METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **21**: 635–643 (2014)
Published online 27 February 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.1386

RMetS
Royal Meteorological Society

Influence of various land surface parameterization schemes on the simulation of Western Disturbances

Liby Thomas,* S. K. Dash and U. C. Mohanty
Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, India

ABSTRACT: Five western disturbances (WDs) are simulated using the National Center for Atmospheric Research (NCAR) Weather Research and Forecasting (WRF) model with different land surface parameterization (LSP) schemes. The LSP schemes used in this study are thermal diffusion, Noah and rapid update cycle (RUC). The spatial distribution and area averaged values of 24 h accumulated rainfall simulated by the model using above LSP schemes are compared with corresponding Tropical Rainfall Measuring Mission (TRMM) observed values. The model simulated rainfall is also compared with those obtained from India Meteorological Department (IMD) station observations. Area averaged root mean square error (RMSE) in rainfall obtained from the three LSP schemes for the five cases are also compared against those in TRMM. Results show that the rainfall obtained using the RUC LSP scheme is closer to the observed values in comparison to those obtained in the thermal diffusion and Noah LSP schemes. It is clear from the results that circulation features and precipitation amounts obtained by the model are sensitive to LSP schemes. Compared to the verification analysis, the wind patterns at 850, 500 and 200 hPa are simulated by the model with reasonable accuracy. The relative humidity and mean sea level pressure are also well simulated by the model when RUC LSP is used.

KEY WORDS Mesoscale model; land surface parameterization (LSP) schemes; western disturbances (WDs); tropical rainfall measuring mission (TRMM); low pressure; rainfall

Received 24 August 2012; Revised 15 November 2012; Accepted 5 December 2012

1. Introduction

The northern states of India such as Jammu and Kashmir, Punjab, Himachal Pradesh, Haryana, Uttarakhand, Northern Rajasthan and Northwest Uttar Pradesh receive rainfall during the winter months, primarily from the Western Disturbances (WDs). So the accurate prediction of rainfall is important for the northern region of India. Today, mesoscale models are found to be very convenient in studying regional weather features in greater detail. Dimri (2004) studied the effect of model resolution and orography in simulating WDs using fifth generation mesoscale model (MM5) and found that simulations with fine horizontal resolution give better results. Further, Rakesh *et al.* (2009) studied the impact of variational assimilation of Moderate-resolution Imaging Spectroradiometer (MODIS) thermodynamic profiles in simulation of WDs using the MM5 model and showed improvements due to data assimilation. Dimri and Mohanty (2009) also carried out a number of studies with the MM5 for the prediction of precipitation associated with WDs.

The mesoscale model Advanced Research WRF (ARW) is used for the first time in this study to simulate and examine the WDs. The ARW model has been successfully used for the simulations of weather phenomena such as thunderstorms (Rajeevan *et al.*, 2010), heavy rainfall events (Chang *et al.*, 2009) and tropical cyclones (Pattanaik and RamaRao, 2009) over the Indian region. Since land surface processes greatly influence the simulation of rainfall and other circulation features, in the present study, different LSP schemes are used for the simulation of WDs using the ARW model. The LSP schemes used here are: the thermal diffusion scheme, the four-layer Noah scheme and the six-layer RUC LSP scheme. The impact of different LSP schemes in simulating Indian summer monsoon circulation was carried out by Singh *et al.* (2007) and they showed that the pattern of rainfall varies with different LSP schemes. There are considerable improvements in the simulation of precipitation and circulation features associated with various weather events over India by the assimilation of different surface parameters such as surface temperature, humidity, soil moisture and surface wind in the MM5 and ARW models (Sandeep and Chandrasekar, 2007; Vinodkumar *et al.*, 2008; Sahu and Dash, 2011).

In this study, five WD events are selected to be simulated by ARW to understand and distinguish the effect of different LSP schemes. The description of ARW model, data and methodology are given in Section 2. Section 3 comprises the synoptic descriptions of the five WDs occurred in north India. The circulation characteristics and rainfall simulated by the model are compared with those observed in Section 4. Section 5 summarizes the important results.

2. Model description and numerical experiments

The NCAR non-hydrostatic model ARW is used in this study. The details of the ARW model are available in Skamarock *et al.* (2008). The centre of the domain of model integration is fixed at the co-ordinates 30° N, 70° E. The model has been configured with 28 vertical levels and has two nested domains

* Correspondence: L. Thomas, Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, Hauz Khas, New Delhi-110016, India. E-mail: liby.thomas@gmail.com

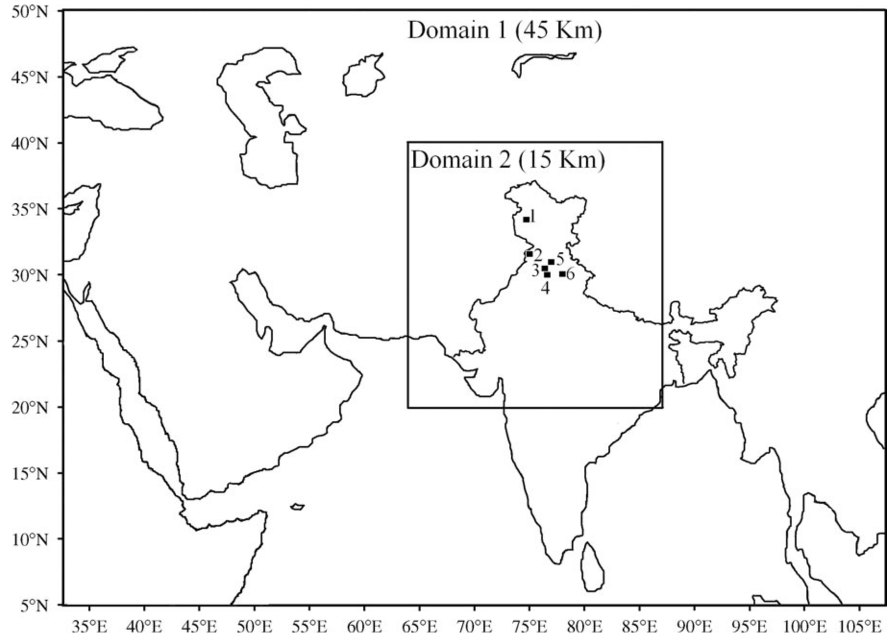

Figure 1. One way nested domains used in ARW simulations with numbers 1, 2, 3, 4, 5 and 6 represent the IMD stations Srinagar, Amritsar, Chandigarh, Ambala, Shimla and Dehradun respectively.

