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Influence of different land-surface processes on Indian summer monsoon circulation

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Abstract The impact of different land-surface parameterisation schemes for the simulation of monsoon circulation during a normal monsoon year over India has been analysed. For this purpose, three land-surface parameterisation schemes, the NoaH, the Multi-layer soil model and the Pleim-Xiu were tested using the latest version of the regional model (MM5) of the Pennsylvania State University (PSU)/ National Center for Atmospheric Research (NCAR) over the Indian summer monsoon region. With respect to different land-surface parameterisation schemes, latent and sensible heat fluxes and rainfall were estimated over the Indian region. The sensitivity of some monsoon features, such as Somali jet, tropical easterly jet and mean sea level pressure, is discussed. Although some features of the Indian summer monsoon, such as wind and mean sea level pressure, were fairly well-simulated by all three schemes, many differences were seen in the simulation of the typical characteristics of the Indian summer monsoon. It was noticed from the results that the features of the Indian summer monsoon, such as strength of the low-level westerly jet, the cross-equatorial flow and the tropical easterly jet were better simulated by NoaH compared with verification analysis than other land-surface schemes. It was also observed that the distribution of precipitation over India during the peak period of monsoon (July) was better represented with the use of the NoaH scheme than by other schemes.

Keywords Indian summer monsoon · Regional model · Land-surface schemes · Parameterisation

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1 Introduction

Numerical experiments on climate sensitivity studies using the General Circulation Model (GCM) as well as the Regional Climate Model (RCM) have shown that land-surface features, such as vegetation, soil moisture/temperature, sea surface temperature, sea ice and snow cover significantly affect surface energy and moisture equilibrium on global, regional and mesoscales, which play an important role in the change in the global and regional circulation and climate (Sellers et al. 1986; Dickinson et al. 1986; Henderson-Sellers 1993; Noilhan and Planton 1989). During the past decade, the land-surface model (LSM) has been developed from the simple module to the complex biophysical module, including the circulation of soil water and vegetation transpiration.

In recent years, studies have been carried out on coupling the LSM with the GCMs as well as the RCMs. At present, a number of models are used for the simulation of global climate change, such as the GCM (Byron et al. 1998), the Atmospheric Ocean GCM (Wu et al. 1997) and the Atmospheric GCM (Zeng et al. 2002; Delire et al. 2002; Rosenzweig and Abramopoulos 1997; Bonan 1998), which include the detailed land-surface process. Much research has shown that the GCM coupled with the land-surface process could improve the simulation of surface flux, energy and water transfer cycle between soil, vegetation and atmosphere (Bonan 1998; Delire et al. 2002).

With the development of the RCM in the early 1990s, the parameterisation of the land-surface process has become an important part of regional climate studies. The RCM can improve the simulation abilities of mean sea level pressure and precipitation with the improved land-surface parameterisation scheme (Ding et al. 1998). At present, the rapid development of the RCM occurs with the inclusion of more detailed physical parameterisation schemes. The National Center for Atmospheric Research (NCAR) has developed the fifth generation mesoscale model (MM5) from the previous version MM4, but these regional models have simple land-surface processes. There are many research works on coupling the detailed land-surface scheme with the NCAR MM5V2 (Crawford et al. 2001; Wei et al. 2002) and the coupled models are used for the experiments and regional climate simulations. The representative one of these models was the Regional Integrated Model System (RIEMS) developed by the global change SysTem for Analysis, Research and Training (START) Temperate East Asia Regional Center (TEA-RC). It was based on the NCAR MM5V2 and coupled with the CCM3 radiation package and Biosphere-Atmosphere Transfer Scheme (BATS) LSM. With the development of the mesoscale model in the NCAR, the MM5V3 model was released in 1999; it included the moderately detailed Oregon State University (OSU) LSM (Chen and Dudhia 2001a, b). This OSU LSM has been modified and replaced by an updated version of the model, known as the NoaH LSM (Chen and Dudhia 2001a, b; Ek et al. 2003), which includes many improvements from the National Center for Environmental Prediction (NCEP), NCAR, Air Force Weather Agency (AFWA) and University of California at Los Angeles (UCLA). In the latest version of MM5V3, three land-surface processes are available, namely: the NoaH, the Multi-layer (5-layer slab model; Dudhia 1996) and the Pleim-Xiu (Xiu and Pleim 2001) schemes. Although several studies have been conducted on the numerical simulation of the Indian summer monsoon (Singh et al. 2006; Bhaskaran et al. 1996), only a limited number

of them have considered the role of land-surface processes, such as vegetation cover and soil moisture, in the mesoscale distribution of monsoon rainfall over India. Numerical modelling studies (McCumber 1980; Anthes 1984; Hong et al. 1995; Xu et al. 1996) indicated a significant change in convective rainfall in the vegetated area. Inclusion of vegetation cover and soil moisture in a dry bare soil model enhances the precipitation and improves the large scale circulation in the simulation of the Indian summer monsoon (Raman et al. 1998). One normal Indian summer monsoon was 1998 (the total observed rainfall was 85.90 cm; in anormal monsoon the total rainfall is 84.68 cm, departure is +1.4%), where the rainfall in the peak period of the monsoon (July) was also normal (normal July rainfall is 27.27 cm, whereas observed July rainfall was 25.75 cm, departure – 5.6%).¹ Therefore, it was seen that in that year, the peak period of the Indian summer monsoon, i.e. July, was normal with respect to rainfall over the Indian region. Here, an attempt is made to study the summer monsoon (July) 1998 over the Indian region with the use of the Noah, Multi-layer and Pleim-Xiu land-surface schemes in a numerical model (MM5).

The next section provides a brief description of the model used in the present study, followed by a section on the experimental design and data used. The results and discussion are then put forward, ending with the broad conclusions drawn from the study in the last section.

