

Numerical study of western disturbances over western Himalayas using mesoscale model

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सार – भारतीय क्षेत्र में शीत ऋतु के दौरान पश्चिमी विक्षोभों (डब्ल्यू.डी.) की महत्वपूर्ण विशेषताओं को प्रतिरूपित करने के लिए पेन स्टेट यूनिवर्सिटी-नेशनल सेन्टर फॉर एटमोस्फेरिक रिसर्च (पी.एस.यू.-एन.सी.ए.आर.) संयुक्त राज्य अमरीका के गैर जल स्थैतिक रूपान्तर के तौर पर मेसोस्केल मॉडल (एम. एम. 5) का उपयोग किया गया है।

इस अध्ययन में दो ग्रहीय परिसीमा स्तर पद्धतियों नामतः-ब्लैकादर एवं हॉग-पैन तथा चार संवहन प्राचलीकरण पद्धतियों नामतः कुओ, ग्रेल, कैनफ्रिश एवं बेट्स-मिल्लर के 60 कि. मी. के क्षैतिज विभेदन मॉडल का उपयोग करके आठ सुग्राहिता प्रयोग किए गए हैं। इसमें क्षैतिज विभेदन मॉडल तथा स्थलाकृति के महत्व के दो कारकों-30 कि.मी., 60 कि.मी. एवं 90 कि. मी. के क्षैतिज विभेदन मॉडल जिसमें एक स्थिति में स्थलाकृति पर विचार नहीं किया गया है तथा दूसरी में सामान्य स्थलाकृति पर विचार किया गया है, के आधार पर छः प्रयोग करके अध्ययन किया गया है। इस अध्ययन के लिए दो सक्रिय पश्चिमी विक्षोभों का चयन किया गया है जिसके कारण पश्चिमी हिमालय क्षेत्र में भारी वृष्टि हुई। प्रथम अध्ययन के लिए 18 जनवरी से 21 जनवरी, 1997 तक की अवधि के दौरान के पश्चिमी विक्षोभ का चयन किया गया है तथा दूसरे प्रयोग के लिए 20 जनवरी से 25 जनवरी, 1999 की अवधि के दौरान के पश्चिमी विक्षोभ का चयन किया गया है। इसमें आरंभिक तथा सीमांत स्थितियों के लिए नेशनल सेन्टर फॉर इन्वाइरॉनमेंट प्रिडिक्शन-नेशनल सेन्टर फॉर एटमोस्फेरिक रिसर्च (एन. सी. इ. पी.-एन. सी. ए. आर.) संयुक्त राज्य अमरीका द्वारा पुनर्विश्लेषित आंकड़ों का उपयोग किया गया है।

इस अध्ययन से यह पता चला है कि हॉग-पैन और बेट्स मिल्लर की क्रमशः ग्रहीय परिसीमा स्तर तथा मेघ संवहन प्राचलीकरण पद्धति के संयोजन का प्रदर्शन उपयोग की गई अन्य संयोजन पद्धतियों के तुलना में सबसे अच्छा रहा है। आदर्श भौतिकी (मॉडल फिजिक्स) अन्य संयोजन पद्धतियों की तुलना में इस संयोजन के द्वारा समुद्र तल का दाब ज्यादा सही प्रतिरूपित करने में सक्षम रही है। इसके अलावा स्थलाकृति रहित क्षेत्र में पश्चिमी विक्षोभ का प्रतिरूपण सामान्य स्थलाकृति में प्रतिरूपित पश्चिमी विक्षोभ की तुलना में कम वर्षा की मात्रा को दर्शाता है। जब इसमें सामान्य स्थलाकृति को शामिल किया गया तो हिमालय क्षेत्र के आस-पास भारी वर्षा हुई। वर्षा के क्षेत्रों के एकीकृत मॉडल सत्यापित विश्लेषण के अनुरूप पाए गए हैं। वर्षा क्षेत्रों के सुग्राहिता अध्ययन से पता चला है कि छोटे प्रभाव-क्षेत्र (30 कि.मी.) के प्रतिरूपित मॉडल अच्छे परिणाम देते हैं।

ABSTRACT. A non-hydrostatic version of the Penn State University - National Center for Atmospheric Research (PSU-NCAR), US, Mesoscale Model (MM5) is used to simulate the characteristic features of the Western Disturbances (WDs) occurred over the Indian region during winter.