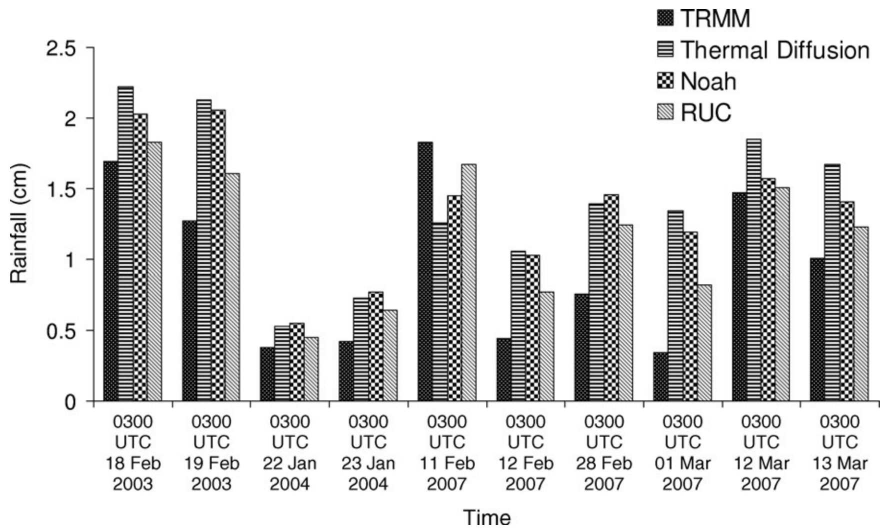

Figure 2. Area (72 ° E to 83 ° E, 27.5 ° N to 38.5 ° N) averaged past 24 h accumulated rainfall valid at 0300 UTC on various days simulated by ARW using three different LSP schemes and corresponding TRMM observed values.

as shown in Figure 1. The outer domain has 45 km resolution with 172×169 grid points and the inner domain has 15 km resolution with 123×163 grid points. The one way nesting is used while integrating the ARW. The outer domain consists of India, Arabian Peninsula, Pakistan, Afghanistan, Iran and Caspian Sea region. The outer domain is selected to capture the circulation features during the passage of WDs. The inner domain consists of north India and Pakistan region. The main objective for the selection of inner domain is to get the accurate spatial distribution of rainfall during the occurrence of WDs. The physical parameterization schemes used in this model run include the Grell Devenyi ensemble scheme (Grell and Devenyi, 2002) for convection, the YSU scheme (Hong *et al.*, 2006) for Planetary Boundary Layer (PBL), the WSM 3-class simple ice scheme (Hong *et al.*, 2004) for microphysics, the RRTM long-wave (Mlawer *et al.*, 1997) and Dudhia short-wave (Dudhia, 1989) for radiation parameterization.

The LSP schemes used are the thermal diffusion scheme (Dudhia, 1996), Noah LSP scheme (Ek *et al.*, 2003) and the RUC LSP scheme (Smirnova *et al.*, 1997, 2000). The thermal diffusion scheme uses soil temperature at five levels. The Noah LSP scheme uses soil temperature and moisture at four levels. It also uses fractional snow cover and frozen soil physics. The RUC LSP scheme uses soil temperature and moisture at six levels along with multi-layer snow and frozen soil physics. The terrain data used are obtained from United States Geological Survey (USGS) with 10 min resolution for the outer domain and 2 min resolution for the inner domain. The National Center for Environmental Prediction (NCEP) Final Analysis (FNL) data with $1^\circ \times 1^\circ$ resolution and 6 h time interval are used