2 Model description

The Pennsylvania State University (PSU)/NCAR mesoscale model MM5 was used in the study of the Indian summer monsoon during July 1998. This is a limited area, non-hydrostatic, primitive equation model that uses the sigma-vertical coordinate. Model equations are written in surface pressure-weighted flux form in the terrain following the sigma co-ordinate and solved in the Arakawa B grid. The Leapfrog time integration scheme with time splitting was used for model integration. The most useful feature of the MM5 model is its flexibility in terms of many options that are specified by the user and by setting these parameters to appropriate values, the model can be used for a wide range of applications. These include number of nests, type of convection, Planetary Boundary Layer (PBL), radiation parameterisation and the land-surfaces processes scheme, etc. Another advantage of this modelling system is that it is a state-of-the-art model and is under continuous development. A detailed description of the model is provided by Grell et al. (1994).

A brief description of the three land-surface processes used in this study is given here. The Noah land-surface scheme is developed by the OSU. In the latest versions of the MM5, the OSU LSM has been replaced by an updated version of the LSM, known as the Noah LSM, hereafter referred to as the NoH. In this scheme, land-surface evaporation consists of three components: direct evaporation from the bare soil surface, transpiration through the leaf stomata and evaporation of precipitation intercepted by the leaf canopy. The model is based on the coupling of the diurnally dependent Penman potential evaporation approach, the multi-layer soil model and the primitive canopy model (Chen and Dudhia 2001a, b). It has a single canopy layer

¹ These normal and observed rainfall values were provided by the India Meteorological Department (IMD).

and includes prognostic variables like soil moisture and temperature in the soil layers and snow stored on the ground. The second land-surface scheme is a 5-layer soil model or multi-layer soil model and hereafter referred to as the ML scheme. In this scheme, the treatment of the ground temperature is carried out at minimal computational cost, in either CPU time or memory. In principle, any number of levels and thicknesses could be specified. However, the model uses five layers with thickness from top to bottom of 1, 2, 4, 8 and 16 cm. The third land-surface scheme used here is the Pleim-Xiu scheme, hereafter referred to as the PX scheme. In this scheme, the surface model includes a two-layer soil model, viz. 1-cm surface layer and 1-m root zone layer. Here, evaporation has three pathways: direct soil surface evaporation, vegetative evapotranspiration and evaporation from wet canopies. Ground surface (1 cm) temperature is computed from the surface energy balance using a force-restore algorithm for heat exchange within the soil. Stomatal conductance is parameterised according to root zone soil moisture, air temperature and air humidity, photo synthetically active radiation (PAR) and several vegetation parameters, such as leaf area index (LAI) and minimum stomatal resistance.

3 Experimental design and data used

The model configuration used in this study is given in Table 1. The model domain (figure not shown) was a horizontal resolution of 90 km over south East Asia (30° S–50° N and 30° E–120° E). The model was integrated continuously from 00UTC of 20 June to 00UTC of 31 July 1998. The model outputs were saved every 12 h and compared with mean analysis of NCEP and available observations (IMD and Xie-Arkin). Since only the results for the month of July are compared, the spin-up period for the simulation is in the order of 10 days. Lateral boundary forcing for the domain was one way and provided every 6 h by NCEP-NCAR (Kalnay et al. 1996) reanalysis datasets. The model sea surface temperature provided by NCEP reanalysis was used as a lower boundary condition and was updated every 6 h during

Table 1 Overview of the MM5 model used in the present study

Dynamics	Non-hydrostatic
Model domain	30° S–50° N, 30° E–120° E
Horizontal grid distance	90 km
Map projection	Mercator
Horizontal grid system	Arakawa B-grid
Vertical co-ordinate	Terrain-following sigma co-ordinate 23 sigma levels (7 within boundary layer)
Time integration scheme	Leapfrog scheme (with time split technique)
Spatial differencing scheme	2nd order centred
Lateral boundary condition	Time and inflow/outflow-dependent/relaxation (non-hydrostatic)
Top boundary condition	Rigid lid (non-hydrostatic)
Radiation parameterisation	NCAR CCM2 radiation scheme
Surface layer parameterisation	NoaH (1st experiment), Multi-layer (2nd experiment), Pleim-Xiu (3rd experiment)
Cumulus parameterisation	Grell (Grell et al. 1994)
PBL parameterisation	Medium range forecast model (Hong and Pan 1996)
Microphysics	Simple Dudhia (Grell et al. 1994)

PBL: Planetary Boundary Layer; NCAR: National Center for Atmospheric Research

simulation. Two additional types of data, 1° global maximum snow albedo and 0.15° monthly climatological (snow-free) albedo were used as input in these experiments. The land use/vegetation is characterised by United States Geological Survey (USGS) data set of $10'$ resolution.

4 Results and discussion

The results obtained from the model simulations are discussed in various subsections below.

4.1 Sea level pressure

The monthly mean sea level pressure as obtained from model simulations using all three land-surface process schemes (LSPSs) and from corresponding verification analysis for the month of July 1998 is shown in Fig. 1. This shows that the characteristic features of the Indian summer monsoon circulation viz. lower pressure over the Indian subcontinent, higher pressure over the adjoining Indian Ocean and Mascarene high are reasonably well simulated by the model using different LSPSs and are in close agreement with the verification analysis. It can be noticed from Fig. 1 that the pressure gradient along the west coast of India is stronger in the verification analysis than in model simulations using all LSPSs, although the kinks in the isobars associated with orography on the leeward side of the western Ghat have been observed in the model simulation using NoH and ML schemes. The PX scheme simulates only one isobar along the west coast of India, which represents very poor characteristic features of the normal flow pattern for July. The heat low is simulated by the model using the NoH scheme over north west India, which is closely resembles the verification analysis. The ML scheme shows a rather deep heat low and the PX scheme simulation is poor compared with the verification reanalysis.

