Pure Appl. Geophys. 172 (2015), 2791–2811
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DOI 10.1007/s00024-014-0905-9

Pure and Applied Geophysics

A Study on the Influence of the Land Surface Processes on the Southwest Monsoon Simulations using a Regional Climate Model

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Abstract—Influence of the land surface processes as an important mechanism in the development of the Indian Summer Monsoon is studied by performing simulations with a regional atmospheric model. Seasonal scale simulations are conducted for two contrasting summer monsoons (MJJAS months) in 2008 & 2009 with the Weather Research and Forecasting-Advanced Research regional model at a high resolution of 15 km using the boundary conditions derived from the National Centers for Environmental Prediction (NCEP) reanalysis data and using the NOAH land surface parameterization scheme. Simulations are evaluated by comparison of precipitation with 0.5° India Meteorological Department gridded rainfall data over land, atmospheric circulation fields with 1° resolution NCEP global final analysis, and surface fluxes with 0.75° resolution Era-Interim reanalysis. Results indicated significant variation in the evolution of the surface fluxes, air temperatures and flux convergence in the 2 contrasting years. A lower albedo, higher heating (sensible, latent heat fluxes), higher air temperatures, stronger flow and higher moisture flux convergence are noted over the subcontinent during the monsoon 2008 relative to the monsoon 2009. The simulated surface fluxes are in good comparison with observations. The stronger flow in 2008 is found to be associated with stronger heat flux gradients as well as stronger north-south geopotential/pressure gradients. The simulations revealed notable differences in many features such as zonal and meridional surface sensible heat gradients which, in turn, influenced the low-level pressure gradients, wind flow, and moisture transport. The present study reveals that, even at a regional scale, the physical processes of land-surface energy partitioning do influence the regional behavior of the monsoon system to a certain extent.

Key words: Indian Summer Monsoon, land surface processes, WRF-ARW.

1. *Introduction*

The Indian Summer Monsoon (ISM) (also called the southwest monsoon) is a part of the global scale atmospheric circulation that prevails during June to September over the Indian subcontinent and neighboring regions of South Asia. It forms the principal rainy season over the Indian subcontinent, and studies concerning the understanding and prediction of ISM rainfall on different spatial and temporal scales assumed importance due to the societal impacts associated with agrarian economy\ies such as of India. The ISM results from differential thermal contrast of the Asiatic land mass and North Indian Ocean and the remarkable meridional shift of the Intertropical Convergence Zone (ITCZ) during the northern summer (Goswami *et al.*, 2012). Differential heating of the land and the ocean, latent heat release into the atmosphere, and planetary rotation are considered to be the factors that determine the strength, duration, and spatial distribution of large-scale monsoons (Webster *et al.*, 1998). Studies using atmospheric General Circulation Models (GCM) have shown that land surface features, such as land surface temperature, soil moisture, sea surface temperature, vegetation, and ice and snow cover influence the surface energy and moisture transports on different scales (global, regional, and mesoscales) and play an important role in the global and regional circulation and climate (Jiang *et al.*, 2011; Sellers *et al.*, 1986; Dickinson *et al.*, 1986; Noilhan and Planton, 1989; Henderson-Sellers, 1993; Xue *et al.*, 2006; Li and Xue, 2007, 2010; Ueda *et al.*, 2009). About 70 % of annual rainfall over India is received during the ISM season i.e., from the June to

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September (JJAS) months. Among a number of global and regional factors, land surface characteristics have been suggested as an important factor in the modulation of the monsoon circulation and its associated rainfall variations (Webster, 1987; Lee *et al.*, 2011). Although the role of the land surface processes in the development of the monsoon systems and their regional variation is not clearly understood, it is known that some of the crucial surface parameters that influence the regional features are the Eurasian snow cover, soil moisture, land surface evaporation, land surface temperature, and surface fluxes of sensible and latent heat. For example, observational studies on the relation between winter Eurasian snow cover and the subsequent ISM (e.g., Hahn and Shukla, 1976; Dey and Bhanu Kumar, 1982; Liu and Yanai, 2002), indicated a negative correlation. Datta *et al.* (2009) studied the impact of regional-scale land surface processes related to vegetation cover on the Indian summer monsoon precipitation system and reported that changes in land cover alter the evolution of the surface fluxes, which in turn affect the monsoon system.

Lau and Bua (1998) studied the relative roles of land surface evaporation and sea surface temperature (SST) on the Asian monsoon. They reported that the land-atmosphere interactions contribute to variations in regional circulation and subseasonal scale precipitation variations between land and ocean regions. Meehl *et al.* (1994) reported that stronger Asian summer monsoons were associated with lower surface albedo, higher soil moisture, lesser snow cover, and larger land-sea temperature contrast. A few simulation studies with GCMs (e.g., Xue, 1996) indicated that changes in land cover such as from grassland to desert produced negative monsoon rainfall anomalies in northern and southern China and positive rainfall anomalies along the Changjiang (Yangtze) river region consistent with observed anomalies. It has been shown that land degradation causes reduction in evaporation, reduced convection, lowered atmospheric heating rates, and weaker upward vertical motion that leads to weakened northward movement of the monsoon flow and lowered rainfall and evaporation. All of this leads to a positive feedback system. The ISM is a coupled ocean-land-atmosphere phenomenon and is a highly complex system being dependent on many global, regional, and local parameters (Ueda *et al.*, 2006; Bollasina and Ming, 2012). A pertinent question is that what would be the impact of organized land surface fluxes and horizontal flux gradients from the land mass on the regional monsoon convective systems and rainfall.

Just before the onset of the summer monsoon, low-level northwesterlies prevail over India and the belt of precipitation remains confined along the equatorial Indian Ocean (Bollasina and Ming, 2012). A northward shift and enhancement of convection and a simultaneous acceleration of the westerly wind in the latitude belt 0–10°N occur by mid-May. By the end of May, dramatic changes in precipitation and low-level circulation occur heralding the onset of monsoon and establishing of the monsoon over central India by the end of June. With the initiation of the monsoon circulation, large scale evaporation and sea surface temperature (SST) cooling takes place associated with southwesterly/westerly monsoon flow. Air–sea interaction processes in terms of surface heat and moisture fluxes, and SST influence the monsoon (e.g., Yang and Lau, 2006; Ueda *et al.*, 2006). However, it has been shown that the influence of the SST in the establishment of the ISM circulation is secondary to the response of the land-atmosphere system to solar radiation (e.g., Sud *et al.*, 2002; Lestari and Iwasaki, 2006; Jiang and Li, 2011) and land-atmosphere processes are attributed to be important for the monsoon seasonal cycle (e.g., Wu *et al.*, 2002). The land surface properties such as snow-cover, soil moisture, and vegetation cover influence the monsoon by controlling the surface water and energy budgets, which influence the availability of water over the land, its heating, and the atmospheric stability (Yang and Lau, 2006; Yasunari *et al.*, 2006). Yasunari (2007) provided a good review of the role of the land-surface processes in the Asian monsoon system.

Regional climate models with suitable horizontal resolutions have been used for the simulation of the ISM regional rainfall patterns (Bhaskaran *et al.*, 1996; Bhaskar Rao *et al.*, 2004; Mukopadhyay *et al.*, 2010; Hariprasad *et al.*, 2011; Saha *et al.*, 2011; Srinivas *et al.*, 2012) as these models with higher horizontal resolution than global models better represent the effects of regional orography and subgrid scale physical processes. The application of regional models with advanced land surface process parameterizations has been shown to produce improvements of precipitation and other climate parameters at a regional scale (Xue *et al.*, 2001) as they better resolve the transient eddy moisture fluxes, the flow over complex terrain and associated hydrodynamic instabilities (Gao *et al.*, 2012). The objective of this study is to understand the role of the land surface processes on the evolution of ISM. Towards this objective, the Advanced Research WRF (ARW) model with a full-fledged land surface parameterization is used to perform simulations of ISM during two contrasting monsoons (the stronger monsoon of 2008 and the weaker monsoon of 2009). An attempt is made to understand as to what extent the land surface processes correlate with the variation in the large-scale forcing and regional-scale precipitation of the ISM system.

2. Methods

2.1. Numerical Experiments

The Advanced Research Weather Research and Forecasting (ARW) model version 3.2 (Skamarock *et al.*, 2008) developed by NCAR, USA, is adapted as the regional atmospheric model and used in the present study for monsoon simulations. ARW is a primitive equation, being non-hydrostatic, and a terrain following sigma coordinate model with a large number of physical process parameterizations. The monsoon simulations performed in this study were made following the methodology given by Bhaskaran *et al.* (1996) for regional model integrations. According to this procedure, the large scale dynamics are provided by the synoptic scale boundary conditions from either analysis or global model forecasts while the regional monsoon features such as the low pressure trough and convective systems are simulated by the regional model at high resolution. For the present study the ARW model was configured with two two-way interactive nested domains with horizontal resolutions as 45 km and 15 km and 32 vertical levels with the model top at 10 hPa. The high resolution 15 km domain covers the Indian monsoon region as from 49°E–107°E in the west-east direction and 10°S–43°N in the north-south directions (Fig. 1) (Table 1). The three-dimensional atmospheric fields at the initial time and the time varying boundary conditions are derived from the National Centers for Environmental Prediction (NCEP) global reanalysis fields (Kalnay *et al.*, 1996) available at 2.5° latitude/longitude resolution and at 6 hour interval (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). The sea-surface temperature (SST) in the model is also updated at 6 h intervals from the NCEP reanalysis. By this method the influence of the planetary-scale forcing is supplied via the global model analysis so that the time-averaged Walker circulation and its response to tropical Pacific SST anomalies are represented in the regional model (Bhaskaran *et al.*, 1996; WCRP, 1992) whereas the regional Tropical Convergence Zone (TCZ) will be generated internally within the model simulation. The model simulates the features of organized convection over the Indian subcontinent during the monsoon season through the physics and dynamics (surface evaporation and large-scale dynamical convergence in the monsoon trough region). The high resolution domain (15 km) over the monsoon region supposes simulation of the subgrid scale surface physical processes over land/ water areas more realistically and in turn their influence on the regional-scale monsoon features. The model topography, land cover and soil