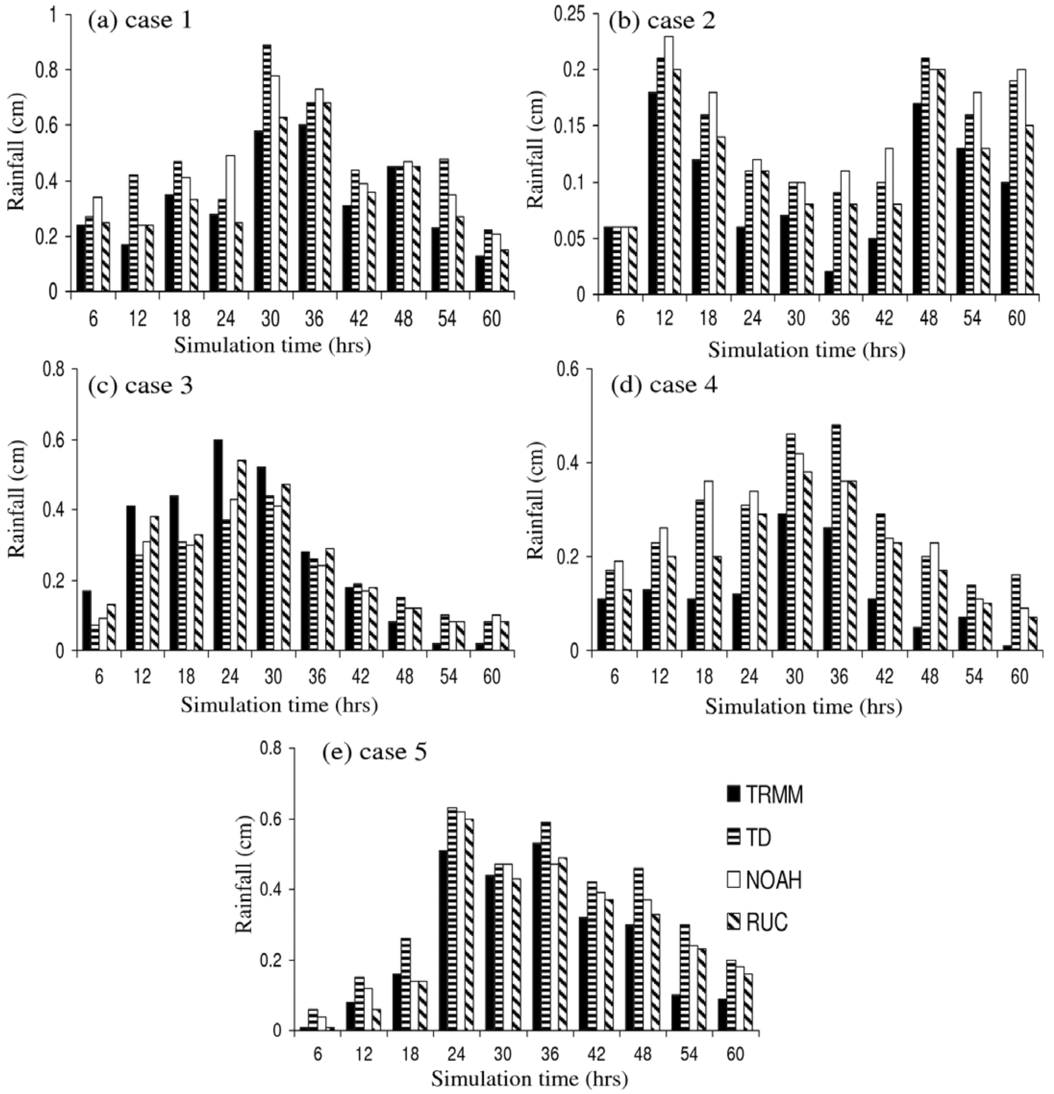

Figure 3. Temporal variation of 6 h accumulated rainfall averaged over the region (72 °E to 83 °E, 27.5 °N to 38.5 °N) for 60 h of model integrations.

to prepare initial and boundary conditions. The configuration of ARW model used in the current study is given in Table 1.

As mentioned earlier, numerical simulations of five selected WDs have been conducted in this study. These cases are selected based on heavy rainfall over northern India. The ARW has been integrated for 60 h in each of the five cases as mentioned below:

Case 1: From 1800 UTC, 16 February to 0600 UTC, 19 February in 2003.

Case 2: From 1800 UTC, 20 January to 0600 UTC, 23 January in 2004.

Case 3: From 1800 UTC, 9 February to 0600 UTC, 12 February in 2007.

Case 4: From 1800 UTC, 26 February to 0600 UTC, 1 March in 2007.

Case 5: From 1800 UTC, 10 March to 0600 UTC, 13 March in 2007.

The rainfall produced from the ARW simulations is compared with TRMM rainfall and IMD (2003, 2004, 2007) recorded rainfall at the selected stations. Variables such as relative humidity, mean sea level pressure and wind patterns (850, 500 and 200 hPa) are compared with the respective NCEP FNL analysis.

3. Synoptic situations during selected Western Disturbances

Based on the information available from IMD (2003, 2004, 2007) daily weather reports, the synoptic situations over the north India and adjoining regions during the five WD events are presented here. Table 2 shows the details of synoptic description associated with above mentioned cases of WDs. The rainfall amounts recorded on these days at some observing stations in the region of study are shown in supporting information Table S1.

In case 1, a cyclonic circulation existed over the western part of Rajasthan on day 1 and the system remained over the same region on day 2. A WD appeared over central Rajasthan

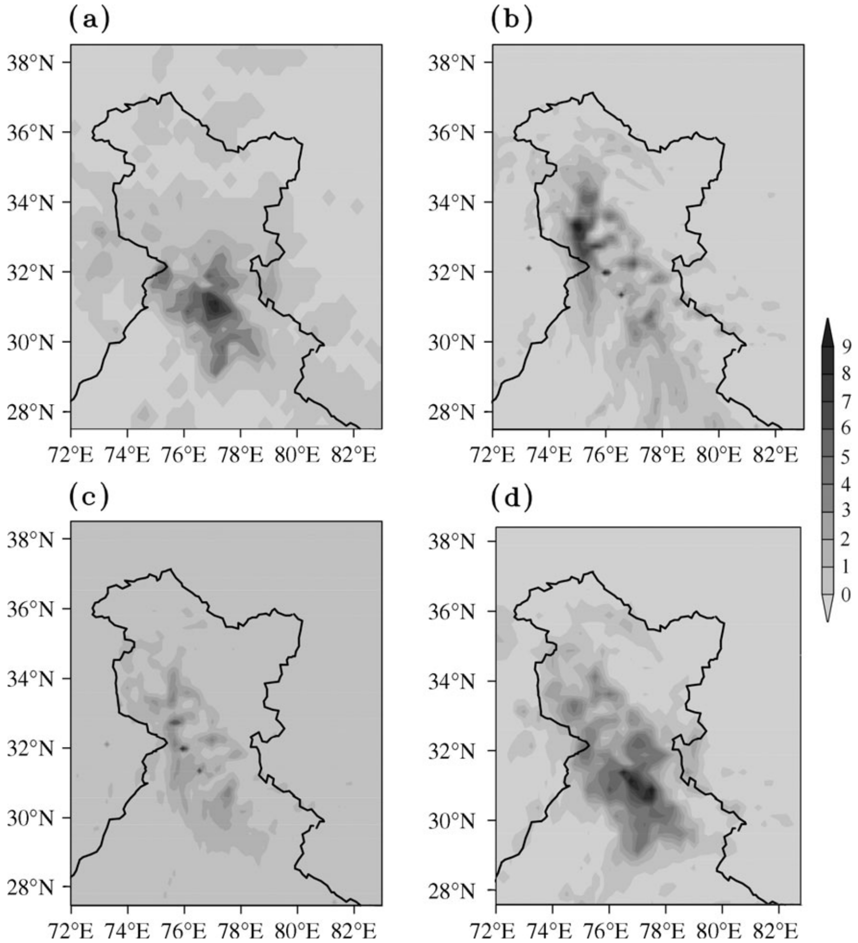

Figure 4. Last 24 h accumulated rainfall (cm) valid at 0300 UTC on 23 January 2004 as (a) observed in TRMM, and ARW simulations using LSP schemes of (b) thermal diffusion, (c) Noah and (d) RUC.

on day 1 and the next day it moved over northern parts of Rajasthan, Punjab and Jammu and Kashmir in case 2. In case 3, the low pressure system associated with WD was visible over central and north Pakistan. The induced cyclonic circulation was formed over south west Rajasthan. On the next day the system moved to west Rajasthan and merged with the induced cyclonic circulation. In case 4, a WD as an upper air system formed over Jammu and Kashmir on day 1 and the induced cyclonic circulation persisted over northwest Rajasthan and adjoining Pakistan. On day 2, the WD remained over Jammu and Kashmir and the induced cyclonic circulation moved to Haryana. In case 5, a cyclonic circulation existed as an upper air system over Jammu and Kashmir and the induced cyclonic circulation formed over Punjab and adjoining northwest Rajasthan on day 1. Both the systems persisted over the same region on day 2.

