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Prediction of precipitation associated with a western disturbance using a high-resolution regional model: role of parameterisation of physical processes

M Azadi[1], U C Mohanty[2], O P Madan[2] and B Padmanabhamurty[1]
[1] *School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India*
[2] *Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India*

In this study a non-hydrostatic version of the PSU/NCAR mesoscale model is used to simulate an active western disturbance (WD) that affected the Indian region in January 1997. The role of the planetary boundary layer (PBL) and convection parameterisation schemes in the development of the WD is investigated. Analysis and predictions for some fields, including sea level pressure, geopotential height, temperature, horizontal wind and precipitation are examined. Some statistical scores are also calculated and compared. It is found that the performance of the Hong-Pan (as implemented in the NCAR MRF model) and Betts-Miller (or Grell) schemes as PBL and convection parameterisation schemes respectively are best compared to the other schemes used in this study.

1. Introduction

Western disturbances (WDs) are cyclonic vortices in the lower troposphere, whose strength and vertical extent are influenced by the position of mid- and upper-tropospheric troughs in extra-tropical zonal westerlies. They have a key role in affecting the weather over countries such as Iran, Iraq, Afghanistan, Pakistan and India, especially during winter. They generally form over the Mediterranean or the West Atlantic region, with secondaries developing over the Persian Gulf either directly or as a result of the arrival of low pressure systems from south-west Arabia. The systems that approach India between the Caspian Sea and Persian Gulf are without any marked frontal structure at lower levels. From the observed weather pattern it appears that they are in an occluded state. However, after reaching Afghanistan, North Pakistan or Jammu and Kashmir in India, some of them take a north-easterly course and move away without giving any weather.

It is known that tropical systems are mainly driven by the latent heat release in the mesoscale cluster clouds. However, in the mid-latitude synoptic-scale systems, zonal available potential energy associated with the latitudinal temperature gradient is the main source of energy. As pointed out in earlier studies (e.g. Pisharoty & Desai, 1956; Kalsi, 1980; Kalsi & Halder, 1992), WDs are manifestations of the interaction between the tropics and mid-latitude systems and are associated with extensive sheets of mid- and high-level clouds and a maxima in the subtropical jet. Kalsi & Halder (1992) suggest that mobile cloud systems, related to short waves on the subtropical jet, facilitate the interaction between the tropics and mid-latitude systems by amplifying the long-wave troughs, leading to a larger influence of mid-latitude westerlies over subtropical and lower latitudes.

The objective of the present study is to investigate the ability of a high-resolution limited area model to simulate weather systems associated with an active WD that occurred over the Indian region in January 1997. Since further reduction in the uncertainties in numerical weather prediction models and global climate models is largely dependent on a better representation of the complex physical processes, which occur on a smaller scale than the resolution scale of the model, the role of different physical parameterisation schemes incorporated into the model in the development of WD have been examined. To achieve a better representation of the elements, which are closely related to topography, a non-hydrostatic version of a model known as MM5 is used with different convection and planetary boundary layer parameterisation schemes.

The model description follows in section 2, and various numerical experiments and the data sets used are described in sections 3 and 4. Results of the model simulation and analysis maps along with a statistical analysis are presented in section 5. Finally, conclusions are presented in section 6.

2. Model description

The model used in this study is a non-hydrostatic version of the MM5 modelling system developed at Penn State University/National Center for Atmospheric Research (PSU/NCAR) Dudhia et al. (1998). MM5 is a limited area, hydrostatic or non-hydrostatic model that uses the terrain-following sigma coordinate in the vertical. In the non-hydrostatic version of the model, a reference-state pressure instead of pressure is used to define the sigma coordinate. A constant reference-state and a perturbation form are defined as:

$$p(x,y,z,t) = p_o(z) + p'(x,y,z,t)$$

$$T(x,y,z,t) = T_o(z) + T'(x,y,z,t)$$

where p and T are pressure and temperature, and subscript o and prime represent the reference-state and perturbation. The temperature profile for the reference-state is based on an idealised hydrostatic equilibrium. It is specified by the following equation:

$$T_o = T_{so} + A\ln\left(\frac{p_o}{p_{oo}}\right) \tag{1}$$

where, p_{oo} is sea-level pressure taken to be 1000 mb, T_{so} is the reference temperature at p_{oo} taken to be 280 K, and A is a measure of lapse rate taken to be 50 K, representing the temperature difference between p_{oo} and p_{oo}/e = 367.88 mb. The vertical coordinate is then defined as:

$$\sigma = \frac{p - p_t}{p_s - p_t}$$

where, p_s and p_t are surface pressure and pressure at the top of the model (50 mb in this study) for the reference-state. The reference-state surface pressure, which depends only on the terrain height, can be derived from equation (1) using the hydrostatic relation:

$$T_o = T_{so} + Z = -\frac{RA}{2g}\left(\ln\frac{p_o}{p_{oo}}\right)^2 - \frac{RT_{so}}{g}\left(\ln\frac{p_o}{p_{oo}}\right)$$

This equation is quadratic in p_o and can be solved if the terrain height, Z, is known. The reference pressure of the model sigma levels are then calculated as:

$$p = (p_s - p_t)\sigma + p_t$$

In the non-hydrostatic model perturbation pressure p' is a predicted quantity.

