisture in northwest India reveals that it is much drier before the monsoon onset, whereas after the monsoon onset the soil moisture increased regionally which had a significant impact on low-level moisture conditions. The break phase simulation results show that rainfall is able to reach the west side of the stationary dryline because high sensible heat flux and high \( \theta_e \) air in northwest India along with orographic forcing provide the lifting mechanism necessary to raise air parcels past their level of free convection.

The sensitivity test (EXP2) to changes in soil type and land cover (greening the Thar Desert) illustrates the subtle and yet definitive role of land atmosphere interactions in the hydrometeorology of the northwest quarter of the Indian subcontinent. The accumulated rainfall differences (EXP2—ONSET) indicate that precipitation increases by 5–10 mm during the monsoon onset in EXP2 (not shown). The cross sections of vertical motion and \( \theta_e \) show increased complexity (increased number of convective cells) in the lower troposphere after the change of soil type and land cover, especially in the late afternoon consistent with higher evapotranspiration in EXP2 than ONSET. Thus, this suggests that some degree of surface greening (wetting) of the arid regions in Northwest India should lead to a decrease of sub-seasonal variability of the monsoon with more uniformity in the temporal distribution of rainfall. Although one would not expect substantially different results from EXP2 because the same lateral (forcing) boundary conditions are used, this...
simulation indicates that land atmosphere interactions in northwest India can affect the regional precipitation regime overall, and especially the ratio of light to heavy rainfall which in turn can impact the diurnal cycle of water and energy budgets.

These numerical experiments further confirm a conceptual model of land-atmosphere interactions that reinforce large-scale dynamical controls of the monsoon onset and break phases (Barros et al. 2004). The premise is that the hydrometeorological dryline in northwest India along the Aravalli range results from the interaction between large-scale conditions and local controls of near-surface moisture (surface fluxes) and vertical updrafts (orography). Following the same notation, Figs. 21a–b illustrate schematically how the dryline separates western, drier, and stable air masses from moist and relatively unstable air masses from the Bay of Bengal. During the active phases of the monsoon, southeasterly depressions from the Bay of Bengal (BoB) propagate over northern India, maintaining sustained convergence.

Fig. 21. Conceptual depiction of land-atmosphere feedbacks in the northern half of the Indian subcontinent during the active and break phases of the monsoon monsoon ($h_M$—moist energy flux; $P$—precipitation; SM—soil moisture; ET—evapotranspiration; CAPE—convective available potential energy; WIO—Western Indian Ocean; BoB—Bay of Bengal). [After Barros et al. 2004].
of moist available energy east of the Aravalli range. Drier air originating from the Arabian Sea in the Western Indian Ocean (WIO) is constrained to the west. Accordingly, the active phase of the monsoon would be maintained via a positive feedback mechanism of land-atmosphere interactions. Increased rainfall in the east leads to an increase in soil moisture storage, increase in surface latent heating due to higher evapotranspiration, increase in convective available potential energy (CAPE), leading to intensification of convective activity and increased rainfall over the region. Cooling periods in the Bay of Bengal (BoB) result in the decrease of moisture convergence over the continent, weakening the regional circulation east of the Aravalli range, thus allowing ventilation of the central portion of the Madhya Pradesh through penetration of westerly dry air and decrease of available soil moisture. Therefore, the break phase of the monsoon would be maintained by a negative feedback mechanism of land atmosphere interactions. Subsequently, increased ventilation by dry westerly flow leads to a decrease of soil moisture that is not replenished, a decrease in evapotranspiration and surface latent heating, lower CAPE, weakening of convective activity and less rainfall. Orographic forcing along the Aravalli provides enough additional upwind lift and downwind subsidence to induce drying of the lower troposphere during the active phase thus suppressing low level instability on the west (downwind) slopes, and to strengthen the ventilation effect over northern India by carrying the dryline across the topographic divide to the eastern slopes during the break phase. In short, the dryline is always on the leewind side of the Aravalli with respect to the dominant low level regional winds.

The significance of these findings can be viewed from three different perspectives. First, the results support the role of evapotranspiration as one key mechanism governing the grid-scale regime of land-atmosphere interactions. Second, the results provide support to the argument concerning the influence of land-surface heterogeneity on the dynamic range of land-atmosphere interactions, and thus the location of the rainfall attractor proposed by Barros and Hwu (2002). From the comparison of the ONSET and BREAK runs, we conclude that soils, and vegetation especially, reinforce the thermodynamic conditions that maintain the dryline spatially quasi-stationary on the slopes of the Aravalli range throughout the course of the monsoon, an effect that cannot be neglected even during the active phase of the monsoon when large-scale conditions are overwhelmingly favorable for moist processes. It is worthy of note that the incoming solar radiation is nearly the same in this case. Nevertheless, the phase plane of moisture-energy interactions (i.e., Bowen ratio) indicates that the surface heat fluxes depend on the initial condition of soil moisture and temperature. The analysis of Bowen ratio indicates that land-atmosphere interactions play an important role in association with dry and wet regimes in northwest India (not shown). Finally, although the Aravalli range is a small terrain feature, it provides orographic forcing to sustain the dryline phenomenon by controlling the spatial organization of downslope and upslope flow fields and moisture in the lower troposphere. The sensitivity of the light precipitation regime to the spatial distribution of soils and vegetation needs careful consideration, because uncertainty in the specification of current soil type and land cover in regional models in tropical monsoon regions can translate into regimes of land-atmosphere interactions at odds with realistic conditions, which will in turn affect precipitation processes and eventually climate at the seasonal timescale.

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