In the present study sensitivity eight experiments are carried out by using two planetary boundary layer schemes, viz., Blackadar and Hong-Pan, and four convection parameterization schemes, viz., Kuo, Grell, Kain-Fristch and Betts-Miller, with 60 km horizontal model resolution. And also the role of horizontal model resolution and topography is studied by carrying out six experiments based on two factors: horizontal model resolution of 30 km, 60 km and 90 km with assumed no topography and normal topography. For this study two active WDs are chosen which yielded extensive precipitation over western Himalayas. WD from 18 to 21 January 1997 is chosen for study one and WD from 20 to 25 January 1999 is chosen for experiment two. National Center for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR), US, reanalyzed data is used for initial and boundary conditions.

It is found that the performance of combination of the Hong-Pan and Betts-Miller as planetary boundary layer and cloud convection parameterization schemes respectively is best compared to the other combinations of schemes used in this study. The model physics could able to simulate sea level pressure better with this combination as compared to the

combinations with other schemes. Further, WD simulations with assumed no topography shows lesser amount of precipitation compared to WD simulations with normal topography. When normal topography is included, intense localized of precipitation was observed along the Himalayan range. Model integrations of precipitation fields are found close to the corresponding verification analysis. Sensitivity studies of precipitation field shows that finer domain (30 km) of the model simulation gives better results.

Key words – Numerical weather prediction, Western disturbance, Horizontal resolution.

1. Introduction

During winter, the western Himalayan region of India receives large amount of precipitation in the form of snow due to western disturbance (WDs). WDs are low pressure systems observed in the midlatitude westerlies over the subtropical region of Asia or Middle East countries. They are observed to move from west to east in all seasons, but are most prominent over Himalayas during winter months of December to March. At times, these weather systems bring calamities in the form of snowstorms and avalanches in the winter months. In order to take some preventive measures to mitigate these adverse effects of weather systems, it is essential that they be predicted as accurately as possible. This is particularly useful for organizations where men and machines are employed to operate in open, *viz.*, for defense force, agriculture, tourism, transport etc. Also, the knowledge of future state of weather associated with an intense WD helps in prediction of cold wave conditions, avalanche release, critical human comfort index, state of snow and frost which is of use to many people at large.

Earlier studies (Pisharoti and Desai, 1956, Kalsi, 1980 and Kalsi and Haldar, 1992) have mentioned that interaction between the tropics and mid latitude systems are associated with extensive sheets of mid and high levels of clouds and maxima in the subtropical jet. Kalsi and Haldar (1992) suggested that mobile cloud systems are related to short waves in the subtropical jet and facilitate the interaction between the tropics and mid latitude systems by amplifying the long wave troughs leading to a large influence of mid latitude westerlies over the subtropics and lower latitudes. Thus, WD is an interesting weather system of mid latitude that is modulated by tropical air mass and the Himalayas.

Further, high resolution limited area models have been successfully used for both the simulation and the prediction of regional and local mesoscale weather events. (Anthes *et al.*, 1989). The success of the model depends upon initial state and lateral boundary conditions of the model domain. Second, horizontal model resolution is an integral and essential issue while simulating weather system on regional and global scale model for prediction. Giorgi and Marinucci (1996) while studying the sensitivity of simulated precipitation to model resolution

and its implication for climate studies found that precipitation amounts do vary with model resolution. Wind fields for the same region get changed when horizontal grid dimension is changed (Kallos and Kassomenos, 1994). Krishnamurty's (1990) global forecasts using high resolution spectral model show substantial improvements in the prediction results.

The objective is to study experiment (i) Role of planetary boundary layer and cloud convection parameterization scheme : eight experiments are carried out by using two planetary boundary layer schemes, *viz.*, Blackadar and Hong-Pan, and four convection parameterization schemes, *viz.*, Kuo, Grell, Kain-Fristch and Betts-Miller with 60 km horizontal model resolution and (ii) Role of horizontal model resolution and topography on simulated meteorological fields : six experiments are conducted with two factors : horizontal model resolution of 30 km, 60 km and 90 km with normal topography and assumed no topography. These two experiments are carried out by using nonhydrostatic version of PSU-NCAR mesoscale model (MM5) to simulated active WDs. Though numbers of case studies are carried out, in present study case pertaining to two active WDs from 18 to 21 January 1997 (for Case I) and from 20 to 25 January 1999 (for Case II) are presented.