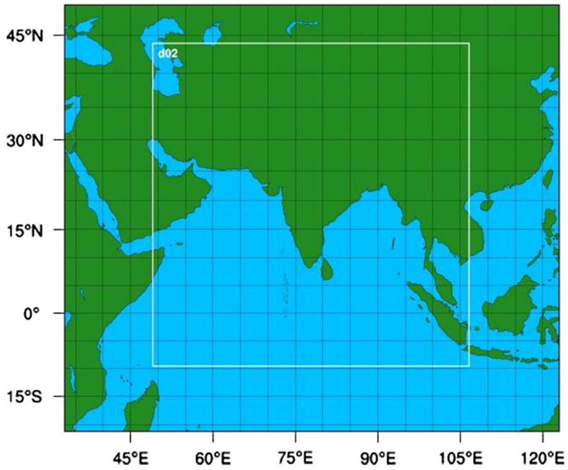

Figure 1
Simulation domains used in ARW model

information are interpolated from USGS and FAO global data sets at arc 5 min (~9 km) and arc 2 min (~4 km) for 45 and 15 km resolution domains, respectively. The dependent parameters derived within the model are albedo, roughness length, thermal inertia, moisture availability, and emissivity for land use and thermal diffusivity, available water capacity, wilting point moisture, etc., for soil category. The vegetation cover over India consisted of mainly croplands, evergreen forests, deciduous forests, grasslands, shrubs and drylands. The model is integrated continuously for five months, starting from 1 May to 30 September for both the years of 2008 and 2009. The selected physics options are the Lin explicit microphysics (Lin *et al.*, 1983), Dudhia scheme (Dudhia, 1989) for shortwave radiation processes, RRTM scheme for longwave radiation processes (Mlawer *et al.*, 1997), the Yonsei University scheme for the PBL turbulence (Noh *et al.*, 2003; Hong *et al.*, 2006), NOAH land surface model (LSM) for land surface physical processes and the Betts-Miller-Janjic (Betts and Miller, 1986; Janjic, 2000) for convection. The NOAH LSM is an improvement to the OSU LSM (Chen and Dudhia, 2001) and treats explicit soil and vegetation effects. It uses the time-dependent soil fields and a 4-layer soil temperature and moisture model with canopy moisture and snow-cover prediction. This scheme estimates the land surface evaporation as direct evaporation from the bare soil surface, transpiration through the leaf stomata and evaporation of precipitation intercepted by the leaf canopy. It solves the time dependent Penman potential evaporation equation in association with the multi-layer soil model and the plant canopy model (Chen and Dudhia, 2001). The soil model solves the thermal diffusivity equation with four soil layers. The energy budget includes radiation, sensible, latent and ground heat fluxes. The NOAH scheme calculates the surface fluxes only over the land surface region using the information provided by surface layer schemes. The NOAH scheme is used in the present study to evaluate the land surface processes as it was reported to produce better simulations of monsoon circulation (Singh *et al.*, 2007). Over the ocean region, the surface fluxes and other diagnostic fields are calculated within the surface layer scheme itself.

The model outputs are retrieved at 6 hourly interval corresponding to 00, 06, 12, 18 UTC for the inner domain with 15-km resolution and are analyzed to derive mean monthly and seasonal (JJA: June, July and August) fields and model diagnostics. The simulated fields of lower (850 hPa) atmospheric winds, with geopotential and divergence at 850 hPa, are compared with the NCEP final analysis (FNL) data at a horizontal resolution of 1°. Simulated surface fluxes (sensible, latent heat) are compared with the corresponding surface fluxes data from the European Center for Medium Range Weather Forecasts (ECMWF) Era-Interim reanalysis (Dee *et al.*, 2011) available at 0.75° resolution. The gridded rainfall data at 0.5 deg resolution over the Indian region available from the India Meteorological Department (IMD) (Rajeevan and Bhate 2008) is used for validation of the model-derived rainfall over the Indian land region.

2.2. *Statistical Methods*

Statistical error metrics proposed by Murphy and Winkler (1987) are used for quantitative comparison of simulated rainfall and surface fluxes (latent heat, sensible heat). The statistical indices include the Pearson correlation coefficient (COR), Mean Bias (MBIAS), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) as given below.

$$\mathrm{COR} = \frac{\sum_{i=1}^{n} (f_i - \bar{f})(o_i - \bar{o})}{\sqrt{\sum_{i=1}^{n} (f_i - \bar{f})^2}\sqrt{\sum_{i=1}^{n} (o_i - \bar{o})^2}}, \qquad (1)$$

$$\mathrm{MBIAS} = \frac{1}{n}\sum_{i=1}^{n} (f_i - o_i) = \bar{f} - \bar{o}, \qquad (2)$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |f_i - o_i|, \qquad (3)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (f_i - o_i)^2}, \qquad (4)$$

where O_i is an observed variable (obtained from analysis), f_i is a forecast variable, overbar represents spatial and temporal average over all the data, and ‘n’ is the sample size. Since the surface fluxes from Era-Interim reanalysis are available at a temporal interval

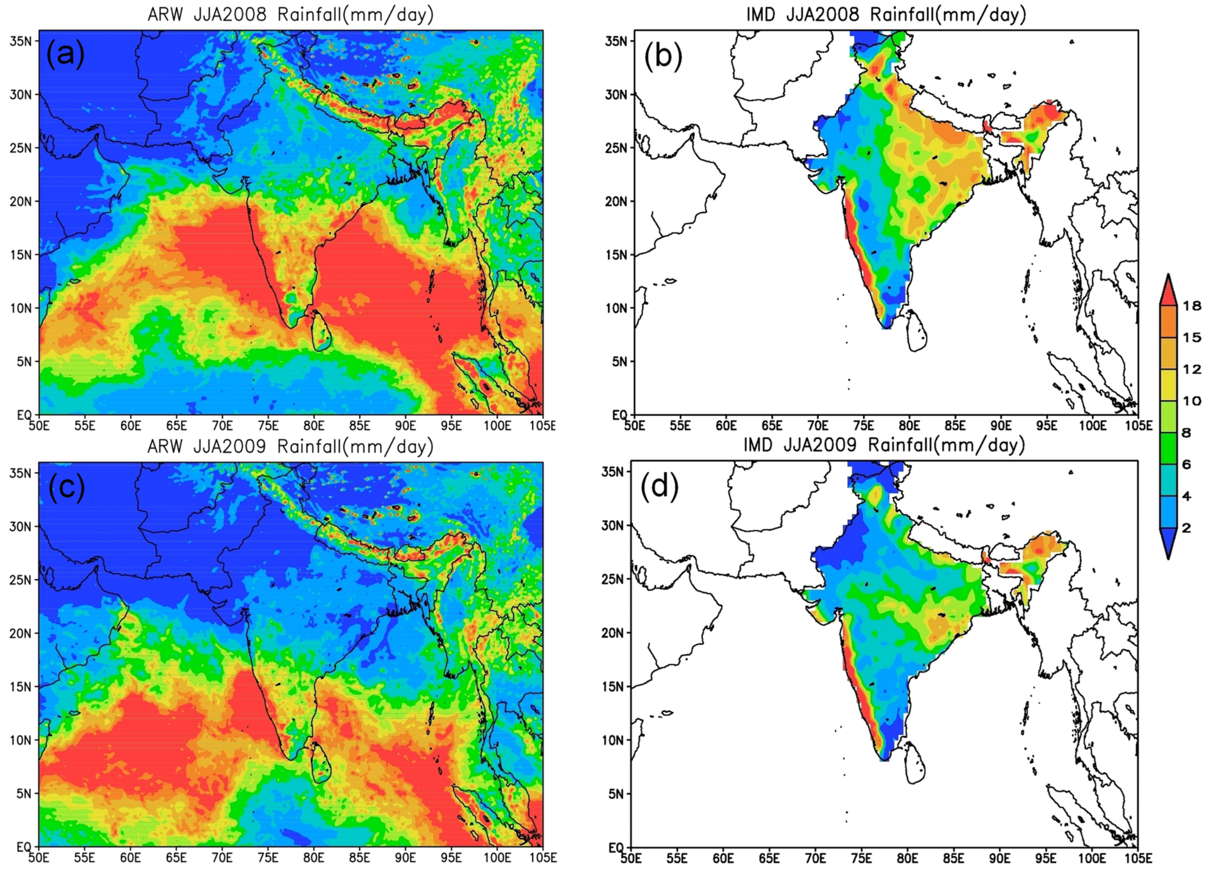

Figure 2
Mean precipitation for June, July, and August months (in mm/day). *Top panels* (**a**, **b**) are for 2008, *bottom panels* (**c**, **d**) are for 2009; *left panels* (**a**, **c**) represent model rainfall and *right panels* (**b**, **d**) represent IMD rainfall

of 12 h (i.e., 00 UTC and 12 UTC), simulated fluxes sampled from model at the same time interval are compared with observations. Simulated rainfall averaged over Indian landmass is compared against the corresponding IMD gridded rainfall data at daily intervals.

3. *Results and Discussion*

3.1. *Spatial and Temporal Rainfall Distribution*

Of the model outputs generated from 1 May to 30 September, forecast fields for the four months of May, June, July, and August are analyzed considering May to represent the pre-monsoon heating, June to represent the onset phase and July–August months to represent the peak of the ISM. Of the two contrasting monsoons selected for the present study, 2008 and 2009 monsoons are noted to be above and below normal (IMD 2009; IMD 2010), respectively.

Spatial distribution of simulated mean JJA precipitation for 2008 and 2009 along with corresponding IMD gridded rainfall data are shown in Fig. 2. The model simulated higher rainfall in humid areas along the west coast, the foot hills of the Himalayas and northeastern states, which are the high rainfall regions, and relatively less rainfall (about 25 %) in the Indo-Gangetic plains and east-central parts, which are known to be core monsoon regions. The monsoon seasonal (June to September) rainfall over India in 2008 was 98 % of its Long Period Average (LPA). Out of 36 subdivisions, Orissa and Punjab received excess rainfall (~+20 %), Kerala, Vidarbha, and West Madhya Pradesh received deficit rainfall (~−20 %) and the rest of the country received normal rainfall (IMD, 2009) . As per the official reports, monsoon onset in 2009 occurred as early as 23 May over southernmost parts, but its advancement was delayed by 1–2 weeks over the central and northern parts of India (IMD, 2010); and the Indian Subcontinent experienced a severe monsoon drought with the rainfall received at 77 % of its long period average (Preethi *et al*., 2011). Regional scale simulation with the ARW model clearly depicts relatively far less (about 40 %) rainfall in 2009 over India as compared to the observed rainfall. The simulated rainfall shows that Orissa and west Bengal regions, where usually monsoon depressions enter from Bay of Bengal into the monsoon trough region, had far less (about 75 %) amount of rainfall and about 60 % of the Indian subcontinent including northwest, northern, southern, eastern, and northeastern parts had received less rainfall in the simulation for 2009 as similar to observations. There was also a corresponding decrease of precipitation over the adjacent oceanic regions from the Bay of Bengal and Arabian streams of monsoon flow in the year 2009. The commencement of monsoon over the Indian subcontinent takes place around 1 June with the west coastal stations in Kerala receiving the first rains. The mean daily rainfall in May from the model and from observations during the 2008 and 2009 years are presented in Fig. 3. According to IMD reports, the onset of monsoon in 2008 was characterized by timely arrival over the south Peninsula and rapid advancement over different parts of the country, especially over Central and Northwest India (IMD, 2009). It arrived over southeast Bay of Bengal, Andaman and Nicobar Islands by the 10th of May, 5 days earlier than the normal time. It reached over Kerala on the 31st of May and covered the entire country on 10 July, 5 days ahead of the normal time.