The primitive hydrostatic/non-hydrostatic model equations in the terrain-following sigma coordinate system are written in flux form and solved on an Arakawa B grid using a time splitting scheme. In this method, time 2Dt from (n–1)Dt to (n+1)Dt is divided into a number of smaller time steps and slowly varying terms are integrated in time with longer time steps, while terms responsible for acoustic waves are integrated with shorter time steps. A second-order centred difference scheme is used for spatial finite differencing. In order to damp the sub-grid advective processes, a fourth-order diffusion is used but this is modified to second-order near the boundaries. For a full description of the model formulation, refer to the model description document (Grell *et al.*, 1994).

An important feature of MM5 is its flexibility as many options can be specified by the user. These include the number of nests, type of convection scheme and planetary boundary layer parameterisation scheme and some other options. A brief description of the model configuration used in this study is given in Table 1.

3. Numerical experiments

A series of eight experiments for producing 48-hour forecasts are carried out using the following PBL and convection schemes:

- two PBL schemes: Blackadar and Hong-Pan as implemented in the NCEP MRF model, hereafter referred to as B and M respectively;
- four convection schemes: Kuo, Grell, Kain-Fritsch and Betts-Miller, hereafter referred to as KU, GR, KF and BM respectively.

A short description of the schemes along with references is given in the MM5 description document (Grell *et al.*, 1994). Experiments with the Blackadar scheme for PBL processes and KU, GR, KF and BM schemes for convection are referred to as experiments B-KU, B-GR, B-KF and B-BM respectively. Similarly, experiments using the MRF scheme for PBL and KU, GR, KF and BM schemes for cumulus parameterisation are referred to as M-KU, M-GR, M-KF and M-BM respectively.

For verification of the model outputs, some variables (including sea level pressure, geopotential height, horizontal and vertical wind velocity and relative humidity at 850, 700, 500, 300 and 200 mb) are compared against a reanalysed data set provided by the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) when interpolated to the same resolution as the model output. For the sake of brevity only some important figures showing sea level pressure, geopotential height at 850, 500 and 200 mb, horizontal wind vector at 200 mb and precipitation forecasts are presented here. Precipitation forecasts are compared with 24-hour station reports issued by the India Meteorological Department (IMD). Some statistical scores, including root mean square error (RMSE) and bias, are calculated at six-hour intervals for all the mentioned variables. The formulae used

Table 1. *Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5), version 2.12*

Dynamics	Non-hydrostatic with three-dimensional Coriolis force
Main prognostic variables	u, v, w, T, p' and q
Map projection	Lambert conformal mapping
Central point of the domain	38° N, 68° W
Number of horizontal grid points	165, 105 grid points for x, y respectively
Horizontal grid distance	60 km
Number of vertical levels	23 half sigma levels (full sigma levels are: 1, 0.99, 0.98, 0.96, 0.93, 0.89, 0.85, 0.8, 0.75, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, 0.1, .05, 0.0)
Horizontal grid system	Arakawa B grid
Time integration scheme	Time-splitting
Lateral boundary conditions	Nudging toward the NCEP/NCAR reanalysis
Radiation scheme	Cloud radiation scheme with radiation frequency of 30 minutes
Planetary boundary layer parameterisation schemes	1. Blackadar 2. Hong-Pan as implemented in the NCEP MRF model. It includes vertical diffusion in the stable atmosphere and moist vertical diffusion in clouds.
Cumulus parameterisation schemes	1. Kuo 2. Grell 3. Kain-Fritsch 4. Betts-Miller
Microphysics	Explicit scheme of Reisner (mixed phase)
Soil model	Multi-layer soil model

for calculating the statistical scores are given in the Appendix.

4. Data used and synoptic features

Earlier studies have generally adopted a synoptic approach and suffer from the lack of adequate surface and upper-air data over the region. Recently some studies (Mohanty *et al.*, 1998, 1999) have been conducted using reanalysed global data sets, which reasonably generate accurate large-scale circulation features over the data-sparse regions. In the present study initial conditions for the model are extracted from NCEP/NCAR reanalyses and interpolated to the model domain in Mercator projection by the auxiliary programs provided in the MM5 modelling system. Generally reanalysis data sets should be used as the first guess in the objective analysis process to enhance them, and more importantly interpolation by itself cannot reproduce small-scale features, which have already been smoothed out in the large-scale reanalyses. To overcome this problem at the outset, six-hour nudging is performed. In this way, at the end of the nudging the small-scale features are generated by the model physics and at the same time they are consistent with the large-scale data set used as initial conditions. The boundary layer variables are excluded from nudging towards the observations. Results of some experiments with different cases (not presented here) show that this kind of data assimilation is necessary if the large-scale reanalyses are to be used as the initial conditions.

It is to be noted that model output is in the Mercator projection. In order to be able to compare the results against the observations, all variables have been back interpolated to the spherical coordinate, and the horizontal wind has been rotated accordingly. The effect of this extra back interpolation from map projection to spherical coordinate leads to a little smoothing of the field, which is negligible.