4. Characteristics of western disturbances simulated by the ARW model

4.1. Rainfall

Comparison of rainfall from model simulations, along with TRMM and IMD observed values at different stations, are discussed in this section. Figure 2 shows the area (72 °E to 83 °E, 27.5 °N to 38.5 °N) averaged past 24 h accumulated rainfall valid at 0300 UTC on various days by model using three LSP schemes and corresponding TRMM observations. In most of the days the area averaged rainfall with thermal diffusion scheme and Noah LSP scheme are overpredicted except at 0300 UTC, 11 February 2007. The comparison also shows that rainfall produced using the Noah and thermal diffusion schemes deviate more from the observed TRMM values over the selected region. Rainfall produced using RUC LSP scheme is close to the TRMM observations in all the days of model integration. Further, the RMSE in area (72 ° to 83 °E, 27.5 ° to 38.5 °N) averaged rainfall obtained using three LSP schemes from five cases against TRMM values are calculated. It shows that the thermal diffusion scheme has the RMSE value of 0.62, the Noah LSP scheme has 0.52 and the RUC LSP scheme has the lowest value of 0.29. The temporal variation of 6 h accumulated rainfall averaged over the region (72 ° to 83 °E, 27.5 ° to 38.5 °N) for 60 h of model integrations for five cases of WDs are given in Figure 3. In all the five cases of model simulations the 6 h accumulated rainfall captured using the RUC LSP is relatively closer to the TRMM observations compared to the other LSP schemes.

The IMD observed past 24 h accumulated rainfall valid at 0300 UTC at various stations (Srinagar, Amritsar, Shimla, Chandigarh, Ambala and Dehradun) and the respective model simulated values for the five cases are shown in supporting information Table S1. On comparison with rainfall recorded at different stations the model is able to capture the rainfall amounts with reasonable accuracy. Rainfall from the supporting

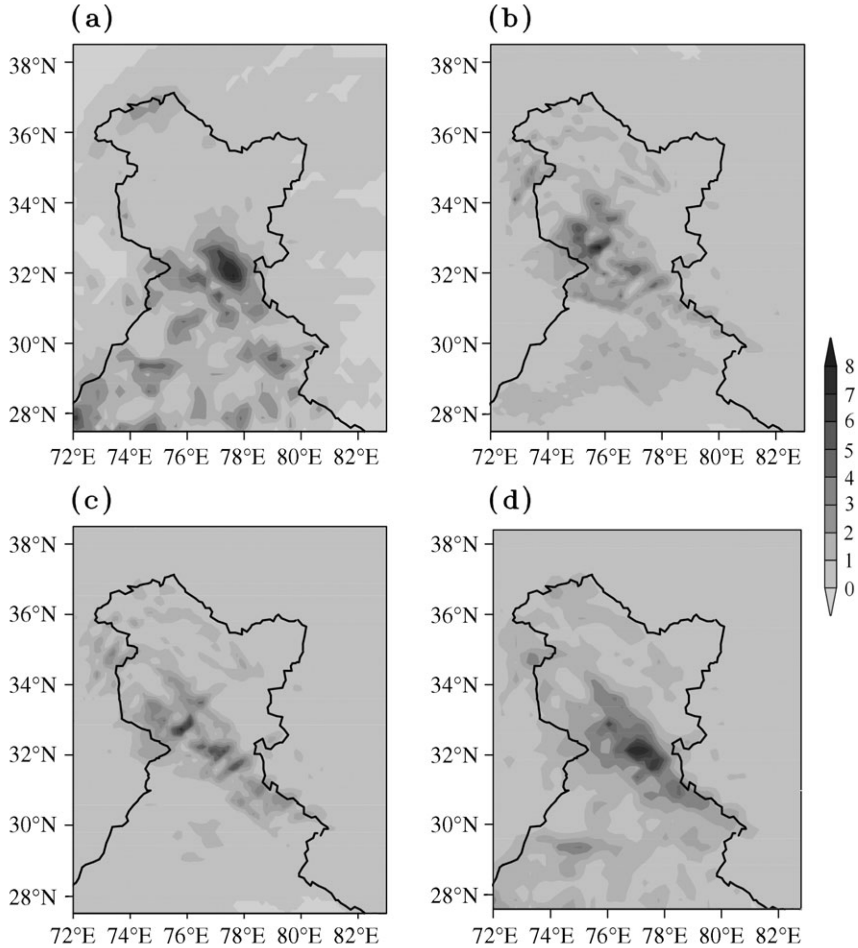

Figure 5. Last 24 h accumulated rainfall (cm) valid at 0300 UTC on 28 February 2007 as (a) observed in TRMM, and ARW simulations using LSP schemes of (b) thermal diffusion, (c) Noah and (d) RUC.

information Table S1 shows that simulated values using RUC LSP scheme is more close to the observed values compared to the other LSP schemes. Table 3 depicts the correlation coefficients (CC) between IMD station observations and corresponding model simulated rainfall using three LSP schemes for the five cases. The RUC LSP scheme gave better CC at all the stations compared to the other two schemes.