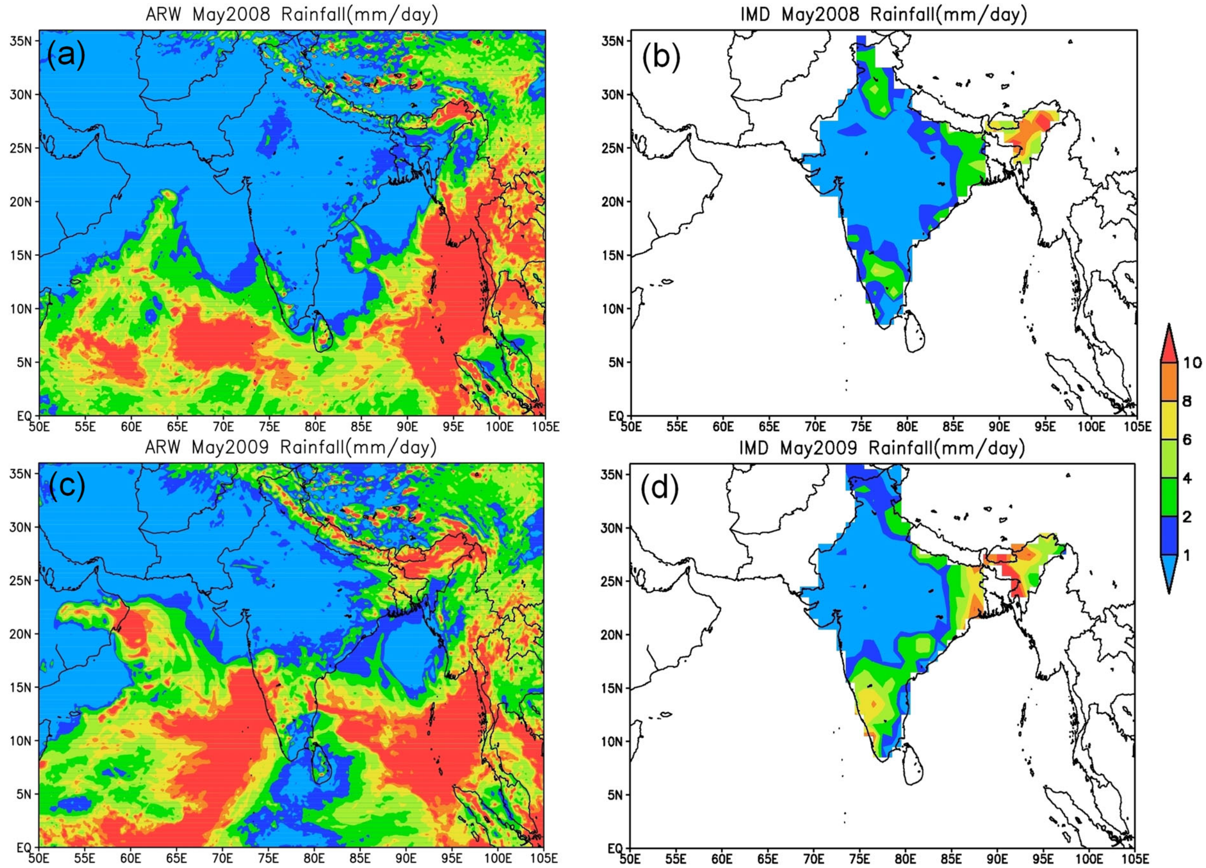

Figure 3
Mean precipitation (mm/day) in May over the simulation domain. *Top panels* (**a**, **b**) are for 2008, *bottom panels* (**c**, **d**) are for 2009; *left panels* (**a**, **c**) represent model rainfall and *right panels* (**b**, **d**) represent IMD rainfall

In 2009, the monsoon onset occurred on the 20th of May over southeast Bay of Bengal and the Andaman Sea, the 23rd of May over Kerala, south Tamilnadu, the 25th of May over coastal Kanataka, the entire Tamilnadu, West Bengal, Sikkim and northeast India and southwest Bay of Bengal, the 1st Jof une over Interior Karnataka, parts of Rayalaseema and south coastal Andhra Pradesh, and the 7th of June over Goa, Konkan. It covered Maharashtra by 26 June, Madhya Pradesh, Orissa, Bihar and parts of Uttar Pradesh by 29 June, and the rest of the country by the 30th of June (IMD, 2010) indicating an early onset of monsoon by at least 10 days over various parts of the country. Simulated rainfall in May 2008 indicated normal onset of monsoon with rainfall (2–4 mm/day) over Kerala, southeast Bay of Bengal, Arabian Sea, parts of north Coastal Andhra Pradesh, Orissa, West Bengal, and northeastern states in agreement with IMD observations. The simulation for 2009 shows early onset of ISM with rainfall (2–4 mm/day) over southern Peninsula that included Kerala, Karnataka, Andhra Pradesh, northern Tamilnadu, Orissa, Bihar, and West Bengal as well as the northeastern states agreeing with IMD observations and confirming early monsoon onset in 2009 relative to 2008. In the year 2008, intense precipitation occurred around 8 June at 12°N, and by 15 June the high precipitation had moved to 22°N and by the 3rd of July it was at 27°N. Similarly in the year 2009, the onset of monsoon was indicated at round 8 June at 12°N, by the 23rd of June at 22°N and by 29 June at 27°N. The temporal evolution of the monsoon for the years 2008 and 2009 is examined from the zonal averaged precipitation in the longitude belt (70–90°E) (Fig. 4) from June through August from both observations and simulation. The observed features of progression and establishment of monsoon are well represented in the simulation. In both the wet and dry contrasting seasons the northward progression of the monsoon rains is well captured by the model except that the simulated rainfall is lesser (about 30 %) than the observations in both years. In the year 2008, higher rainfall is simulated in all the latitude belts than in 2009. The time series from IMD observations shows five dry spells (22–29 June; 2–9 July; 15–25 July; 1–5 Aug; 17–31 Aug) distributed in different zonal belts. Out of these, two significant dry spells in the belt 25–30°N during the periods of 15–25 July, 22–31 Aug, and two dry spells in the belt 7–12°N during the periods of 22–29 June, 1–5 Aug could be clearly noticed in the simulation. The rainfall time series in 2009 indicates many breaks in the zonal belts of 7–15°N, 20–25°N, and 25–30°N, i.e., over southern, central, and northern India. The IMD data indicates five significant and prolonged dry spells (1–5 June, 6–20 June, 18–24 June, 20–27 July, 4–12 Aug) distributed in different latitude belts. The model could simulate the all India dry spells during 1–5 June, 6–20 June, and 4–12 Aug, and the dry spell during 24–30 Aug in the zonal belt 7–15°N reasonably well in duration and zonal extent. Observations indicate higher northward propagation of rainfall from 8th June onwards in 2008 and the 18th of June onwards in 2009 with higher quantities in 2008 than the simulated rainfall. The simulated rainfall in the zonal belts 15–20°N is relatively higher in both years.

3.2. *Spatio-Temporal Distribution of Land Surface Parameters*

The model simulated land surface parameters such as albedo, sensible heat flux, upward heating flux (sum of the sensible and latent heat fluxes) and soil moisture during the two contrasting monsoon seasons of 2008 and 2009 was analyzed to gain insight into the variations in the land surface processes. Although the land surface features are expected to have a higher influence on the overall monsoon system on a continental scale, the characteristics and behavior of monsoon on a regional scale are likely to be influenced more by the regional scale land surface processes. Surface albedo is a critical parameter that controls the net solar radiation which drives the surface energy and water budget (Qu and Hall, 2006). Albedo is the fraction of the solar radiation that is reflected by the earth's surface and is a function of the type of land surface. It gives a measure of the available energy at the surface for absorption and heating. The lower the albedo, then the higher is the available energy. The albedo varies from high values of 0.8 for highly reflective surfaces like snow and ice, medium values of 0.4 for desert sand and to lower values of 0.08–0.15 for coniferous forest and water surface. Albedo of vegetative lands

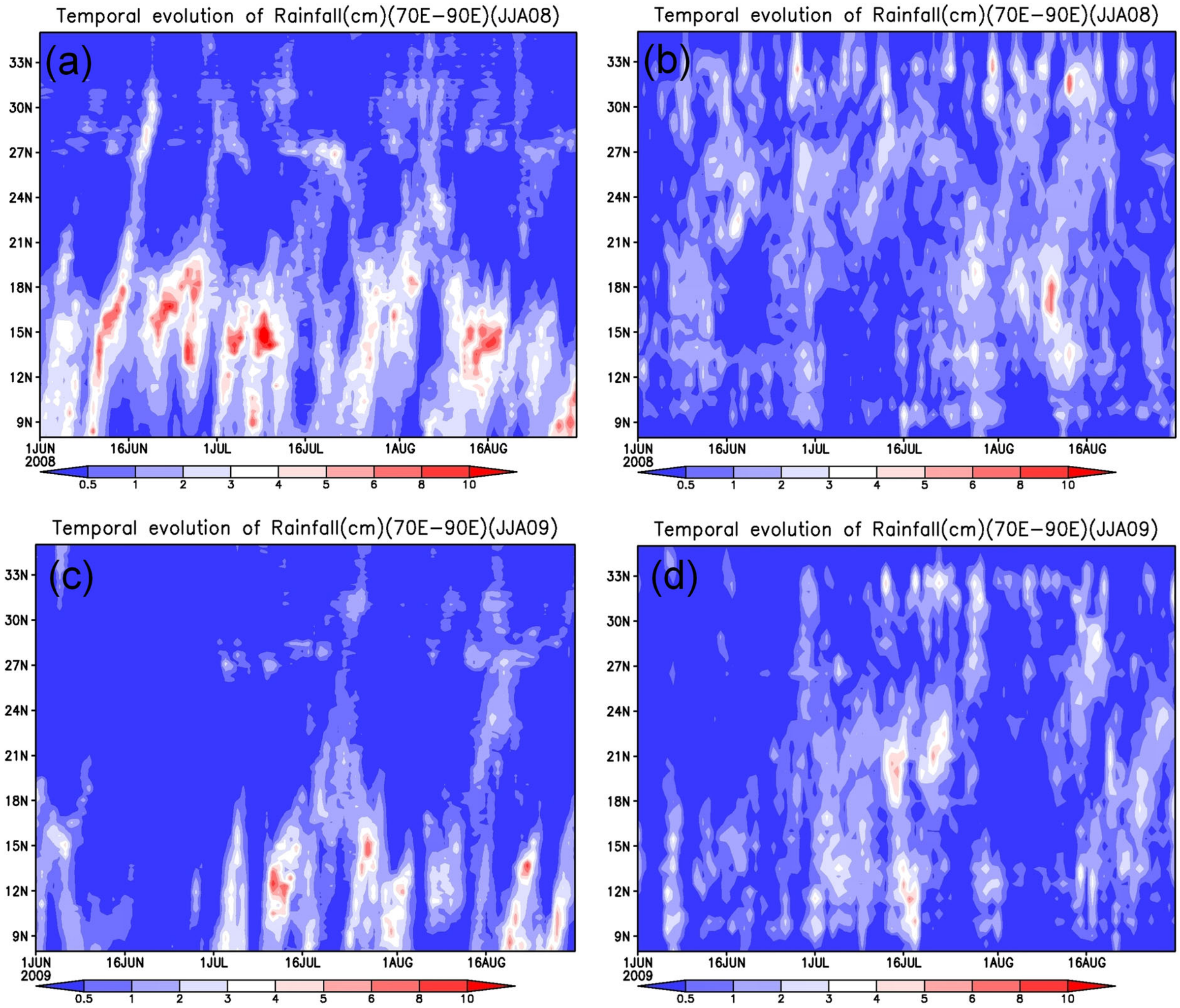

Figure 4

Temporal evolution of Rainfall (cm/day) averaged over the longitude belt (70E–90E) during JJA. *Top panels* (**a**, **b**) are for 2008 and *bottom panels* (**c**, **d**) are for 2009; *left panels* (**a**, **c**) are ARW simulations, *right panels* (**b**, **d**) are IMD observations