The correlation coefficient (CC) and the root mean square error (RMSE) are the important factors for validating the model's simulation ability (Zhao et al. 1997). Table 2 shows the RMSE, CC and biases between verification and simulated analyses using three LSPSs over four homogenous subregions of India (Parthasarathy et al. 1995), namely: north west India (NWI), central India (CI), north east India (NEI) and southern peninsular India (SPI). From Tables 2 and 3, it was found that the CCs and level of significance of the three schemes are remarkably good. The NoH scheme shows the lowest RMSE except for the CI region. Table 2 also shows the bias in percentage of the simulation results for all three schemes. Bias represents the percentage of deviation of the results simulated by the model with regard to the verification analysis. It was observed that bias is more in the case of the PX scheme than with other schemes. Through statistical study, it was also noticed from Table 2 that the simulation results with the ML scheme are better than that with the PX LSM.

4.2 Mean circulation features

The wind vectors at 850 hPa as obtained from model simulations using the three LSPSs and corresponding verification analyses for the month of July 1998 are shown in Fig. 2. This shows that the characteristic features of the Indian summer monsoon

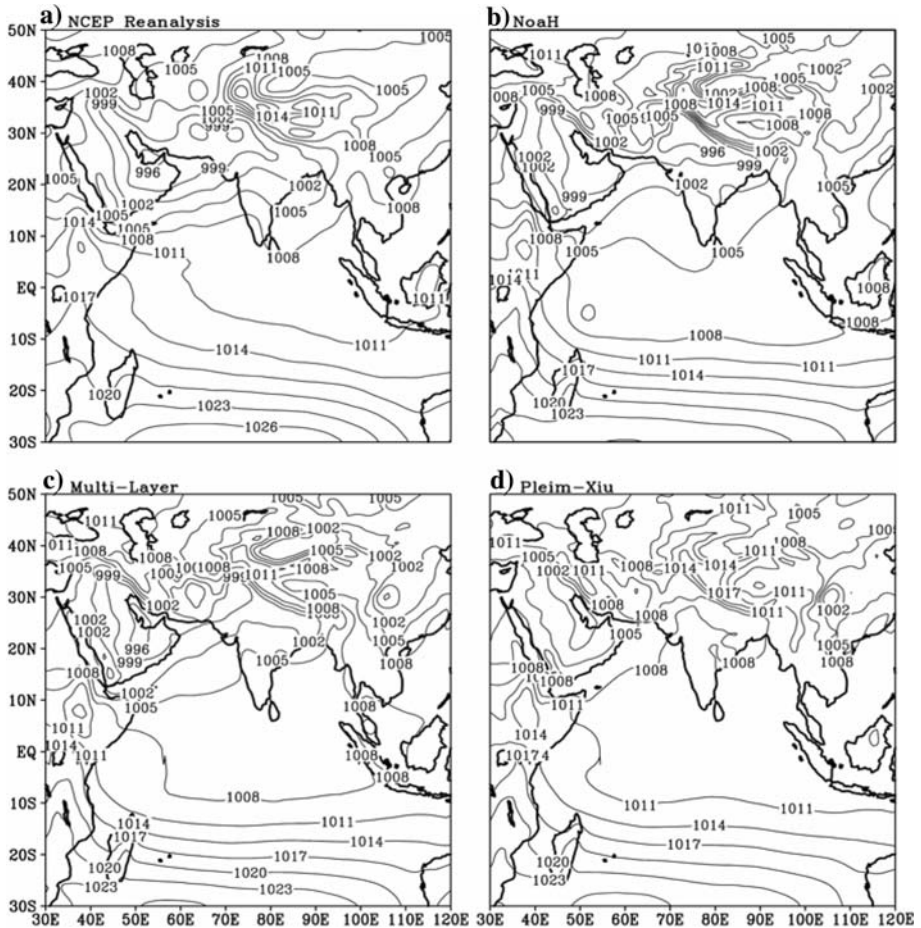


Fig. 1 Monthly mean sea level pressure (in hPa) for July 1998 from (a) NCEP (National Center for Environmental Prediction) reanalysis, (b) model simulation using the NoH scheme, (c) same as (b) but using the ML (Multilevel) scheme and (d) same as (b) but using the PX (Pleim-Xiu) scheme

Table 2 Statistical relationship between reanalysis and the model results using three land surface schemes for the July 1998 sea level pressure over four regions in India

Region	NCEP/NCAR	Average value simulated by model			RMSE			CC			Bias (%)		
		NoH	ML	PX	NoH	ML	PX	NoH	ML	PX	NoH	ML	PX
NWI	1,003.5	1,003.7	1,006.1	1,009.1	1.41	2.30	8.41	0.59	0.89	0.53	0.02	0.26	0.56
CI	1,002.6	1,004.0	1,003.2	1,008.2	1.66	1.17	4.66	0.87	0.82	0.67	0.14	0.06	0.56
NEI	1,004.5	1,005.2	1,002.5	1,010.2	1.06	1.74	5.06	0.83	0.75	0.63	0.07	-0.02	0.57
SPI	1,005.4	1,005.8	1,003.9	1,008.9	0.70	1.51	4.70	0.80	0.86	0.80	0.04	-0.15	0.35

NWI: north west India; CI: central India; NEI: north east India; SPI: southern peninsular India; NCEP: National Center for Environmental Prediction; ML: multilayer; PX: Pleim-Xiu

Table 3 Level of significance (Student’s *t* distribution) of the results simulated by the model using three land surface schemes for the July 1998 sea level pressure over four homogeneous regions in India