5. Results and discussions

The 0000 UTC reanalysis of sea level pressure for 18 and 19 January 1997 is given in Figure 1. On 18 January, one WD appears over Iran and Afghanistan with central pressure of 1005 mb. On the following day an induced low pressure appears over Pakistan and adjoining Rajasthan with a central pressure of 1008 mb, the main WD having moved north-east towards Jammu and Kashmir. On 20 January the induced low-pressure area lies over Punjab and adjoining areas and becomes unimportant on 21 January 1997 (figures not presented). Widespread precipitation has been reported from stations in Jammu and Kashmir, Himachal Pradesh, Punjab and hills of west Uttar Pradesh from 0300 UTC on 19 January to 0300 UTC on 21 January.

5.1. 24-hour forecasts for all experiments

Figures 2 depicts the 24-hour forecast of sea level pressure for 19 January 1997 for the eight experiments, as mentioned in section 3. The model predictions of sea level pressure of these experiments are compared with the NCEP/NCAR reanalysis data sets (Figure 1(*b*)). In all these experiments, the sea level pressure simulation is reasonably good, but some noise is seen over the Himalayan region. This could be attributed to possible

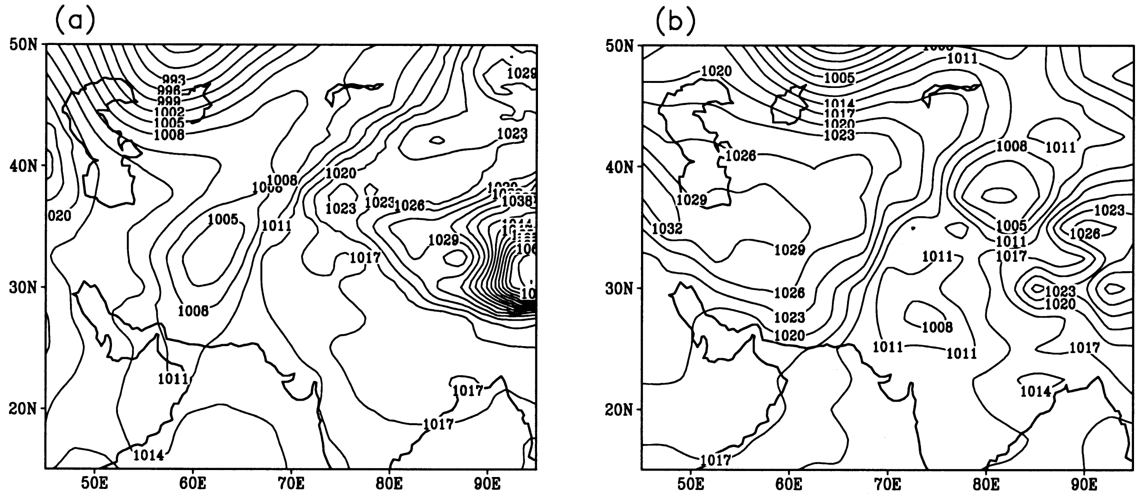

Figure 1. *Reanalysis of sea level pressure at 0000 UTC on (a) 18 January and (b) 19 January 1997.*

errors in converting the model simulated surface pressure to sea level pressure over steep orography.

It has been noticed that the predicted position of the induced low pressure with the M-BR experiment (Figure 2(*b*)) is 73.5° E, 29.8° N which is closer to the position of the system as seen in the reanalysis map (Figure 1(*b*)) at 73.7° E, 27.8° N compared to the other experiments.

Figure 3 shows the 24-hour accumulated precipitation, measured at 0300 UTC on 20 January, obtained from the India Meteorological Department (IMD) charts for the region between 74°E–80°E and 27°N–35°N. Maximum precipitation of 10.5 cm is located close to Batote in Jammu and Kashmir at about 33°N and 75.2°E. Figure 4 shows the 24-hour accumulated precipitation prediction for 20 January, in the eight experiments, for the same region as in Figure 3.

Comparing Figures 3 and 4 shows that the precipitation maxima are better predicted in experiment B-GR which has a value of 8 cm. In experiments B-KU, B-KF, B-BM, M-KF and M-BM maximum value of precipitation is 6 cm and in experiments M-KU and M-GR the maximum is 7 cm. In terms of the location of the precipitation maxima, all experiments are more or less similar. Some part of the precipitation field associated with the WD is large-scale precipitation; as expected this part is predicted well in the simulation. But some part of the precipitation is orographically induced in which small-scale features have an important effect. These features such as the channelling effect cannot be resolved by the model resolution. Hence generation of the small-scale features of the precipitation field could not be simulated.

5.2. Statistical scores

Figures 5(*a*) and 5(*b*) give the root mean square error (RMSE) calculated at 6-hour intervals for geopotential height at 700 and 200 mb. Figures 5(*c*) and 5(*d*) show the RMSE for temperature at 850 and 700 mb. Bias for temperature at 850 mb and geopotential height at 700 mb are also given in Figures 5(*e*) and 5(*f*). In order to avoid too many curves in the figures, statistical scores are plotted only for experiments M-BM, M-KF, B-KU and B-GR. It is clear from these figures that experiment M-BM gives better statistical results. Examination of all the statistical scores calculated for geopotential height, temperature, horizontal wind and relative humidity at some pressure levels and sea level pressure (not shown here) reveal that changing the PBL scheme has a larger effect in the prediction than changing the convection scheme. In general, the MRF scheme gives better results than the Blackadar scheme for this case. Also, the experiment with BM or GR as the convection scheme and MRF as the PBL scheme tends to be superior to the other configurations.