The distribution pattern of rainfall from the TRMM data sets and the model simulations are discussed below. The model simulated past 24 h accumulated rainfall valid at 0300 UTC on 23 January 2004 and the corresponding TRMM rainfall amounts are shown in Figure 4. Widespread rainfall is recorded from both TRMM observation and model simulations. The model simulated rainfall amounts are maximum along the Himalayan mountain region with all the three LSP schemes. The region where maximum rainfall occurred from TRMM observation is captured relatively closer to the RUC LSP scheme by the simulation. In the other two schemes, the region where maximum rainfall occurred is shifted northwest to the TRMM rainfall maxima. The past 24 h accumulated rainfall valid at 0300 UTC on 28 February 2007 from the TRMM and corresponding model simulations are shown in Figure 5. The observed rainfall maxima, spatial distribution and intensity of precipitation are better simulated by RUC scheme. There is a change in position of rainfall maxima in simulations using thermal diffusion and Noah schemes. Rainfall is under predicted in the southern areas of the selected region with the thermal diffusion and Noah LSP schemes. Simulations of five selected WDs in ARW model using three different LSP schemes show that RUC scheme produces the spatial distribution of rainfall reasonably accurate compared to the other schemes.

4.2. Circulation features

Some important figures describing the simulated winds at 850, 500 and 200 hPa are presented here along with the FNL verification analysis.

Model simulated winds at 850 hPa and their corresponding FNL analysis on 10 February 2007 are shown in Figure 6. The model produced wind pattern is relatively closer to the FNL analysis. In model simulations and verifying analysis there is a cyclonic flow over the Pakistan, but the circulation is stronger in the model simulations. The anticyclonic flow over the Arabian region, northeast India and north of Afghanistan is well captured by the model. Wind magnitudes are higher in the model simulations, especially in the Himalayan region with a maximum magnitude of 22 m s^{-1}. Figure 7 represents the simulation of the 200 hPa wind pattern on 10 February 2007 and corresponding FNL analysis. Here, the wind patterns from the three model simulations are almost similar to the FNL verification analysis in terms of flow pattern and its intensity. The strength and position of the subtropical jet is also captured by the model at 200 hPa with a maximum wind speed of 72 m s^{-1} between 25°N to 35°N. The pattern of

Table 1. Specifications of ARW used in this study.

Dynamics	non-hydrostatic
Prognostic variables	*u, v, w, T′, P′* and *q*
Centre of the domain	30 °N, 70 °E
Map projection	Mercator
Model resolution	45 km for outer domain and 15 km for inner domain
Number of grids	172, 169 grid points for outer domain and 123, 163 grid points for inner domain
Horizontal grid	Arakawa C-grid
Vertical co-ordinate	Terrain following hydrostatic pressure co-ordinate
Vertical levels	28
Time scheme	Runge–Kutta second and third order time integration schemes
Spatial differencing scheme	Second to sixth order advection options (horizontal and vertical)
Initial conditions	Three dimensional real data (FNL:1° × 1°)
Lateral boundary condition	Three dimensional real data (FNL:1° × 1°)
Radiation parameterization	rrtm long-wave Dudhia short-wave
Cumulus parameterization	Grell Devenyi ensemble scheme
PBL parameterization	YSU scheme
Microphysics	WSM 3-class simple ice scheme
LSP	1. Thermal diffusion scheme 2. Noah LSP scheme 3. RUC LSP scheme

Table 2. Details of synoptic situation associated with five cases of WDs.

Case number	Dates	Maximum height of cyclonic circulation above mean sea level (km)
Case 1	Day 1 (17 February 2003)	2.1
	Day 2 (18 February 2003)	3.6
Case 2	Day 1 (21 January 2003)	3.6
	Day 2 (22 January 2003)	3.6
Case 3	Day 1 (10 February 2007)	4.5
	Day 2 (11 February 2007)	4.5
Case 4	Day 1 (27 February 2007)	2.1
	Day 2 (28 February 2007)	3.0
Case 5	Day 1 (11 March 2007)	3.1
	Day 2 (12 March 2007)	3.1

troughs and ridges is produced in model simulations. The winds from model simulation and verification analysis at 500 hPa on 10 February 2007 show a trough over Pakistan and Afghanistan region (Figure 8). The trough is slightly elongated in all the three model simulations compared to the FNL analysis. The wind magnitude up to 36 m s^{-1} is produced in the simulations and 30 m s^{-1} in the FNL analysis with the maximum wind between 20 °N to 35 °N. The troughs and ridges in the verification analysis are also reproduced in the model simulations.

4.3. Relative humidity

The distribution of relative humidity (%) at 700 hPa on 10 February 2007 from the model simulations with three LSP schemes and the respective verification analysis (FNL) is depicted in Figure 9. The model could produce the magnitude of relative humidity relatively well. The maximum value of relative humidity can be seen in western Himalayan regions and it extends to central India. In the simulation with the Noah and thermal diffusion schemes, the region of high relative humidity did not extend southward over the southern parts of India. The relative humidity pattern in the southwestern part of peninsular India is captured relatively well only when the RUC scheme is used. The maximum value of relative humidity over northern India is 90%.

Table 3. CC between rainfall recorded at IMD stations and ARW simulations using three LSP schemes.

IMD stations	TD	NOAH	RUC
Srinagar	−0.09	0.55	0.81
Amritsar	−0.31	−0.23	0.50
Shimla	0.61	0.68	0.77
Chandigarh	0.11	0.39	0.74
Ambala	0.16	0.48	0.83
Dehradun	0.11	0.12	0.35

4.4. Mean sea level pressure

Mean sea level pressure (hPa) on 10 February 2007 from the ARW simulations and FNL analysis are shown in Figure 10. The region of lowest mean sea level pressure is over Pakistan and northwest India in both the verification analysis and the model simulations. The lowest value mean sea level pressure recorded is 1008 hPa over Pakistan and west Rajasthan. The region of low mean sea level pressure exactly coincides with the region of the WD on 10 February 2007. Simulations with the thermal diffusion, Noah and RUC schemes captured the region of low pressure area similar to the verification analysis. However, the mean sea level pressure is relatively better simulated using RUC LSP scheme especially over the central India, southwestern parts of peninsular India and the Arabian Peninsula, compared with other schemes.