varies as 0.2–0.5 depending on the type of vegetation and crops. Major variations in albedo can be caused by snow cover variations in the seasons. The surface albedo is calculated in the NOAH LSM (Chen and Dudhia, 2001) using a simple weighting of the snow-free vegetation dependent background albedo and the maximum albedo over deep snow based on the fractional snow free and snow cover area within a model grid cell. The background snow-free surface albedo is updated by temporally interpolating between the prescribed vegetation-dependent background surface albedo for the summer and winter. The mean albedo for the months June, July, and August for 2008 and 2009 is presented in Fig. 5. Most of the Indian subcontinent had lower albedo values varying from 0.2 to 0.3. Albedo varied as 0.3–0.4 over the desert regions in the northwest, 0.2–0.3 over central Maharashtra in central India and the higher albedos are found over the hilly glacier regions of Jammu and Kashmir and Tibet (0.4–0.6). The lowest albedos are noted along the forest vegetative areas in Kerala coast, Madhya Pradesh, and northeast. As the same vegetation data (land cover, vegetation fraction) are used for both years (2008, 2009), no significant differences of albedo are noticed between the 2 years over the land area while

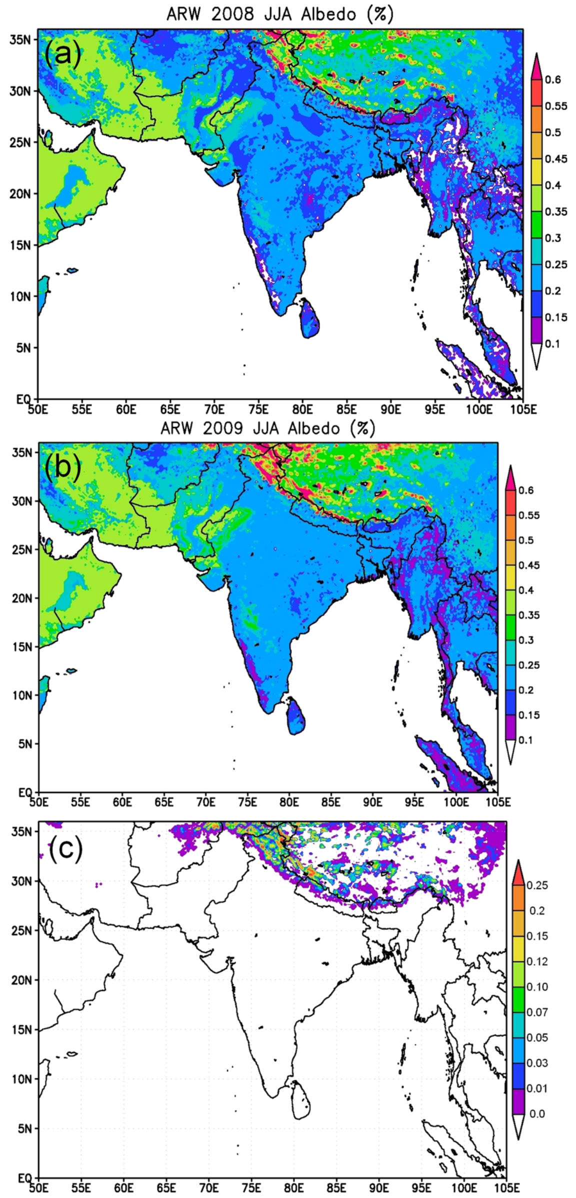

Figure 5

Seasonal mean albedo (%) for June, July and August months over the simulation domain. *Top panel* (**a**) is for 2008, *middle panel* (**b**) is for 2009 and *bottom panel* (**c**) is for the albedo difference between 2009 and 2008

higher albedo are simulated over Afghanistan, northern Pakistan, Jammu & Kashmir, Himachal Pradesh, Nepal and Tibetan plateau due to snow cover dynamics. The albedo is lower by roughly 20 % in 2008 in the above areas and is indicative of changes in the aerial coverage of snow and glaciers. This feature of higher albedo simulation on regional scale seems to be important to establish north-south heat gradients. Overall the average albedo in the domain is reduced by ~10 % in 2008 relative to 2009. The lower albedo in 2008 would lead to a higher net radiation and larger surface energy fluxes (latent, sensible heat) particularly in the northern parts of the domain leading to development of stronger south-north gradients in heat flux and temperatures in 2008 relative to 2009. The monsoon in 2008 is associated with a relatively lower albedo as well as with a large positive bias in precipitation.

3.3. Simulated flow characteristics and surface fluxes

Some of the earlier studies examined the physical and dynamical mechanisms of land surface and atmospheric effects on the monsoon system (e.g., Xue *et al.* 2004; Lee *et al.* 2011). The differences in the land surface parameters during the two contrasting monsoon seasons of the present study would manifest in the energy and moisture budgets over the land surface, which in turn influences the atmosphere through land/atmosphere interactions (fluxes). During the ISM, the southwest monsoon air flow brings moisture to the Indian subcontinent. The moisture advection depends on the strength of the flow and stronger advection leads to higher moisture influx into the region. The mean low-level wind flow and divergence in the 2 years during the month of June is presented in Fig. 6. It is seen that the wind flow in 2008 is relatively stronger with convergence along the west coast ($-10 \times 1.e{-}5$ to $-20 \times 1.e{-}6\ s^{-1}$), northwest, central, eastern, and northeastern parts of India. The strong convergence along the west coast and western India is consistent with the precipitation as shown in Fig. 4 for 2008. In contrast, a strong flow divergence ($\times 10.e{-}06\ s^{-1}$) is noticed in the northeastern parts of India in 2009 indicating subsiding motion. The mean June circulation features of the 2 years (2008, 2009) show that the location of the low-level jet over the Arabian Sea, the westerly flow below 10°N, and south-westerly flow along the west coast are well captured by the model. The low-level jet off the Somali coast and strong westerlies over the western part of the Arabian Sea are simulated in close agreement with verification analysis. However, the wind speed is slightly weaker in the simulation

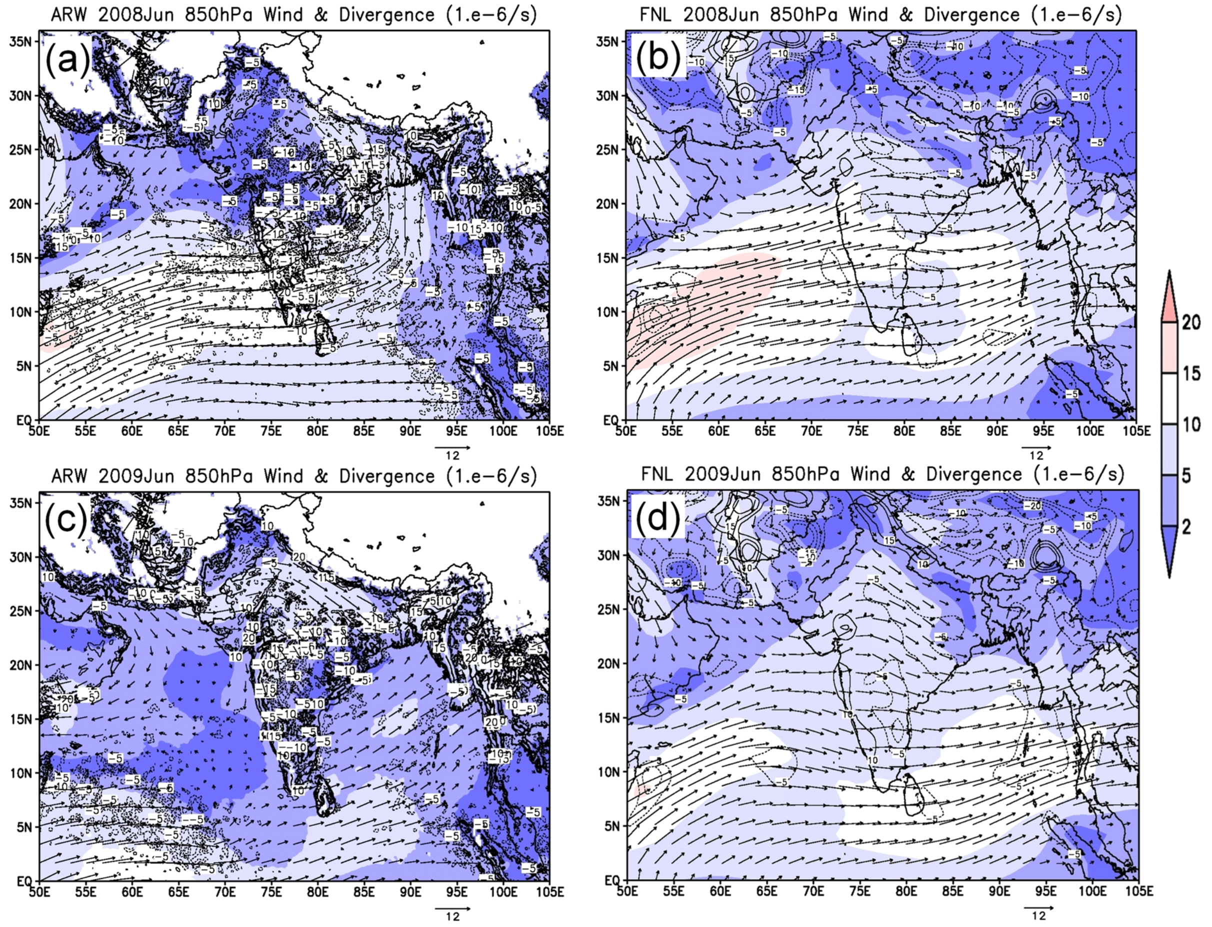

Figure 6
Wind field (ms^{-1}) and divergence ($\times$1.0e$-$6 s^{-1}) in May over the simulation domain. *Left panels* (**a**, **c**) are for ARW; *right panels* (**b**, **d**) are for FNL analysis; *top panels* (**a**, **b**) are for 2008 and *bottom panels* (**c**, **d**) are for 2009