Wang & Seaman (1997) conducted a comparative study using MM5 and the same four cumulus parameterisation schemes as used in this study. They ran the model for six precipitation events over the continental United States for both cold and warm seasons. They examined the performance of the schemes by calculating threat and bias skill scores for precipitation. They also examined the precipitation, sea level pressure, wind and temperature fields against the analysis. Their results show that the forecast skill of the model was fairly good in predicting four out of the six cases considered. The forecast skill was better for the cold seasons than for the warm season events. The KF scheme gave better results than other schemes. As they point out, part of the precipitation forecast errors are not related directly to the convection scheme in the model, but it could be associated with the uncertainties in the model's initial conditions. Some errors may be due to the deficiencies in the internal model components, or coupling of a convection scheme with other model physics.

It is to be noted that statistical scores are sometimes confusing, and sometimes contradictory. Also, because

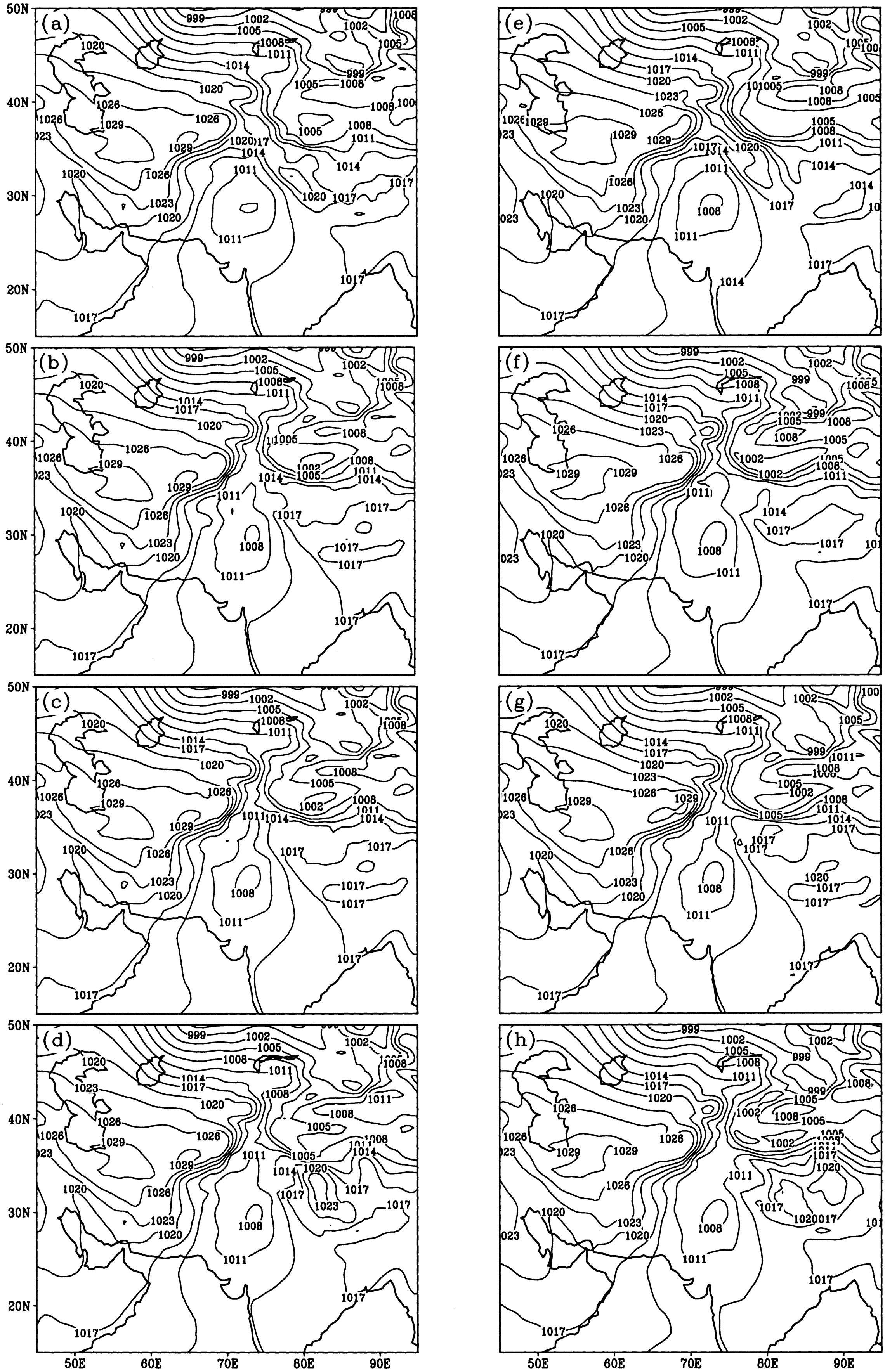

Figure 2. *24-hour forecast of sea level pressure valid at 0000 UTC on 19 January 1997. (a) Experiment B-KU. (b) Experiment B-GR. (c) Experiment B-KF. (d) Experiment B-BM. (e) Experiment M-KU. (f) Experiment M-GR. (g) Experiment M-KF. (h) Experiment M-BM.*