5. Conclusions

In this study, five selected Western Disturbances (WDs) have been simulated with the thermal diffusion, Noah and RUC LSP schemes. The model simulated circulation features and rainfall amounts are compared with respective FNL analysis and TRMM observed rainfall in order to select the best LSP scheme. Results indicate that circulation features and precipitation simulated by the model are sensitive to the selection of LSP schemes. Rainfall is slightly overpredicted by the model in most of the cases. The rainfall averaged over the region encompassing 72 ° to 83 °E to 27.5 ° to 38.5 °N obtained from TRMM data sets are compared with corresponding model simulations. Comparison shows that the spatial distribution and the area averaged rainfall simulated by RUC scheme is close to that obtained from TRMM. Further, the RMSE values of area averaged rainfall using three LSP schemes from the five cases are calculated against corresponding TRMM data. The results show that thermal diffusion has the RMSE value of 0.62, Noah LSP scheme has 0.52 and RUC LSP scheme has the least value of 0.29. The CC between IMD observed rainfall at various stations and corresponding model simulated values obtained

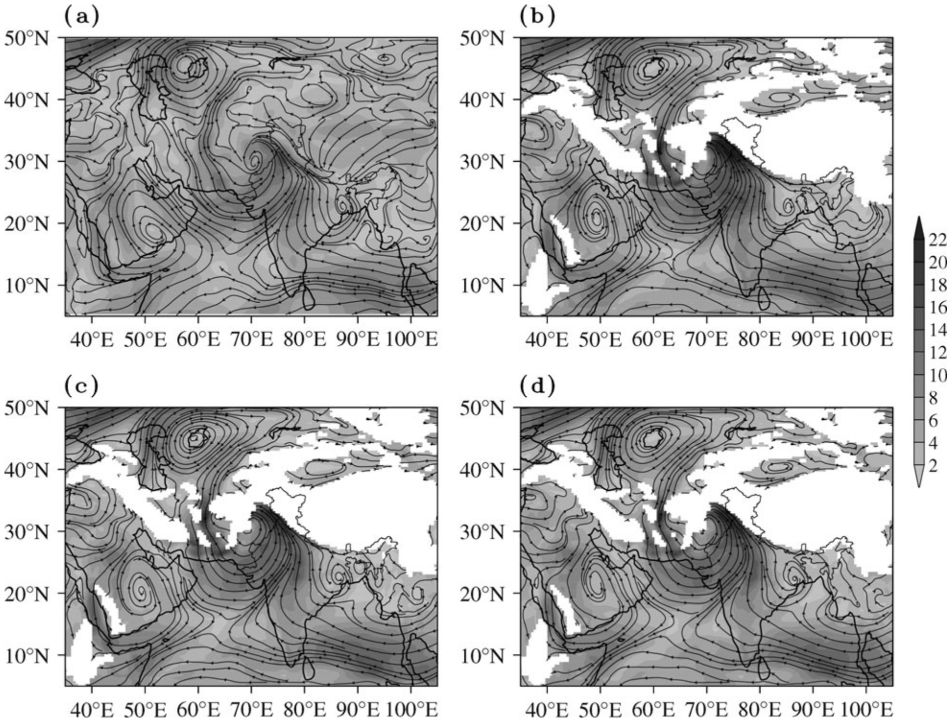

Figure 6. Wind (m s^{-1}) at 850 hPa on 10 February 2007 as (a) observed in verification analysis, and ARW simulations using LSP schemes of (b) thermal diffusion (c) Noah and (d) RUC.

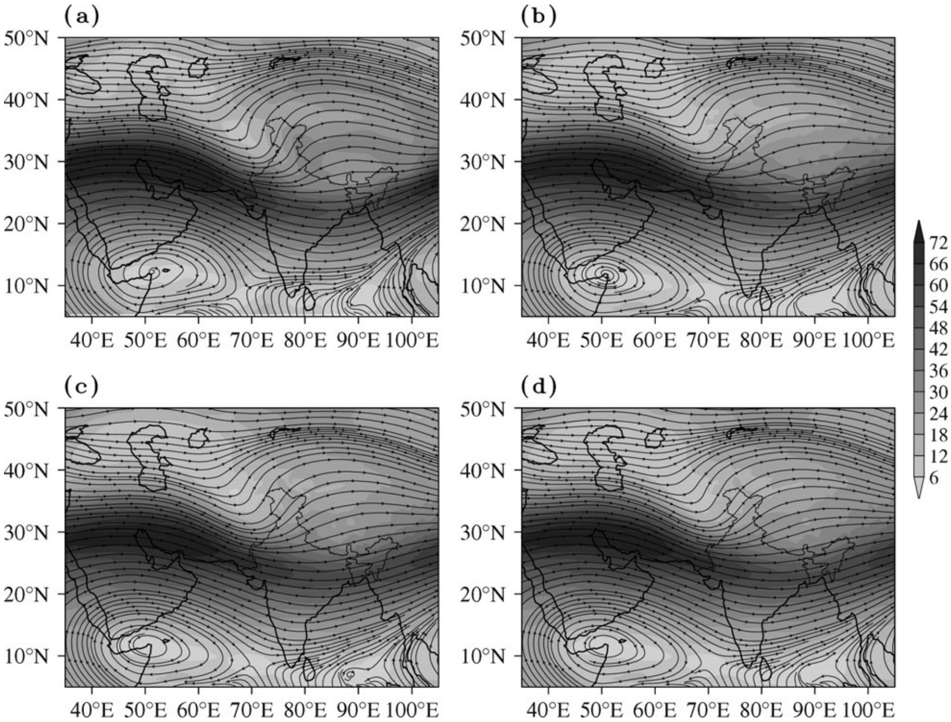

Figure 7. Wind (m s^{-1}) at 200 hPa on 10 February 2007 as (a) observed in verification analysis, and ARW simulations using LSP schemes of (b) thermal diffusion, (c) Noah and (d) RUC.

using three LSP schemes are also compared. Results show that RUC LSP scheme yields higher value of CC at various observing stations compared to those obtained in other schemes. The simulated relative humidity, mean sea level pressure and winds at 850, 500 and 200 hPa are compared with the respective FNL fields. The patterns of relative humidity and mean sea level pressure are captured relatively well in model simulations when RUC scheme is used. The wind magnitudes are found to be stronger compared with the corresponding FNL analysis. In this study it is inferred that amongst the three different LSP schemes available in the ARW model, the RUC LSP scheme is best suited for the simulation of WDs.