Region	Student’s <i>t</i> distribution [<i>t</i> _{cal}]			<i>t</i> _{table}	
	NoH	ML	PX	<i>t</i> _{0.995}	<i>t</i> _{0.99}
NWI	3.94	10.51	3.365	2.76	2.46
CI	9.50	7.72	4.86		
NEI	8.01	6.11	4.36		
SPI	7.18	9.08	7.18		

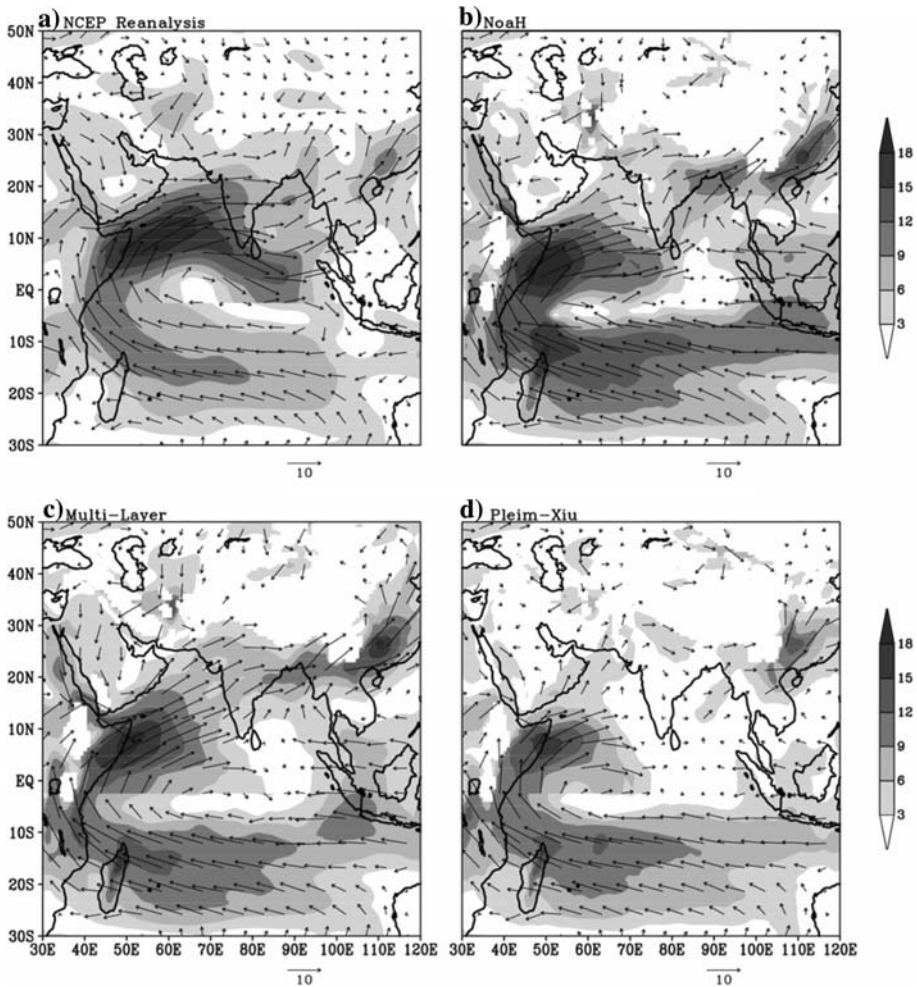


Fig. 2 Monthly mean wind vector (in ms^{-1}) at 850 hPa for July 1998 from (a) NCEP reanalysis, (b) model simulation using the NoH scheme, (c) same as (b) but using the ML scheme and (d) the same as (b) but using the PX scheme

viz. the strong cross-equatorial flow, the low-level jet off the Somali coast and the intense westerlies over the western part of the Arabian Sea were reasonably well-simulated by the model and were in close agreement with the verification analysis. A close comparison of the three simulations showed that the strong westerly flow over the Arabian Sea, which brings heavy rainfall over the west coast of India (Findlater 1969) was not well represented in the simulation using the PX scheme. The westerly flow over the Indian land mass was clearly under-predicted by the model. The strength of the Somali jet was better simulated using the NoH scheme, whereas the westerly flow over the Indian region was slightly better simulated using the ML scheme. The characteristic flow pattern over the eastern part of the Arabian Sea, Indian land mass and Bay of Bengal was not reproduced in the model simulation using the PX scheme.

The wind vectors at 200 hPa as obtained from the model simulations and verification analysis are shown in Fig. 3. The characteristic features of the monsoon circulations, namely: elongated Tibetan anticyclone, the subtropical westerly jet and the tropical easterly jet were reproduced in the model simulations. The strength of the tropical easterly jet was very poorly represented in the simulation using the PX scheme, whereas in other two simulations it was found to be slightly weaker compared with verification analysis.

It would be of interest to examine the vertical structure of both these jets. For this purpose, a latitude cross section of the sectorial (30° E– 120° E) monthly mean zonal wind for July 1998 is shown in Fig. 4 for verification analysis, for the NoH, the ML and the PX LSPSs. Figure 4 indicates that the low-level jet was well-simulated in all three schemes, but the location and area of the jet for the NoH scheme were in good agreement with the verification analysis. However, the strength of the low-level jet is weaker in the model simulations compared with the analysis. It may be partly attributed to the coarse horizontal resolution. The strong upper level tropical easterly jet (200 hPa) is well-simulated by all three schemes (Fig. 4).

The latitude cross-section of the sectorial (30° E– 120° E) mean meridional wind simulated by the model and the corresponding verification analysis are shown in Fig. 5. The verification analysis (Fig. 5a) clearly indicated a strong inflow into the monsoon land mass at lower levels, and outflow at higher levels. This kind of flow pattern is typical of summer monsoon circulation. This meridional circulation led to low-level incursion/influx of moisture into the monsoon region, leading to intense convective activity and upper level strong divergent flow from the region. This low level of flux of moisture and the upper level of strong divergent flow sustained and intensified the entire monsoon circulation and caused strong convective activity with heavy rainfall over the region. These characteristics of the Indian summer monsoon were better simulated by the NoH and ML schemes than by the PX scheme.