especially in the low-level jet region in both years. An interesting result is that the strong westerly flow over the Arabian Sea, which brings heavy rainfall over the west coast of India (Findlater, 1969) is simulated relatively weakly in 2009 in agreement with verification analysis. Comparison of the flow fields in the 2 years indicates that the monsoon low-level jet is stronger by 40 % in 2008 relative to 2009 in both simulation and analysis. Recent studies related the strength of zonal wind over southern Arabian Sea to define the onset of monsoon and its rainfall pattern (Wang *et al*., 2009; Saha *et al*., 2011). The stronger simulated low-level flow in 2008 would lead to a more vigorous monsoon in 2008 relative to that of 2009. The flow and divergence features simulated with ARW are consistent with the FNL analysis (Fig. 6). The stronger atmospheric circulation in 2008 may be related to the thermal forcing through surface heating. Lee *et al.* (2011) have shown that changes in the heat fluxes over the land during the pre-monsoon season (March–May) affect the differential heating between land and ocean, which in turn controls monsoon development. To examine this aspect, the surface fluxes in the season May–August are analysed from simulation. The mean upward heating (due to sensible and latent heat fluxes) over the Indian subcontinent and adjoining regions for 2008 and 2009 are shown in Fig. 7 for the months of May and June. Simulation shows that the upward heat flux in May is relatively higher in 2009 than in 2008, but from June onwards the simulated upward fluxes are larger in 2008 than in 2009 indicating a higher

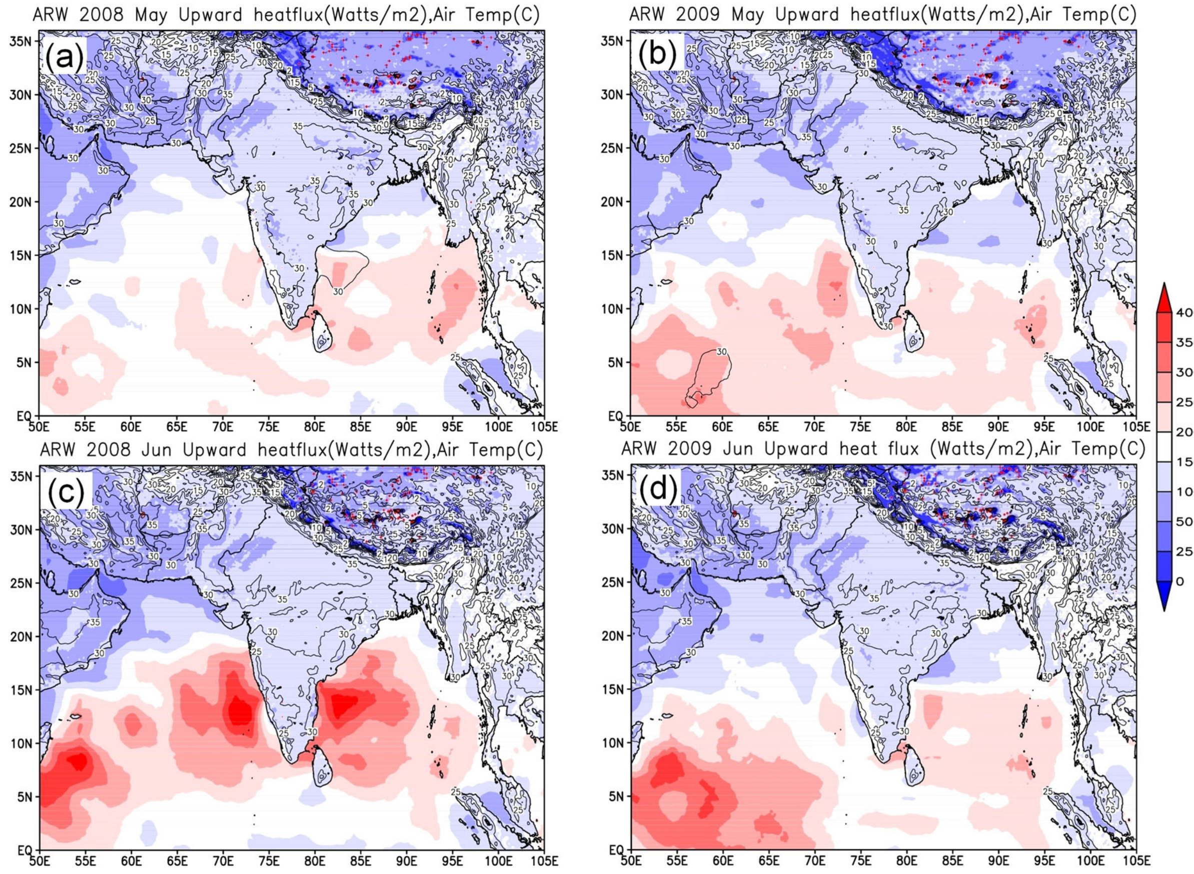

Figure 7

Surface upward heating fluxes (W/m^2) and low level air temperature over the simulation domain. *Left panels* (**a**, **c**) are for 2008, *right panels* (**b**, **d**) are for 2009; *top panels* (**a**, **b**) are for May and *bottom panels* (**c**, **d**) are for June

heating in 2008 as compared to 2009. During May of 2008, relatively larger areas under the energy band 100–200 W/m^2 over the land region and under 150–400 W/m^2 over the oceanic region relative to 2009 are noted. Similarly in June, both the land and ocean regions are identified with higher upward flux in 2008 as compared to 2009. The simulation also reveals relatively higher upward flux over the Arabian Sea as compared to the Bay of Bengal in June in both years. Thus, the circulations in May and June had considerable differences with higher upward heat flux during the above normal ISM of 2008 than the below normal ISM of 2009.

To gain further insight into land surface heating, sensible heat fluxes during the two contrasting ISM seasons are examined. Simulated sensible heat flux (Fig. 8) during May shows relatively higher fluxes in 2008 especially in northwest India (covering parts of Gujarat and Rajasthan), southern Peninsular India, northeast India, Tibetan plateau, Afghanistan as well as many parts of the north Indian Ocean. The sensible heat fluxes during June shows relatively higher fluxes in the northwestern parts of India and over the Bay of Bengal and Arabian Sea regions. In both the years, a clear south-north gradient in the sensible heat flux over the Indian subcontinent with higher fluxes over north India and a west-east gradient across the Indian Peninsula with higher fluxes over western parts are noted. The heat flux contrast between land and ocean is about 120 W/m^2 in 2008 and 100 W/m^2 in 2009. Lee *et al.* (2011) have shown that such large land-ocean flux contrasts (>30 W/m^2) during the pre-monsoon period would affect the conditions of monsoon development through a change in contrast of surface pressure from land to ocean. Considering both sensible and latent heat fluxes, a reverse gradient (to that of sensible heat) is noted in the net upward heat flux from north to south (Fig. 7) with higher upward fluxes distributed in the southern parts. This reverse gradient in the net upward heat flux is due to the latent heat, which is maximum over the ocean area. The sensible heat flux and 850 hPa geopotential heights (Fig. 8) from the simulation shows that the Indian landmass and areas further north of 23°N acts as a heat source and the North Indian Ocean acts as a heat sink. The relatively high sensible heat flux over the Indian Ocean in 2008 is indicative of higher SST and higher land-ocean thermal contrast in 2008 relative to 2009. After the onset of monsoon, the sensible heat contrast is expected to be controlled by the cooling effect of surface air by monsoon precipitation. After the onset, the monsoon is likely to be more controlled by the latent heat flux contrast between ocean and land through a positive feedback between latent heat contrast and rainfall enhancement by latent heat fluxes over the land (Lee *et al.,* 2011). The time evolution of surface fluxes (sensible, latent heat) averaged over the longitude belt 70–90°E (Indian land region) from the 1 June to 31 August period are presented in Fig. 9. Simulation shows that a relatively larger land mass had a high sensible heat flux in 2008 (regions north of 15°N in 2008) up to 16 June as compared to 2009 (regions north of 18°N). From 16 June to 1 July, due to widespread monsoon activity in 2008 leading to flux transfer mainly in the form of latent heat, regions north of 19°N alone in 2008 had a higher sensible heat flux, whereas due to poor monsoon rainfall in 2009, regions north of 18°N had a high sensible heat flux up to 1 July, and thereafter the area-flux propagation compares well with 2008. Simulation also shows propagation of strong latent heat flux from the equator to 17°N in 2008 and up to 15°N in 2009. Relatively large sensible and latent heat fluxes are noted in 2008 rather than in 2009 throughout the monsoon season. The time evolution of net upward heat fluxes (Fig. 10) indicates occurrence of relatively stronger upward surface fluxes and their propagation into regions up to 18°N in 2008 as compared to 2009. This shows a relatively strong north-south gradient as well as higher upward heat flux in 2008 than in 2009. The simulated north-south geopotential gradients over the Indian subcontinent are stronger in 2008 relative to 2009 and are consistent with the upward heat flux gradient (Fig. 8). Results from these simulations suggest that the larger north-south heat flux gradient in 2008 induced relatively stronger geopotential gradients, which in turn produced strong southwesterly winds. From the above analyses, considerable differences in the spatial distribution of upward heat fluxes in the monsoon season, and particularly the sensible heat flux in the pre-monsoon and early stages of monsoon and latent heat flux in the peak monsoon (July and August), are noted in the two cases. The temporal evolution of simulated surface fluxes (latent, sensible, net upward fluxes in W/m^2) in 2008 and 2009 years are presented in Fig. 11. It is noted that, while the sensible heat flux is almost of the same order of variation, there are large differences in the latent heat and net upward flux quantities between the 2 years. The sensible heat flux is slightly higher (by $\sim$ 5 %) during the onset phase (June), progression and peak phases in 2008 than in 2009. Throughout the monsoon season, sensible, latent and net upward fluxes are higher by about 20–40 % in 2008 relative to 2009. The relatively larger latent heat fluxes over the land region in 2008 could be related to the accumulated soil moisture occurring by storage of higher monsoon rainfall.