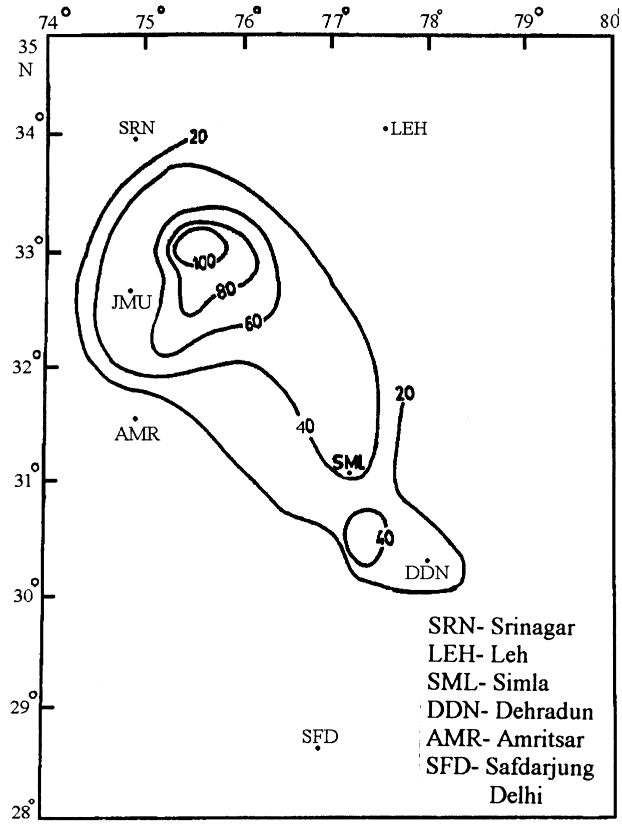

Figure 3. *Analysis of 24-hour accumulated precipitation (mm) measured at 0300 UTC on 20 January 1997.*

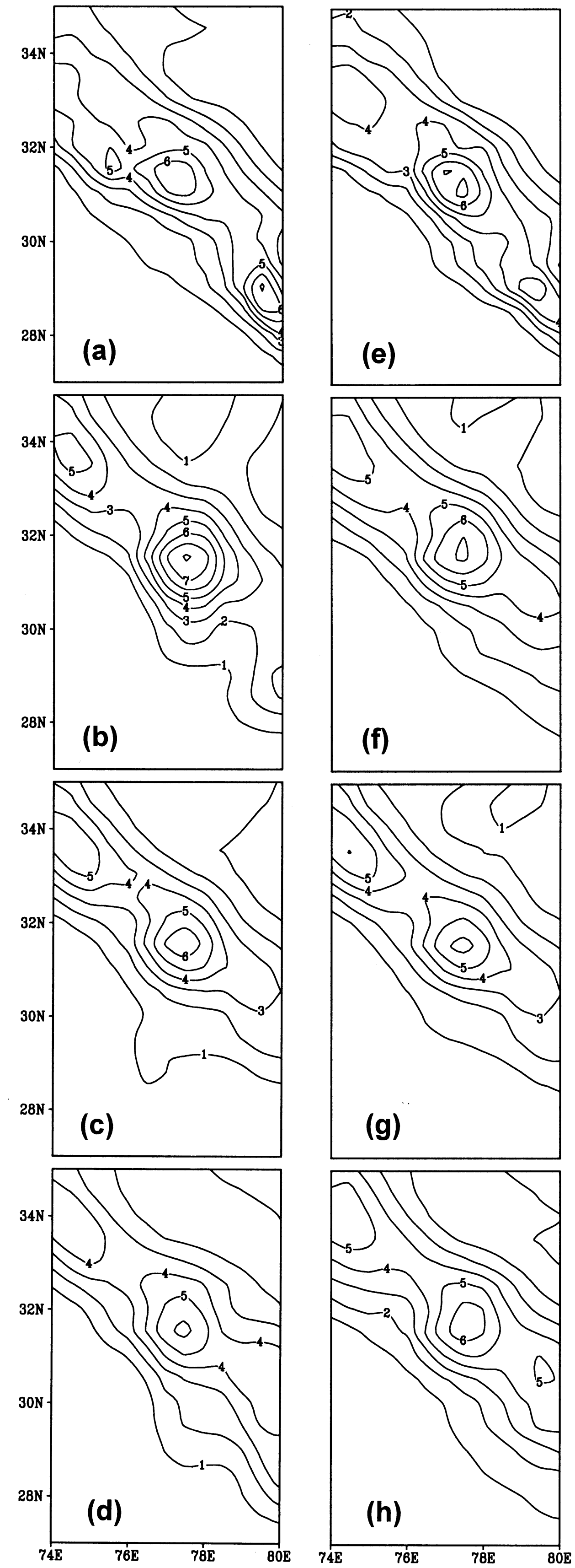

Figure 4. *Forecast of accumulated precipitation between 19 and 20 January 1997 at 0000 UTC (calculated from 48-hour forecast). Panels (a) to (h) refer to the eight experiments as in Figure 2.*

of the space or time shifting of the pattern, statistical scores may be misleading. So statistical scores should not be considered in isolation, and on the basis of small differences between them one cannot simply come to a conclusion about the performance of the schemes. For example, as shown in Figure 5(*f*), the differences between the scores are small. But in this study it is seen that M-BM (or M-GR) experiment performance is almost always better than the other configurations of the model, and hence acceptance of this configuration is more or less justified.