4.3 Surface fluxes and rainfall

Simulated monthly mean latent heat fluxes and sensible heat fluxes during July 1998 for the NoH, ML and PX schemes are shown in Fig. 6. The convective and non-convective precipitation simulated by the models for the month of July is shown in Fig. 7 and the total rainfall as obtained from model simulations using the three LSPSs and corresponding India Meteorological Department (IMD) observation for the same time are shown in Fig. 8. Figure 6a shows the following similarities in the simulated results for the three schemes:

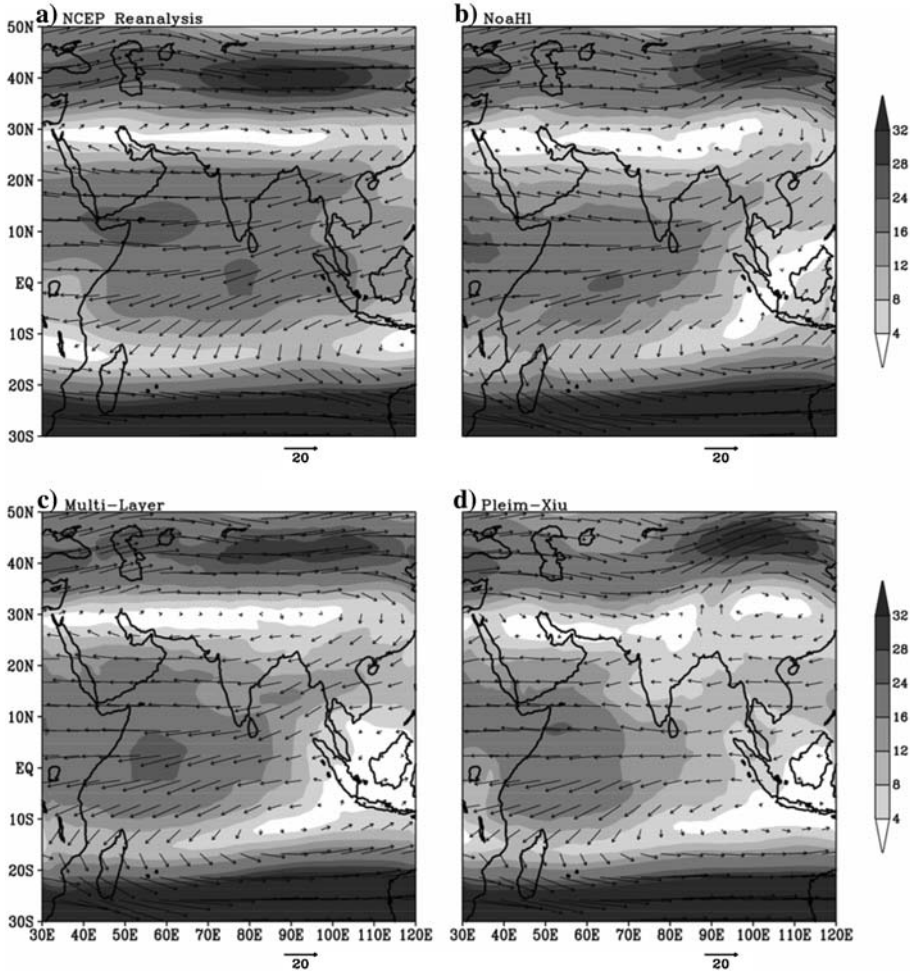


Fig. 3 Mean monthly wind vector (in ms^{-1}) at 200 hPa for July 1998 from (a) NCEP reanalysis, (b) model simulation using the NoH scheme, (c) same as (b) but using the ML scheme and (d) same as (b) but using the PX scheme

1. Latent heat fluxes were larger over ocean than over land
2. Latent heat fluxes were larger over land areas where precipitation had occurred

However, differences in simulated latent heat fluxes also exist among the three schemes. Over the desert region, the NoH scheme showed the weakest latent heat fluxes, whereas the ML scheme simulated strong latent heat flux. In particular, using the NoH land-surface scheme simulated strong latent heat flux along the western Ghats (Fig. 6a) compared with the ML and PX schemes. These gradients would further increase the precipitation over this region. Observation also confirmed significant amounts of rainfall in the same region. Thus, it was found that the spatial distribution of latent heat flux was better represented by the NoH scheme. From Fig. 6b, it was noticed that the NoH and ML schemes showed weak sensible heat than latent heat flux over the Indian subcontinent except north west India. It was