Moist convection and rainfall during the monsoon season occurs by convergence of moisture flux (Jiang and Li, 2011). Simulation shows that the Indian subcontinent has higher soil moisture amounts (0.1–0.4 m^{3}m^{-3}) in 2008 and lesser soil moisture (0.05–0.2 m^{3}m^{-3}) in 2009 (Fig. 12). It is noted that the entire southern Peninsular India has about 33 % and the northern India has about 40 % higher soil moisture in 2008 relative to 2009. The domain average soil moisture is about 25 % higher in 2008 compared to that in 2009. The higher soil moisture would lead to higher evaporative flux and, hence, a higher latent heat in 2008. The surface moisture flux and its divergence averaged for the three month period June–August for the 2 years 2008 and 2009 are presented in Fig. 13. Both oceanic and land areas in the domain are noted to have higher moisture flux in 2008 relative to 2009. The regions identified with relatively high soil moisture up to 32°N in 2008 are

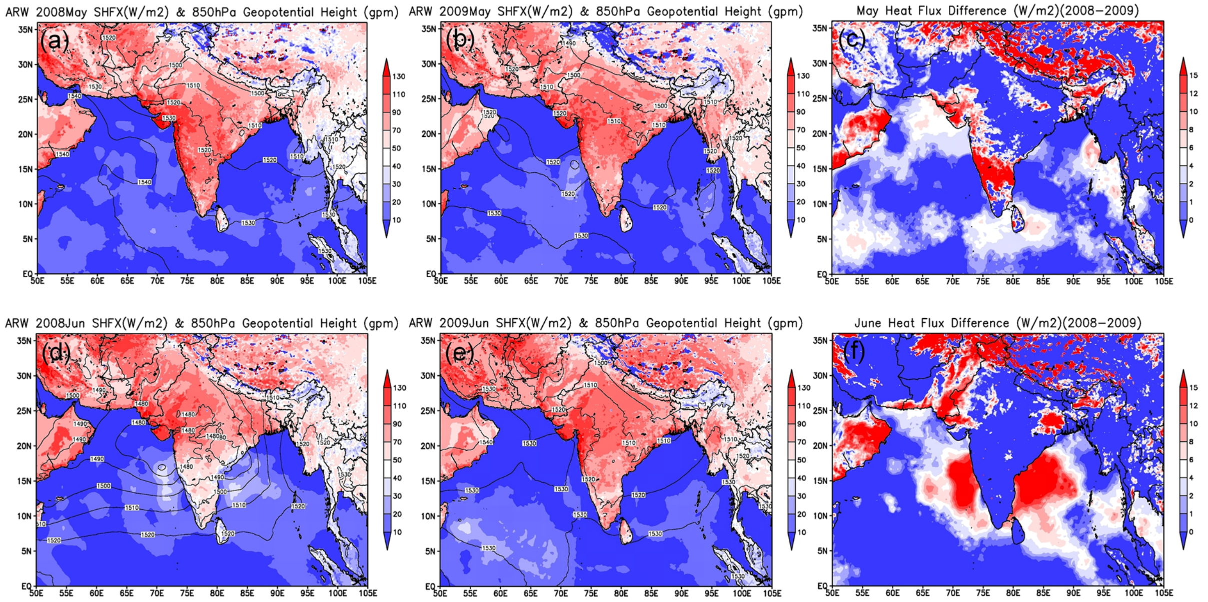

Figure 8

Sensible Heat flux (W/m^2) and Geopotential height (gpm) over the simulation domain. *Left panels* (**a**, **d**) are for 2008, *middle panels* (**b**, **e**) are for 2009 and *right panels* (**c**, **f**) are for the difference in heat flux between 2008 and 2009; *top panels* (**a**–**c**) are for May and *bottom panels* (**d**–**f**) are for June

found to be associated with relatively larger moisture flux (>2.e−5 kg/m^2/s), whereas moisture flux over the land portion in 2009 is lesser and is consistent with a less soil moisture amount. Considering both land and ocean areas the domain average moisture flux is about 30 % higher in 2008 relative to 2009. The band of high precipitation over the Arabian sea, the high precipitation areas in the west coast, the central east coast in Andhra Pradesh and Orissa states, and the foot hills of the Himalayas as well as northeastern areas in both years, are consistent with larger moisture flux ($-10.0e{-}10\ s^{-1}$ to $-40.0e{-}10\ s^{-1}$) as well as stronger moisture flux convergence in those areas (Fig. 13). The areas of low precipitation in northwest India and parts of central and northern India are associated with relatively low moisture flux as well as with divergence of moisture flux ($\sim 10.0e{-}10\ s^{-1}$). It is noted that the net surface moisture flux and its convergence are higher in 2008 as compared to 2009. These moisture flux differences are consistent with the diverse rainfall characteristics in the 2 years. The simulation indicates eastward/northeastward transport of moisture from the Arabian Sea to Peninsular India with strong flux convergence along the west coastal plains and many areas inland. The moisture flux and its convergence in the year 2009 are confined mainly to the lower latitudes (0–10°N) and to the longitude belt 50–60°E near the Somalian coast. The simulation shows drastic reduction of moisture flux during the June–Aug period in the year 2009. The analysis also indicates that the differences in the precipitation pattern in the wet and dry monsoon years are closely related to the moisture divergence and the magnitude of the surface moisture flux, which in turn indicates the significant role of the land surface processes in the evolution of the system.

Figure 14 shows the time evolution of the relative humidity, zonally averaged over the longitude belt (50–105°E), at 925 hPa during the JJA period. The northward transport of moisture is noted to be stronger in the year 2008 as compared to 2009. The year 2008 is marked with a steady progression of moisture transport after 6 June which produced a relatively wetter condition in 2008 than in 2009. In 2009, a dry phase is noted during 1–15 June. The stronger northward progression of moisture transport up to 25°N and above in 2008 is evident from the maximum humidity (RH $\geq$ 65 %) confined up to 25°N from 6 June whereas in the year 2009 the maximum humidity is curtailed to 17°N (Fig. 14). A

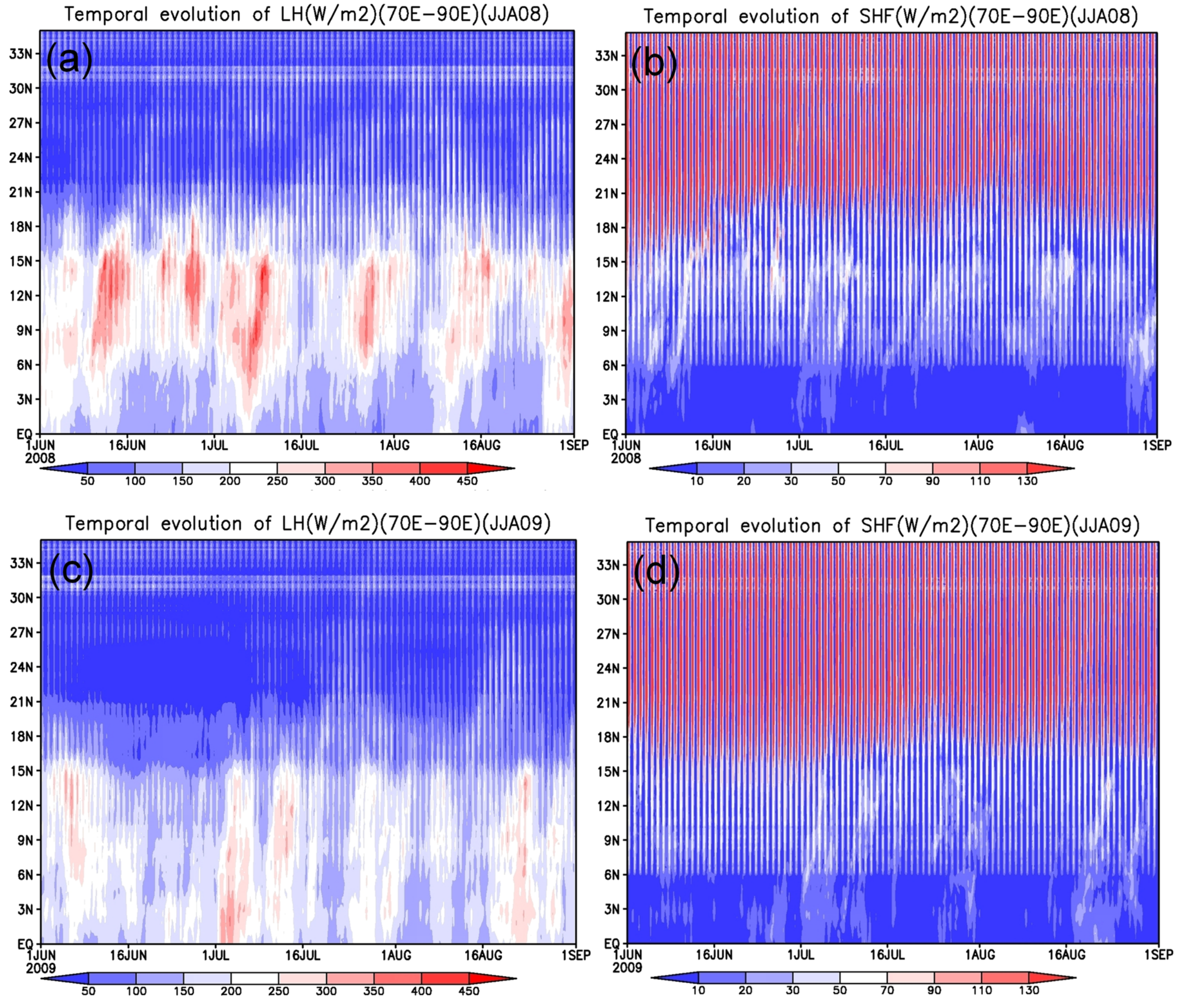

Figure 9

Temporal evolution of surface fluxes (W/m^2) averaged over the longitude belt (70E–90E) during JJA. *Left panels* (**a**, **c**) are for latent heat flux, *right panels* (**b**, **d**) are for sensible heat flux; *top panels* (**a**, **b**) are for 2008 and *bottom panels* (**c**, **d**) are for 2009

slow phase or delayed progression of monsoon is noted in 2009 with RH crossing 65 % at 20 N at around 15 June. The evolution of the humidity field also shows more breaks in the wet periods north of 17°N in the year 2009. Since the northward propagation of humidity during the monsoon is related to the advection of moisture by the meridional winds, the temporal evolution of the meridional winds is examined (Fig. 15). The meridional winds are stronger up to the first week of June and confined to 15°N in the year 2009, but subsequently their propagation was weaker. After 26 June, stronger winds (≥6 m/s) progressed to north of 15 N. The period between 10 July to 11 August is noted to have the strongest meridional winds extending up to 15–20°N. This period is consistent with stronger transport of moisture as seen in Fig. 14. Further, the meridional winds became weak from 10 Aug onwards in 2009 which is also consistent with reduced moisture transport after 16 Aug. Unlike in 2009, the year 2008 is noted to have steady progression in meridional winds as well as with winds peaking with a strength of 6–8 m/s between 20 June–16 Aug. The propagation of stronger winds is seen up to 20–25°N and is consistent with the transport of moisture to 20–25°N as noted in the previous discussion. These results indicate that