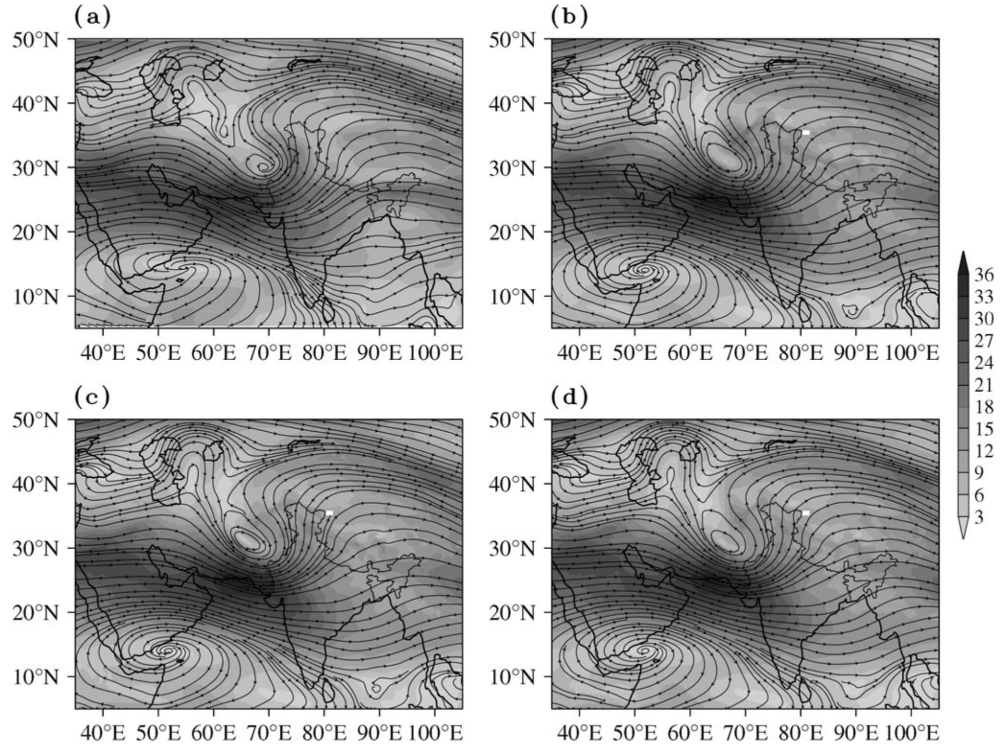

Figure 8. Wind (m s^{-1}) at 500 hPa on 10 February 2007 as (a) observed in verification analysis, and ARW simulations using LSP schemes of (b) thermal diffusion, (c) Noah and (d) RUC.

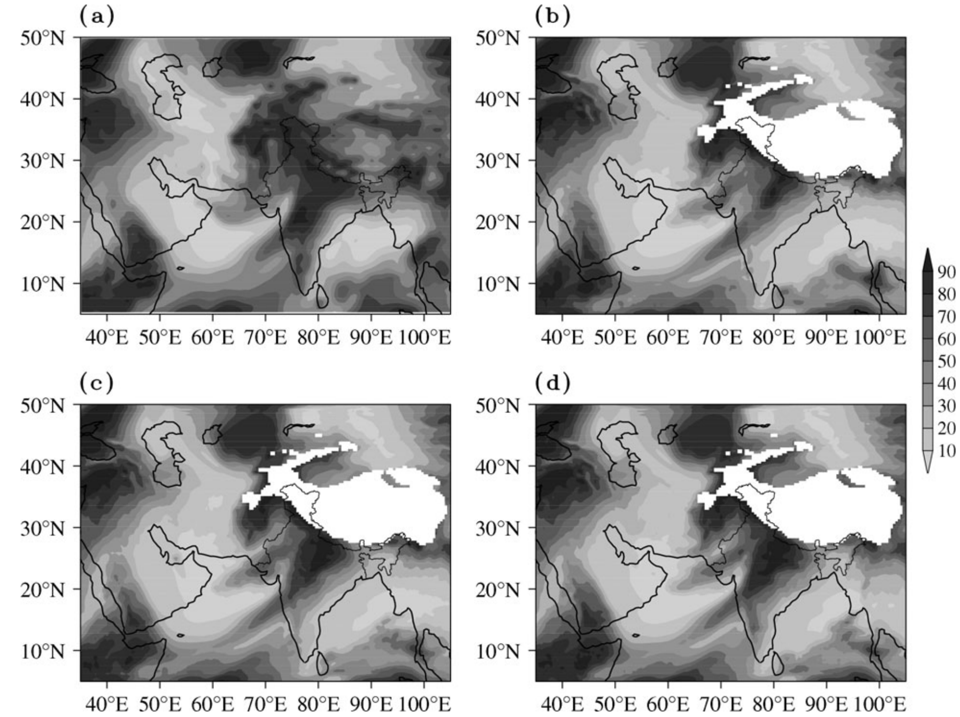

Figure 9. Relative humidity (%) at 700 hPa on 10 February 2007 as (a) observed in verification analysis, and ARW simulations using LSP schemes of (b) thermal diffusion, (c) Noah and (d) RUC.

Acknowledgements

The authors use ARW model of NCAR, FNL data sets from NCEP, daily weather reports of IMD, GrADS software and TRMM data in the present study. Liby Thomas acknowledges the Council of Scientific and Industrial Research (CSIR), Government of India for providing the research assistance to carry out this study.