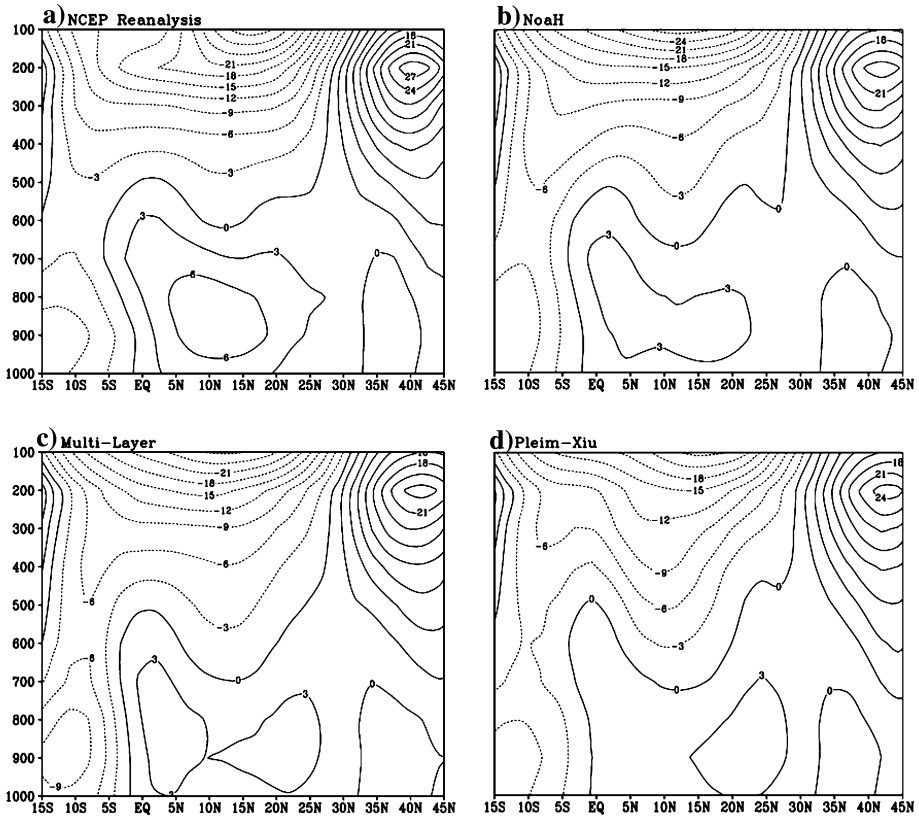


Fig. 4 Sectorial zonal mean velocity (in ms^{-1}) during July 1998 from (a) NCEP reanalysis, (b) model simulation using the NoH scheme, (c) same as (b) but using the ML scheme and (d) same as (b) but using the PX scheme

observed from Fig. 6a(i) and b(i) that the sensible heat flux was stronger in the NoH scheme than the latent heat flux over north west India, but the reverse in the case of the ML scheme (Fig. 6a(ii) and b(ii)). The PX scheme showed a strong sensible heat rather than latent heat flux over whole Indian region (Fig. 6a(iii) and b(iii)). A strong sensible heat flux signified that the air is cooler than the earth surface, which indicated less moisture in the air over the same regions.

The maximum convective rainfall was simulated by the NoH scheme (Fig. 7a(i)) compared with the ML and PX schemes (Fig. 7a(ii–iii)). This is consistent with the fact that during the summer monsoon season over the Indian land mass most of the rainfall is of the convective type (Upadhyay 1995). It was observed that maximum rainfall during the monsoon along the west coast occurred due to cumulus showers or sometimes continuous rain from a deep layer cloud (Rao 1976). The ML scheme produces maximum non-convective rainfall (Fig. 7b(ii)) over western Ghat, central India and north east India compared with the NoH (Fig. 7b(i)) and PX schemes (Fig. 7b(iii)). This would suggest that the orographically enhanced precipitation could fall out in the form of non-convective precipitation at the west coast of India where there is a strong interaction between the Somali jet (Fig. 2c), which carried large amounts of moisture from the Indian Ocean, the Arabian Sea and the western

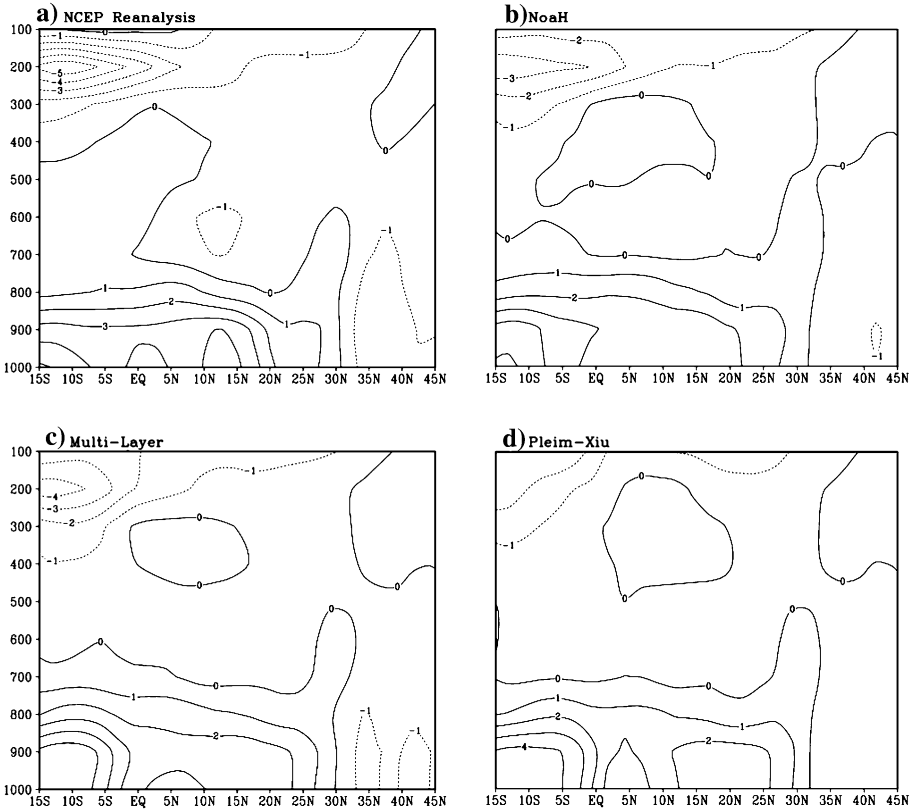


Fig. 5 Sectorial meridional mean velocity (in ms^{-1}) during July 1998 from (a) NCEP reanalysis, (b) model simulation using the NoH scheme, (c) same as (b) but using the ML scheme and (d) same as (b) but using the PX scheme

Ghat mountains. But the PX land-surface scheme simulated poorly convective (Fig. 7a(iii)) and non-convective (Fig. 7b(iii)) rainfall over the whole Indian subcontinent.