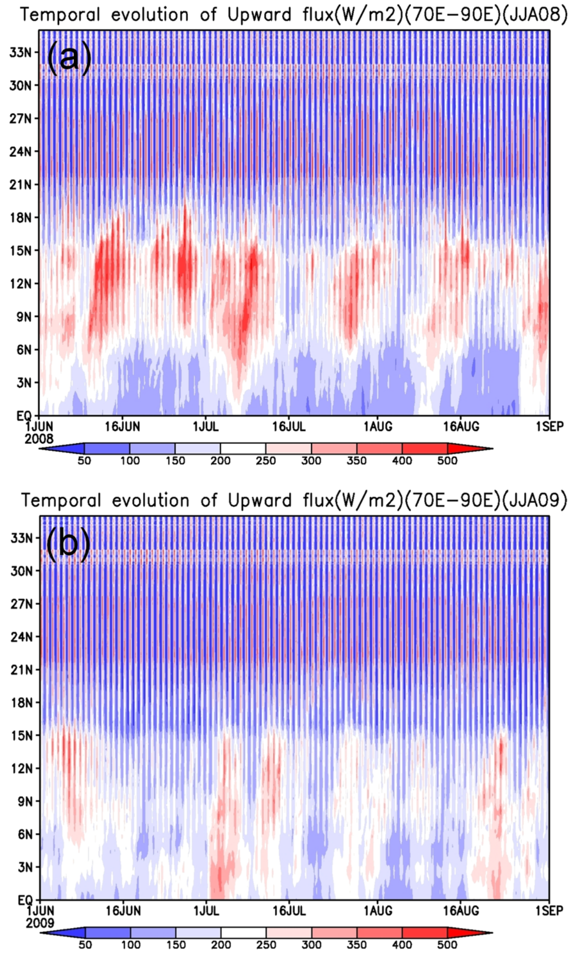

Figure 10

Temporal evolution of sensible heat flux (W/m^2) averaged over the longitude belt (70E–90E) during JJA in **a** 2008 and **b** 2009

the northward transport of moisture/water vapour is distinctly different in the years 2008 and 2009, with stronger transport simulated in 2008 relative to 2009 due to stronger meridional winds simulated in the year 2008.

These differences are further examined from the land surface processes in the 2 years. From the sensible heat flux evolution it is noted that many areas over the land region in especially the southern Peninsular India, have become heat sinks in both May and June during both years. However, in 2008 strong north-south as well as west-east gradients of sensible heat flux over the land portion and north-south gradient between the land and the ocean are noted from the simulations. These strong north-south gradients in sensible heat flux have resulted in strong geopotential gradients and, hence, stronger monsoon winds in the year 2008 relative to 2009. This in turn produced strong northward transport of moisture as evident from the time evolution of the humidity (water vapour) and meridional winds. These results clearly show the influence of the land surface processes in the regional monsoon characteristics.

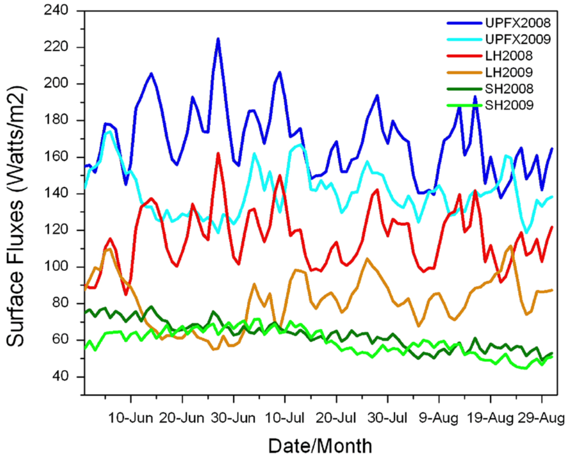

Figure 11

Temporal evolution of surface fluxes (W/m^2) over the Indian land mass (8–35°N; 70–90°E) from 1 June to 31 Aug in 2008 and 2009 years. *UPHF* upward heat flux, *LH* latent heat flux, *SH* sensible heat

4. *Verification of Simulated Rainfall and Surface Fluxes*

A quantitative verification of model-derived rainfall and surface fluxes (sensible, latent heat) is made by computing the statistical indices Correlation, Bias, Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) between simulated and analysis data for rainfall and surface fluxes (Table 2). The comparisons of simulated fluxes are made with corresponding data from Era-Interim analysis taking area averaged values over ocean and land areas separately at 00 UTC and 12 UTC times for the season JJA. For rainfall, simulated daily rainfall averaged over the Indian land mass is compared with corresponding IMD gridded daily average rainfall for the season JJA. Computed statistical metrics (Table 2) shows that the average daily rainfall in 2008 is higher than in 2009 in both the model simulation and

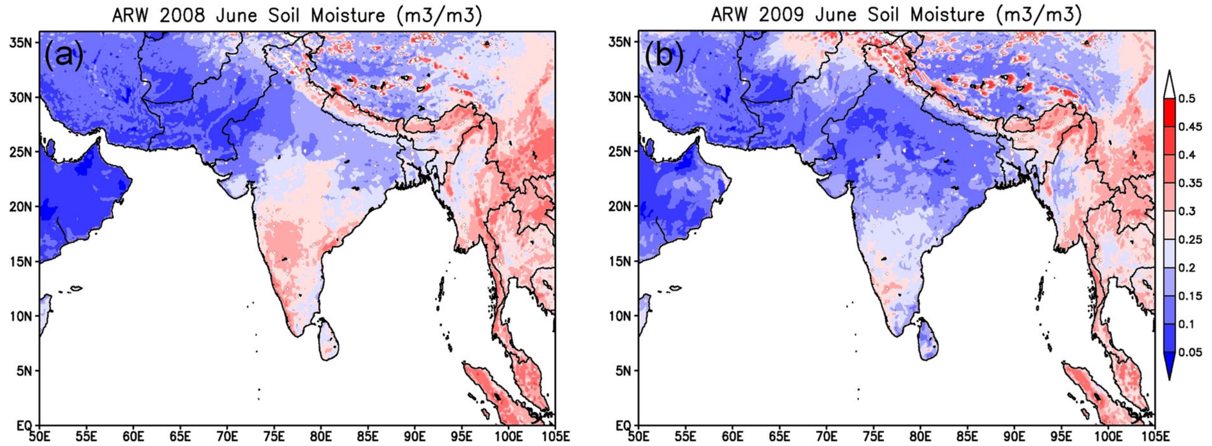

Figure 12
Mean Soil moisture in June (m^3 m^{-3}) in **a** 2008 and **b** 2009

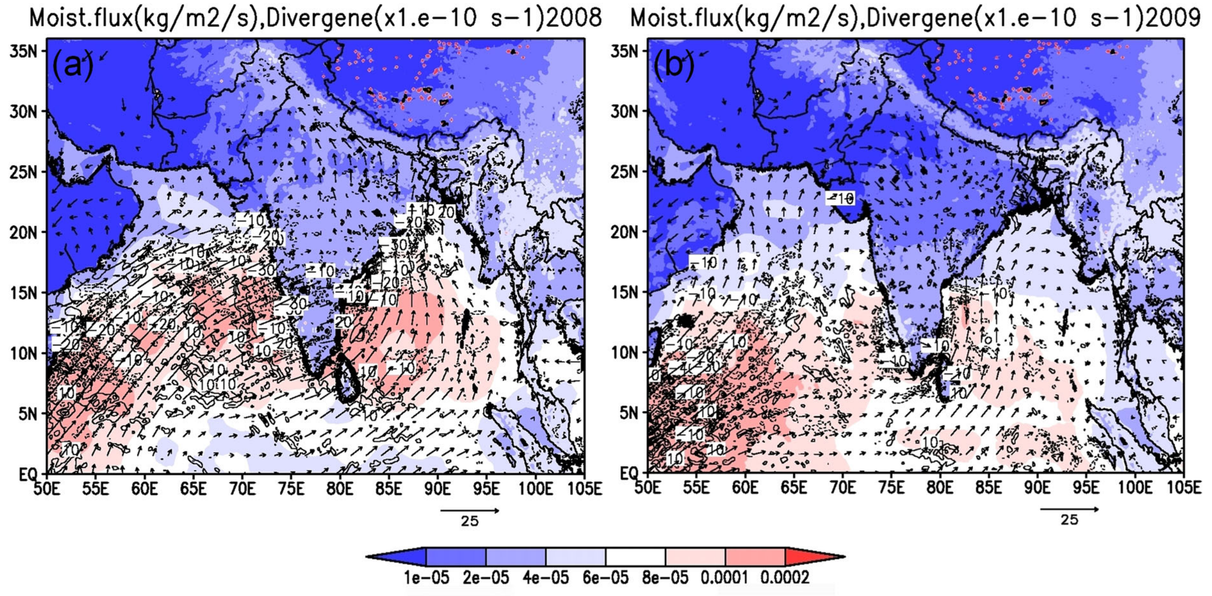

Figure 13
Average upward surface moisture flux (kg/m^2s^{-1}) and its divergence ($\times10^{-10}$ s^{-1}) for the period in Jun–Aug in **a** 2008 and **b** 2009

observations and have good correlations (>0.625) at 95 % significance level but with a negative bias of 1.65 mm/day in 2008 and 1.42 mm/day in 2009 indicating a slight dry bias in the simulation. The rainfall simulation errors in terms of MBIAS, RMSE are 1.98 mm/day, 1.75 mm/day in 2008 and 2.14 mm/day, 1.537 mm/day in 2009, respectively. The average sensible heat flux over ocean areas in the domain is higher in 2008 (11.21 W/m^2) than in 2009 (10.51) with a slight negative bias of −0.611 W/m^2 in 2008 and a positive bias of 0.396 W/m^2 in 2009. Similarly, the heat flux over the land area is also higher in 2008 (17.35 W/m^2) relative to 2009 (15.96 W/m^2) with negative bias (∼−1.65 W/m^2) in both the years indicating under-prediction of sensible heat flux over the land areas. Similarly a higher average latent heat flux is simulated in 2008 (33.10 W/m^2) relative to 2009 (32.3 W/m^2) over ocean area and the simulated fluxes are found to be in good agreement with observations with correlations of >0.89. A positive bias of 2.31 W/m^2 and RMSE of 10.9 W/m^2 are found in 2008 and a positive bias of 2.79 W/m^2