Also, Figure 5 shows that sometimes RMSE decreases with time. This kind of behaviour in the evolution of scores is seen in similar studies conducted earlier (Wang & Seaman, 1997). It may be due to the precipitation spin-up of the model.

5.3. Further results from the M-BM experiment

It is seen that experiment M-BM (or M-GR), namely MRF and Betts-Miller (or Grell) schemes for PBL and cumulus parameterisation respectively, consistently gives better results. Thus, in the rest of the paper only experiment M-BM is considered.

Figure 6 represents 24-hour and 48-hour forecasts of 850-mb geopotential height and their corresponding verification analysis. The location of the forecast low

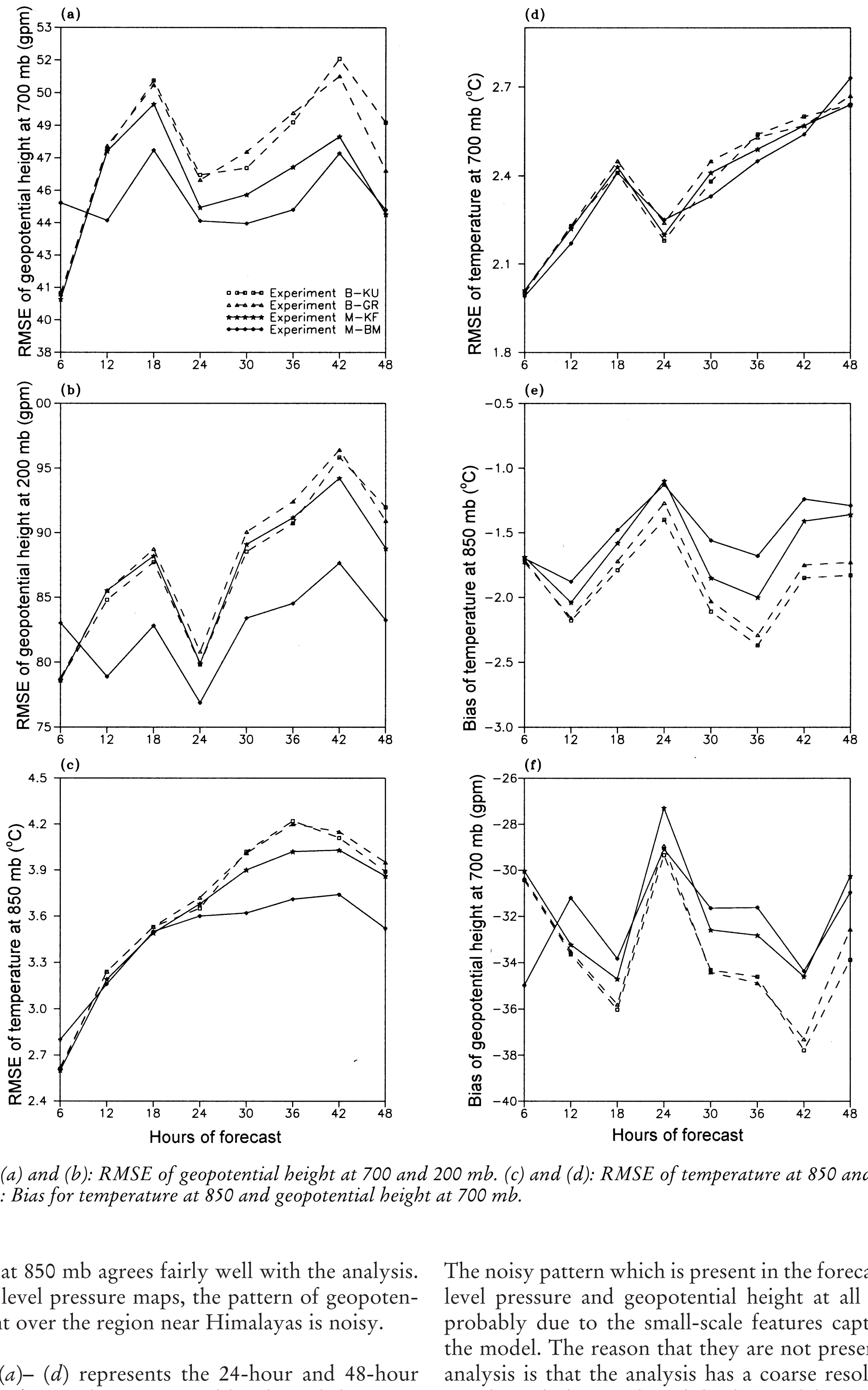

Figure 5. *(a) and (b): RMSE of geopotential height at 700 and 200 mb. (c) and (d): RMSE of temperature at 850 and 700 mb. (e) and (f): Bias for temperature at 850 and geopotential height at 700 mb.*

pressure at 850 mb agrees fairly well with the analysis. Like sea level pressure maps, the pattern of geopotential height over the region near Himalayas is noisy.