The IMD and the Xie-Arkin (figure not shown) observations show that the characteristic features of the Indian summer monsoon rainfall peaks were located in the southern periphery of the Himalayas, along the monsoon trough line, the Bay of Bengal, the Arabian Sea, the west coast of India and the southern Indian Ocean. These features were well-captured by the NoH and ML schemes as they are in close agreement with the observations. However, the PX scheme was not able to capture all these features. Over the oceanic regions, precipitation (Fig. 8b–d) was overestimated by all LSPSs. Also, model simulations produced a strong heat flux gradient over the same regions. The ML scheme showed a large amount of precipitation (Fig. 8b) over north west India, which is not supported by the observations. It may be due to the presence of strong latent heat fluxes (Fig. 6a(ii)) and weak sensible heat fluxes (Fig. 6b(ii)) over the same region. In general, precipitation distribution over Indian subcontinent by the NoH scheme is better simulated than the ML and PX schemes.

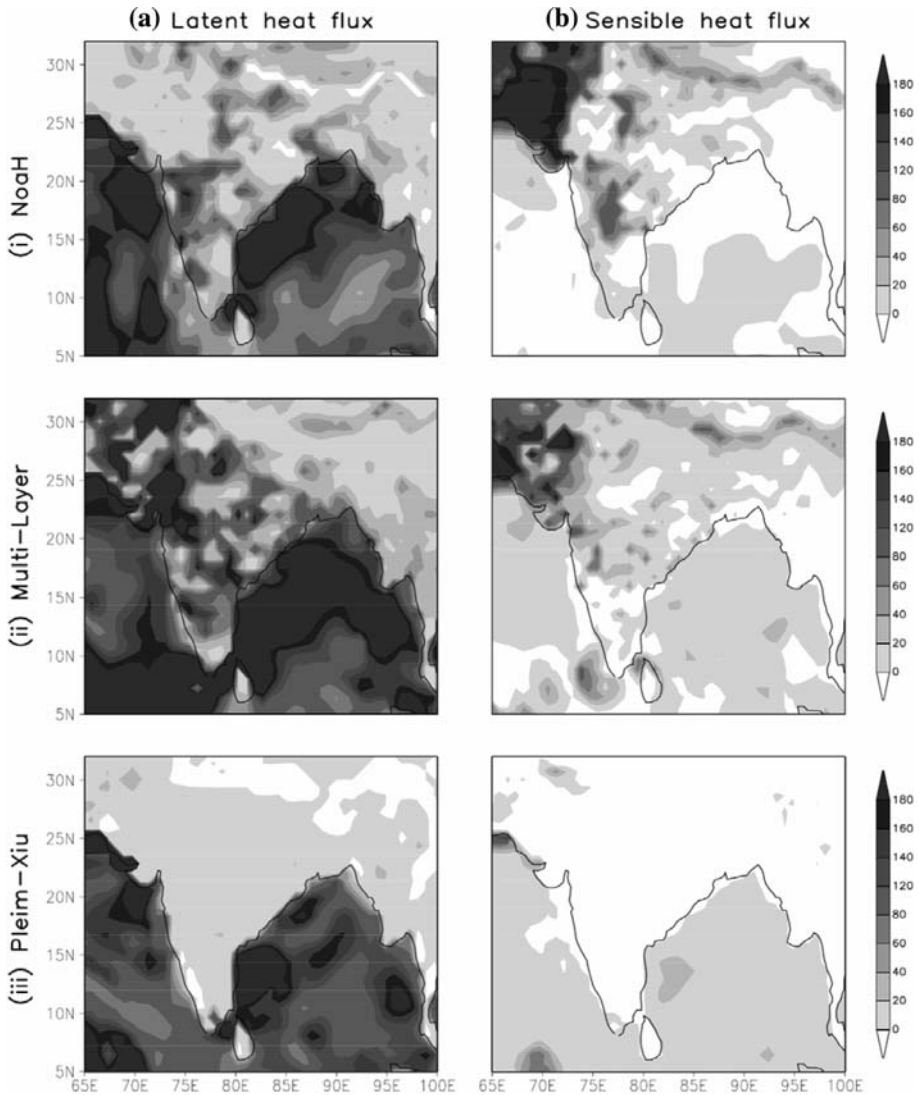


Fig. 6 (a) Monthly mean latent heat and (b) sensible heat fluxes (in W m^{-2}) valid for July 1998 from model simulation using (i) NoH scheme, (ii) ML scheme and (iii) PX scheme

5 Summary and conclusion

Based on the numerical simulation experiments with three LSPSs over the Indian summer monsoon circulation, the following broad conclusions can be drawn:

1. The statistical and dynamical analysis of mean sea level pressure showed that the NoH scheme predicted well the heat low over north west India, the monsoon trough and the Mascarene high
2. Both the lower level westerlies and the upper level easterlies were underestimated by the model for all three types of LSPSs. However, both low-level jet