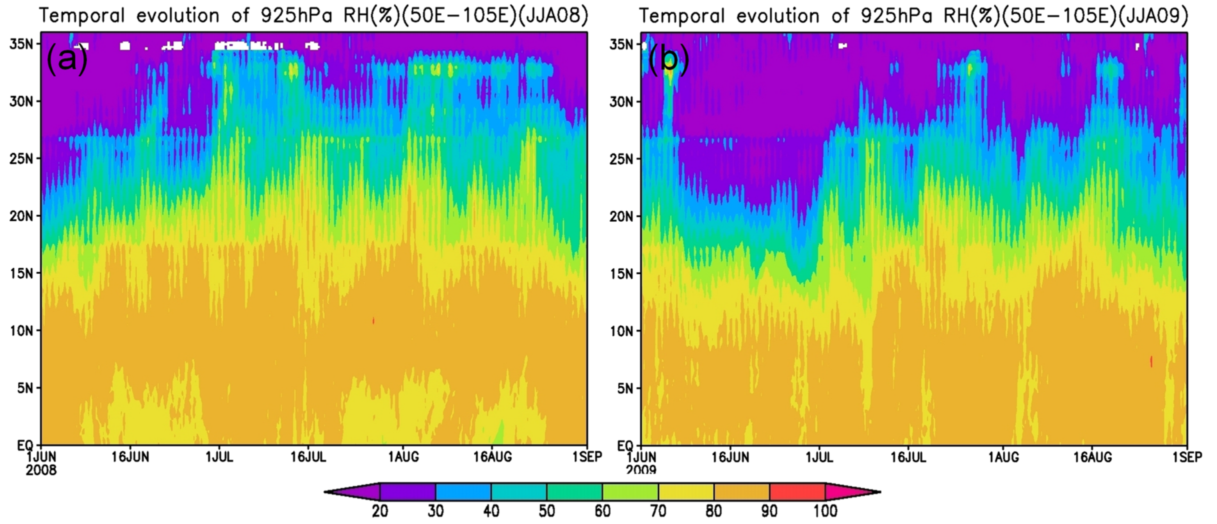

Figure 14

Temporal evolution of relative humidity (%) averaged over the longitude belt (50E–105E) during JJA in **a** 2008 and **b** 2009

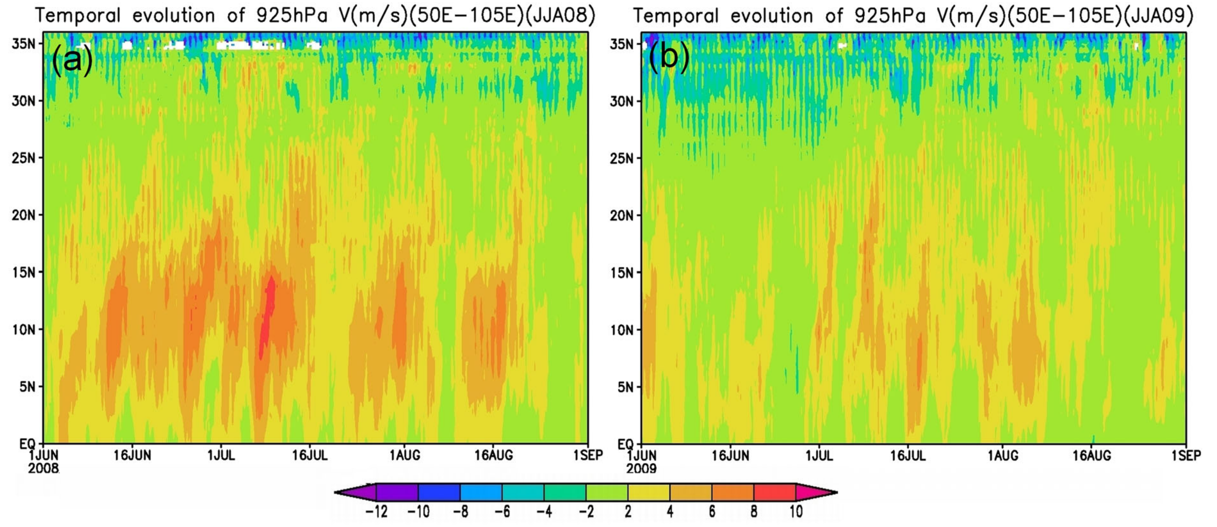

Figure 15

Temporal evolution of meridional wind (ms^{-1}) averaged over the longitude belt (50E–105E) during JJA in **a** 2008 and **b** 2009

and RMSE of 11.289 W/m^2 are found in 2009. The average latent heat fluxes over the land areas are also higher in 2008 relative to 2009 both in simulation and observations and are in good correlation ($\sim$ 0.95) with observations. Considering both years the BIAS and RMSE are of the order of -1.765 W/m^2 and 7.3 W/m^2 in the latent heat fluxes over the land areas. The simulated vis-à-vis observed means, correlations, and bias values indicate the surface fluxes are simulated reasonably well in both the years. Error values of $\sim$10 W/m^2 in latent heat flux and 5.0 W/m^2 in sensible heat fluxes in simulations are due to the limitation of comparison with coarse resolution (0.75°) Era-Interim flux analysis.

5. *Conclusions*

The present study examined the differences in the land surface processes during two contrasting ISM seasons (2008 and 2009) by making seasonal time scale and regional spatial scale simulations of

Table 1

Details of Domains and physics configuration used in the ARW regional model

WRF-ARW Version 3.2		
Domains	Domain1	Domain2
Horizontal resolution	45 km	15 km
Vertical levels	32	32
Grid points	220 × 190 (−20.9°N to 48.69°N) (33°E to 123°E)	421 × 430 (0°N to 36°N) (50°E to 105°E)
Domain centre	17.00°N, 78.00°E	19.66°N, 77.77°E
Physics		
Radiation	Dudhia (1989) scheme for shortwave; Rapid Radiative Transfer model (RRTM) for longwave	
Surface processes	NOAH land surface scheme (no: of soil layers 4)	
Boundary layer	YSU PBL scheme	
Microphysics	Lin scheme	
Convection	Betts-Miller-Janjic scheme	
Initial/boundary conditions	6 hourly NNRP (2.5° x 2.5° resolution)	

Table 2

Error metrics between simulated and observed (analysis) rainfall (mm) land surface fluxes (sensible, latent heat in W/m^2) for May–Aug

Period	Region	Parameter	Mean of simulation	Mean of observations	Correlation	MBIAS	RMSE	MAE
2008	India	Rainfall (mm/day)	8.75	9.21	0.723	−1.65	1.98	1.75
	Ocean	Sensible heat flux (W/m^2)	11.21	10.73	0.965	−0.611	4.767	4.62
		Latent heat flux (W/m^2)	33.10	28.79	0.742	2.311	10.9	10.71
	Land	Sensible heat flux (W/m^2)	17.35	20.645	0.968	−1.648	3.202	1.994
		Latent heat flux (W/m^2)	24.44	27.97	0.946	−1.765	7.310	6.905
2009	India	Rainfall (mm/day)	6.5	7.18	0.625	−1.42	2.14	1.537
	Ocean	Sensible heat flux (W/m^2)	10.51	10.11	0.891	0.396	5.073	4.844
		Latent heat flux (W/m^2)	32.308	26.714	0.974	2.797	11.289	10.625
	Land	Sensible heat flux (W/m^2)	15.96	20.43	0.967	−2.23	3.749	2.478
		Latent heat flux (W/m^2)	22.926	26.884	0.953	−1.979	7.384	6.949

the Indian Summer Monsoon using the WRF-ARW model. The ISM of 2008 is a normal monsoon with surplus rainfall and 2009 is a deficit year with below normal rainfall during the monsoon season. To examine the influence of the land surface processes on the monsoon system, the ARW model is run at 15 km resolution with an advanced land surface physics adopted NOAH land surface model driven by the real boundary conditions derived from NCEP NNRP reanalysis. The gridded rainfall observations from IMD, three-dimensional meteorological data from NCEP final analysis, are used to compare the simulated precipitation and atmospheric variables, respectively. The parameters of albedo, sensible heat flux, upward heating flux (sum of the sensible and latent heat fluxes), moisture flux and their divergence, and the northward transport of water vapour and meridional winds are analysed from the simulation and compared with corresponding observations. Notable differences in these parameters are found in the 2 years of the simulation and agree with corresponding variations in the available observations. The albedo is lower by ~10 % over the Indian subcontinent in 2008 relative to 2009 and conforms to lower albedo and stronger ISM correlation. The simulation with 15 km resolution brought out higher albedo values over Jammu and Kashmir, Himachal Pradesh of India, and the Tibetan plateau, which may be playing an important role in establishing north-south heat gradients. The wind flow is noted to be relatively stronger with flow convergence along the west coast ($-10 \times 1.e{-5}$ to $-20 \times 1.e{-6}$ s^{-1}), and several parts of Peninsular India consistent with higher precipitation in 2008 and a relatively weak flow and divergence in the northeastern parts of India in 2009 indicating lesser upward motion of air in 2009.

Considerable differences in the spatial distribution of upward heat fluxes (both sensible heat flux and latent heat flux) in the monsoon season are noted in the two contrasting ISM seasons. Analysis of the surface upward fluxes indicated that the stronger atmospheric circulation in 2008 was related to the larger thermal forcing through relatively larger surface heating and larger upward sensible and latent heat fluxes in the year 2008. It is inferred that the large heat flux gradient in the case of 2008 induced relatively stronger geopotential gradients, which in turn produced strong southwesterly winds. In both years, the areas of high precipitation are found to be associated with larger moisture flux as well as stronger moisture flux convergence, and the areas of low precipitation are associated with relatively low moisture flux as well as with divergence of moisture flux. The surface moisture flux and its convergence are higher in 2008 as compared to the year 2009. The northward transport of moisture and the evolution of the meridional winds are noted to be stronger in 2008 relative to 2009, which is due to the stronger surface flux gradients in the year 2008. The differences in the precipitation pattern in the wet and dry monsoon years are closely related to the moisture divergence and the magnitude of the surface moisture flux, which in turn indicates the significant role of the land surface processes in the evolution of the system. The study is conducted with inspiration from several earlier studies conducted by various workers using GCM simulations on the overall Asian monsoon system, where the continental scale influences were given main thrust. The present study reveals that, for even at a regional scale, the physical processes of land-surface energy partitioning do influence the regional behavior of the monsoon system to a certain extent.

Acknowledgments

The authors thank Sri S.A.V.Sathya Murty, Director EIRSG, for encouragement and support. The NCEP Reanalysis data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site http://www.esrl.noaa.gov/psd/. The Era-Interim reanalysis was obtained from the ECMWF through web site http://data-portal.ecmwf.int/data/d/interim_daily/. The authors acknowledge the NCEP, USA for the use of the NNRP/FNL analysis data, the ECMWF for the use of ERA reanalysis, and the India Meteorological Department for the gridded rainfall observations used in the study.

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(Received November 15, 2013, revised June 19, 2014, accepted July 11, 2014, Published online August 12, 2014)