Figure 7(*a*)– (*d*) represents the 24-hour and 48-hour forecasts of 500-mb geopotential height and their corresponding verifying analyses. The location and intensity of the main upper-level trough is fairly well represented in both the forecasts. The splitting of the upper trough over the north Indian region has also been brought out in the 48-hour forecast.

The noisy pattern which is present in the forecast of sea level pressure and geopotential height at all levels is probably due to the small-scale features captured by the model. The reason that they are not present in the analysis is that the analysis has a coarse resolution of 2.5° latitude/longitude, while the model resolution is 60 km, which is almost 0.5°. Figures 7(*e*) and 7(*f*) show the 24-hour and 48-hour forecast of 500-mb geopotential height, but interpolated to the same resolution as the analysis, namely 2.5°. It is seen that small-scale features are completely smoothed out and the

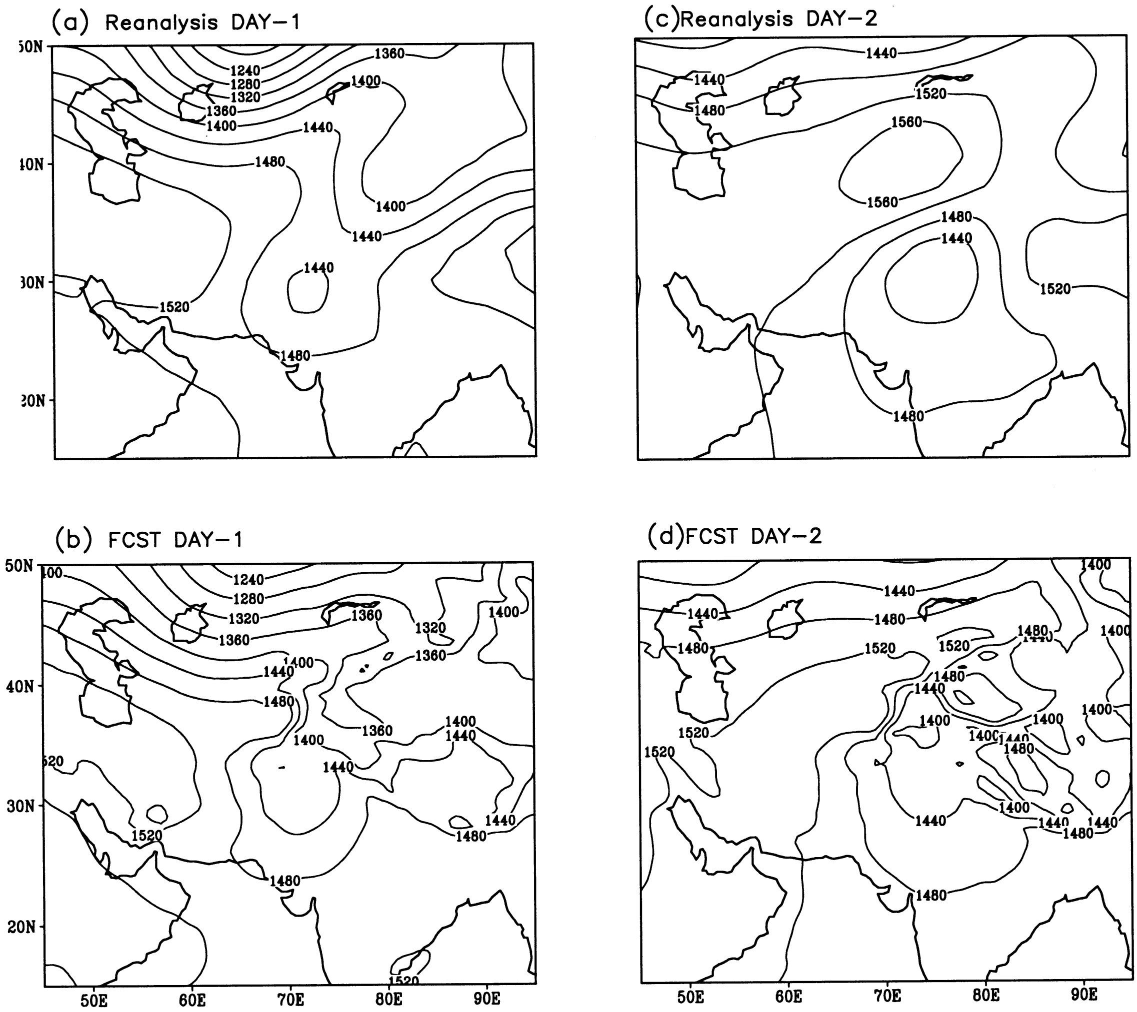

Figure 6. *Forecast and verification reanalysis of 850 mb geopotential height (all at 0000 UTC) in the M-BM experiment. (a) Reanalysis on 19 January 1997. (b) 24-hour forecast valid at 19 January 1997. (c) Reanalysis on 20 January 1997. (d) 48-hour forecast valid at 20 January 1997.*

geopotential prediction is more similar to the verifying analysis.