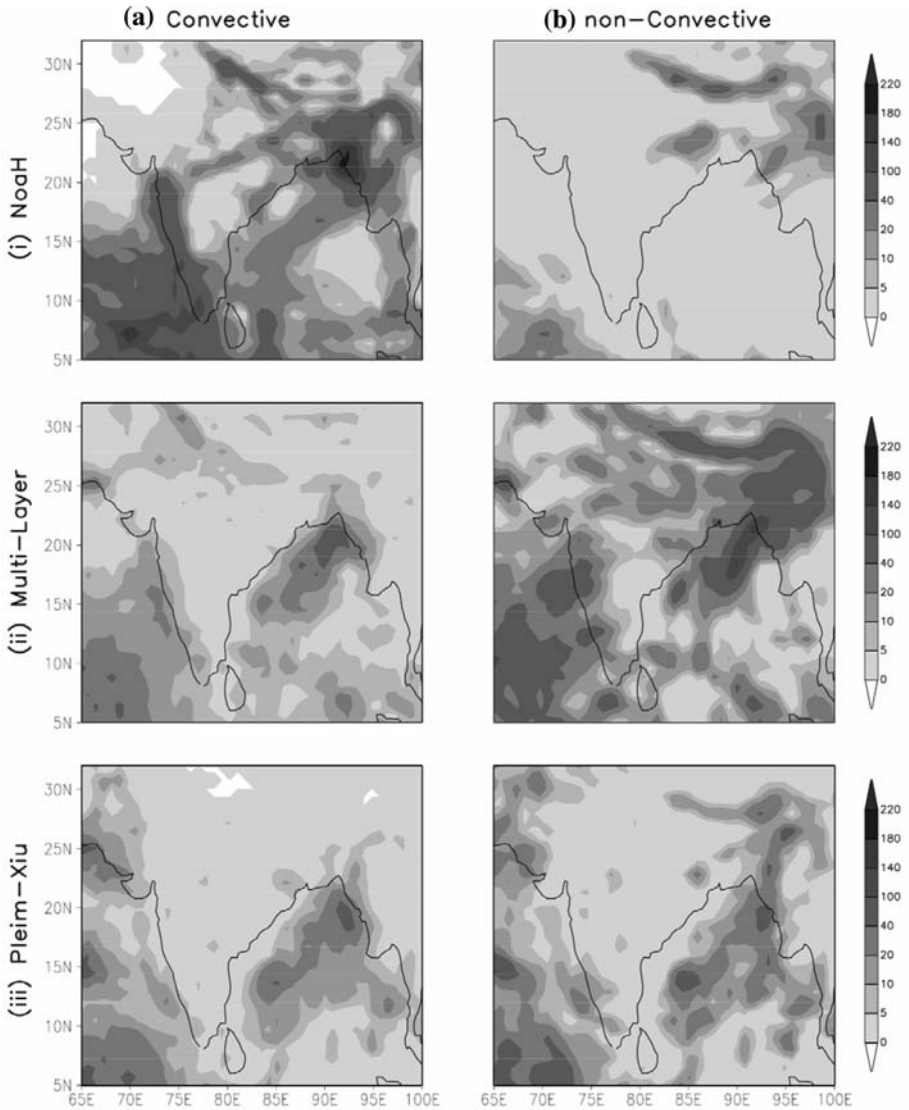


Fig. 7 (a) Convective and (b) non-convective total precipitation (in cm) valid for July 1998 from model simulation using (i) the NoH scheme, (ii) the ML scheme and (iii) the PX scheme

- and upper-level jet were better represented by the NoH scheme. The NoH scheme also better predicted the zonal and meridional winds at each level compared with other schemes
3. The distribution of rainfall and heat fluxes is overestimated in the model simulation over the oceanic region using all three schemes. However, the NoH scheme may be able to capture reasonably the spatial distribution of rainfall over India, including western Ghats, north east India and north west India.

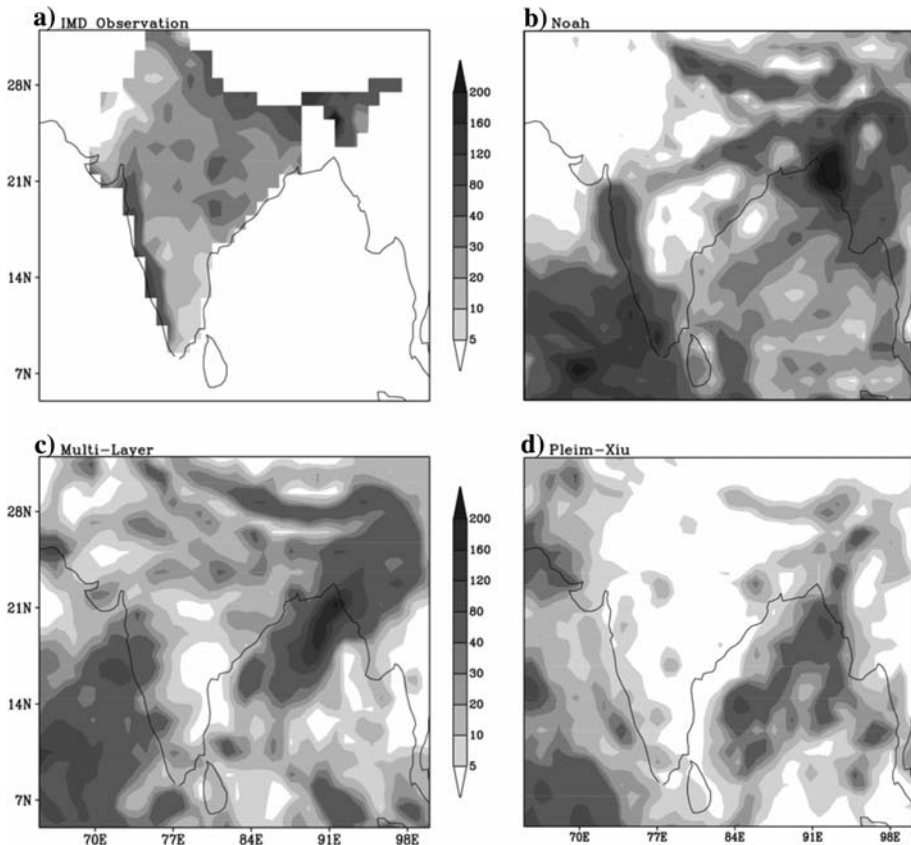


Fig. 8 Total precipitation (in cm) valid for July 1998 from (a) IMD observations, (b) model simulation using the NoH scheme, (c) same as (b) but using the ML scheme and (d) same as (b) but using the PX scheme.

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