Supporting information

The following material is available as part of the online article:

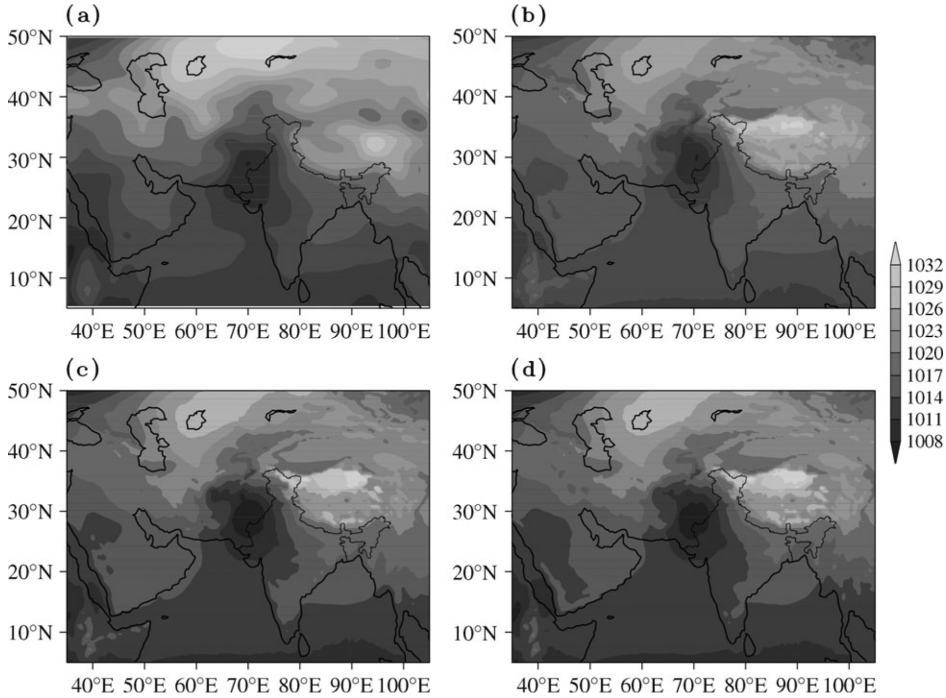

Figure 10. Mean sea level pressure (hPa) on 10 February 2007 as (a) observed in verification analysis, and ARW simulations using LSP schemes of (b) thermal diffusion, (c) Noah and (d) RUC.

Table S1. Comparison of 24 h accumulated rainfall recorded at IMD stations with corresponding model simulated values using three different LSP schemes.

References

Chang H, Kumar A, Niyogi D, Mohanty UC, Chen F, Dudhia J. 2009. The role of land surface processes on the mesoscale simulation of the July 26, 2005 heavy rain event over Mumbai, India. *Glob. Planet. Change* **67**: 87–103.

Dimri AP. 2004. Impact of horizontal model resolution and orography on the simulation of a western disturbance and its associated precipitation. *Meteorol. Appl.* **11**: 115–127.

Dimri AP, Mohanty UC. 2009. Simulation of mesoscale features associated with intense western disturbances over western Himalayas. *Meteorol. Appl.* **16**: 289–308.

Dudhia J. 1989. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two dimensional model. *J. Atmos. Sci.* **46**: 3077–3107.

Dudhia J. 1996. A multi-layer soil temperature model for MM5. *Preprints, 6th Annual MM5 Users Workshop*, Boulder, CO.

Ek MB, Mitchell KE, Lin Y, Rogers E, Grummann P, Koren V, Gayno G, Tarpley JD. 2003. Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta mode. *J. Geophys. Res.* **108**(D22): 8851, 16 pp.

Grell GA, Devenyi D. 2002. A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.* **29**: 1693, 4 pp.

Hong SY, Dudhia J, Chen SH. 2004. A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Weather Rev.* **132**: 103–120.

Hong SY, Noh Y, Dudhia J. 2006. A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Weather Rev.* **134**: 2318–2341.

India Meteorological Department (IMD) 2003. All India daily weather report.

India Meteorological Department (IMD) 2004. All India daily weather report.

India Meteorological Department (IMD) 2007. All India daily weather report.

Mlawer EJ, Taubman SJ, Brown PD, Iacono MJ, Clough SA. 1997. Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the long-wave. *J. Geophys. Res.* **102**: 16663–16682.

Pattanaik DR, RamaRao YV. 2009. Track prediction of very severe cyclone 'Nargis' using high resolution weather research forecasting (WRF) model. *J. Earth Syst. Sci.* **118**: 309–329.

Rajeevan M, Kesarkar A, Thampi SB, Rao TN, Radhakrishna B, Rajasekhar M. 2010. Sensitivity of WRF cloud microphysics to simulations of a severe thunderstorm event over Southeast India. *Ann. Geophys.* **28**: 603–619.

Rakesh V, Singh R, Yuliya D, Pal PK, Joshi PC. 2009. Impact of variational assimilation of MODIS thermodynamic profiles in the simulation of western disturbance. *Int. J. Remote Sens.* **30**: 4867–4887.

Sahu DK, Dash SK. 2011. Assimilation of surface observations in a high resolution WRF model. In *Challenges and Opportunities in Agrometeorology*. Springer-Verlag: Berlin Heidelberg; 83–99, DOI: 10.1007/978-3-642-19360-6_6.

Sandeep S, Chandrasekar A. 2007. Improvements in the forecast of a tropical cyclone by the assimilation of QuikSCAT wind data using a mesoscale model. *J. Mar. Atmos. Res.* **3**: 18–29.

Singh AP, Mohanty UC, Sinha P, Mandal M. 2007. Influence of different land surface processes on Indian summer monsoon circulation. *Nat. Hazard.* **42**: 423–438.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG. 2008. A Description of the Advanced Research WRF. Technical Note TN-475 STR. NCAR: Boulder, CO; 113 pp.

Smirnova TG, Brown JM, Benjamin SG. 1997. Performance of different soil model configurations in simulating ground surface temperature and surface fluxes. *Mon. Weather Rev.* **125**: 1870–1884.

Smirnova TG, Brown JM, Benjamin SG, Kim D. 2000. Parameterization of cold-season processes in the MAPS land-surface scheme. *J. Geophys. Res.* **105**: 4077–4086.

Vinodkumar, Chandrasekar A, Alapaty K, Niyogi D. 2008. The impacts of indirect soil moisture assimilation and direct surface temperature and humidity assimilation on a mesoscale model simulation of an Indian monsoon depression. *J. Appl. Meteorol. Climatol.* **47**: 1393–1412.