6. Conclusions

In this paper we present the results of numerical simulation of an active WD case, using version 2.12 of the PSU/NCAR mesoscale model known as the MM5 modelling system. The following conclusions are drawn from this study:

- results of the experiment presented in this paper and similar experiments (not shown here) show that the model is reasonably successful in simulating the development/evolution of the WDs in 48-hour forecast; and
- the model is sensitive to different physical parameterisation schemes. It is revealed that the type of the PBL processes scheme used has a larger effect on the simulation results than the convection schemes and also that the combination of MRF and BM (or Grell) for PBL and convection schemes respectively gives consistently better results than other configurations.

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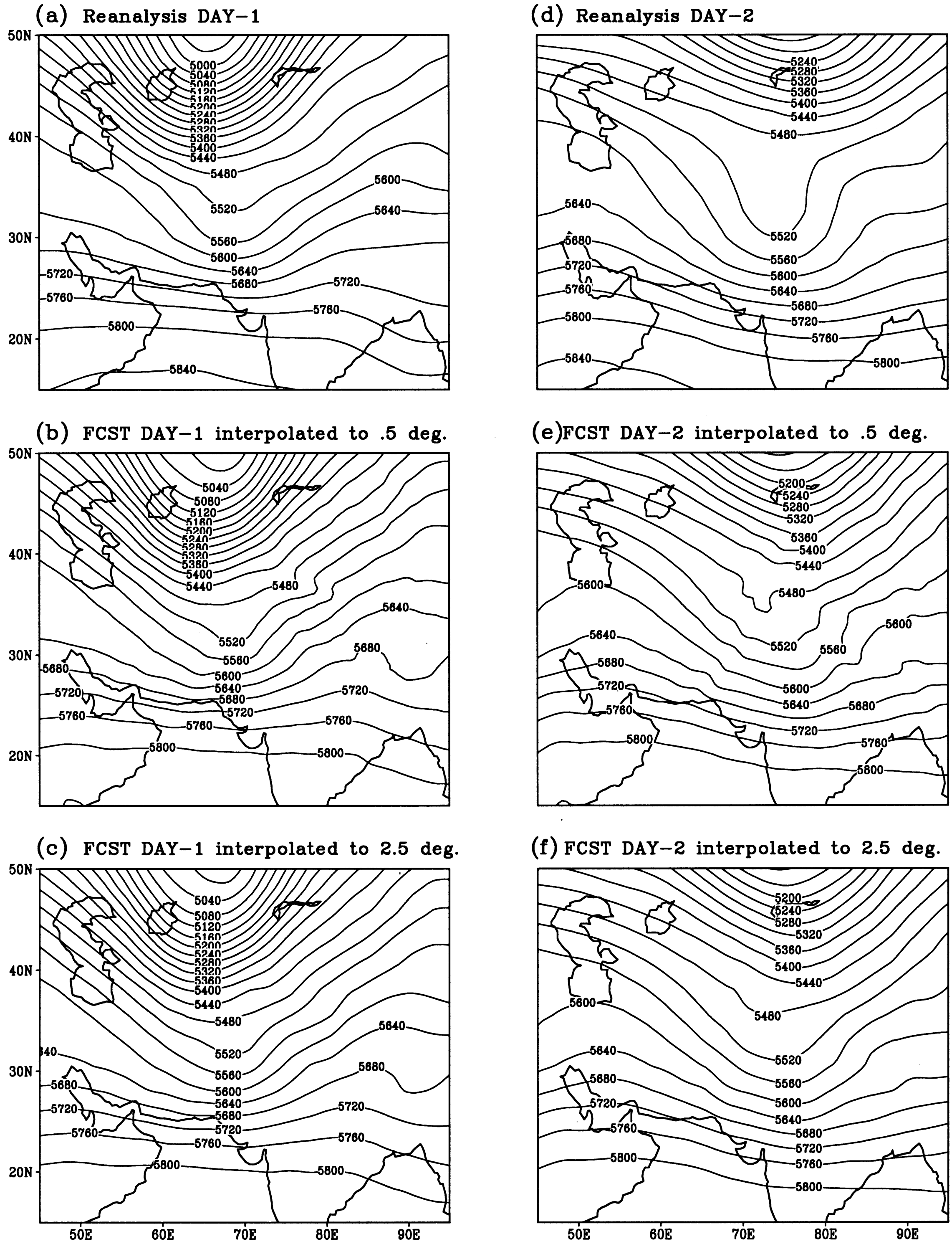

Figure 7. *Verification reanalysis and forecast of 500 mb geopotential height (all at 0000 UTC for M-BM experiment). (a) Reanalysis on 19 January 1997. (b) 24-hour forecast valid at 19 January 1997, interpolated to 0.5°. (c) 24-hour forecast valid at 19 January 1997, interpolated to 2.5°. (d) Reanalysis on 20 January 1997. (e) 48-hour forecast valid at 20 January 1997, interpolated to 0.5°. (f) 48-hour forecast valid at 20 January 1997, interpolated to 2.5°.*

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