In the present study, section 2 presents brief description of the model configuration. Section 3 illustrates data used and numerical experiments. Section 4 illustrates synoptic situations of the two WDs considered for the study. Results are discussed in section 5. Main conclusions are presented in section 6.

2. Model description

MM5 modeling system, developed by Anthes and Warner (1978) at Penn State University-National Center for Atmospheric Research (PSU-NCAR), US, is used for numerical prediction of the WD. MM5 is a limited area, hydrostatic or non-hydrostatic model that uses terrain-following sigma coordinate in the vertical. In this study non – hydrostatic version of the model is used (Dudhia, 1993, Dudhia, *et al.*, 1998, Grell *et al.*, 1994).

In non-hydrostatic version of the model, the meteorological fields are separated into constant reference

state and perturbation state. A constant reference and perturbation states are defined as

$$p(x, y, z, t) = p_0(Z) + p'(x, y, z, t)$$

$$T(x, y, z, t) = T_0(Z) + T'(x, y, z, t)$$

$$\rho(x, y, z, t) = \rho_0(Z) + \rho'(x, y, z, t)$$

The reference state pressure instead of pressure is used to define the sigma coordinate.

$$\sigma = \frac{p_0 - p_t}{p_s - p_t}$$

where p_s and p_t are surface pressure and pressure at the top of the model (50 hPa in this study) for the reference-state. The reference pressure of the model sigma levels are then calculated as

$$p = p^* \sigma + p_t + p'$$

where, $p^*(x, y) = p_s(x, y) - p_t$.

In terrain following sigma coordinate system (x, y, σ) , basic prognostic equations in pressure weighted flux form are given below.

Horizontal momentum equations

$$\begin{aligned} \frac{\partial p^* u}{\partial t} = & -m^2 \left[\frac{\partial p^* uu/m}{\partial x} + \frac{\partial p^* vu/m}{\partial y} \right] \\ & - \frac{\partial p^* u \dot{\sigma}}{\partial \sigma} + u \text{DIV} - \frac{mp^*}{\rho} \left[\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial x} \frac{\partial p'}{\partial \sigma} \right] \\ & + p^* fv + Du \end{aligned}$$

$$\begin{aligned} \frac{\partial p^* v}{\partial t} = & -m^2 \left[\frac{\partial p^* uv/m}{\partial x} + \frac{\partial p^* vv/m}{\partial y} \right] \\ & - \frac{\partial p^* v \dot{\sigma}}{\partial \sigma} + v \text{DIV} - \frac{mp^*}{\rho} \left[\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial y} \frac{\partial p'}{\partial \sigma} \right] \\ & + p^* fu + Dv \end{aligned}$$

Vertical momentum equation

$$\begin{aligned} \frac{\partial p^* w}{\partial t} = & -m^2 \left[\frac{\partial p^* uw/m}{\partial x} + \frac{\partial p^* vw/m}{\partial y} \right] \\ & - \frac{\partial p^* w \dot{\sigma}}{\partial \sigma} + w \text{DIV} + p^* g \frac{\rho_0}{\rho} \left[\frac{1}{p^*} \frac{\partial p'}{\partial \sigma} + \frac{T'v}{T} - \frac{T_0 p'}{T p_0} \right] \\ & - p^* g [(q_c + q_r)] + Dw \end{aligned}$$

Pressure

$$\begin{aligned} \frac{\partial p^* p'}{\partial t} = & -m^2 \left[\frac{\partial p^* up'/m}{\partial x} + \frac{\partial p^* vp'/m}{\partial y} \right] - \frac{\partial p^* p' \dot{\sigma}}{\partial \sigma} + p' \text{DIV} \\ & - m^2 p^* \gamma p \left[\frac{\partial u/m}{\partial x} - \frac{\sigma}{mp^*} \frac{\partial p^*}{\partial x} \frac{\partial u}{\partial \sigma} + \frac{\partial v/m}{\partial y} - \frac{\sigma}{mp^*} \frac{\partial p^*}{\partial y} \frac{\partial v}{\partial \sigma} \right] \\ & + \rho_0 g \gamma p \frac{\partial w}{\partial \sigma} + p^* \rho_0 g w \end{aligned}$$

Temperature

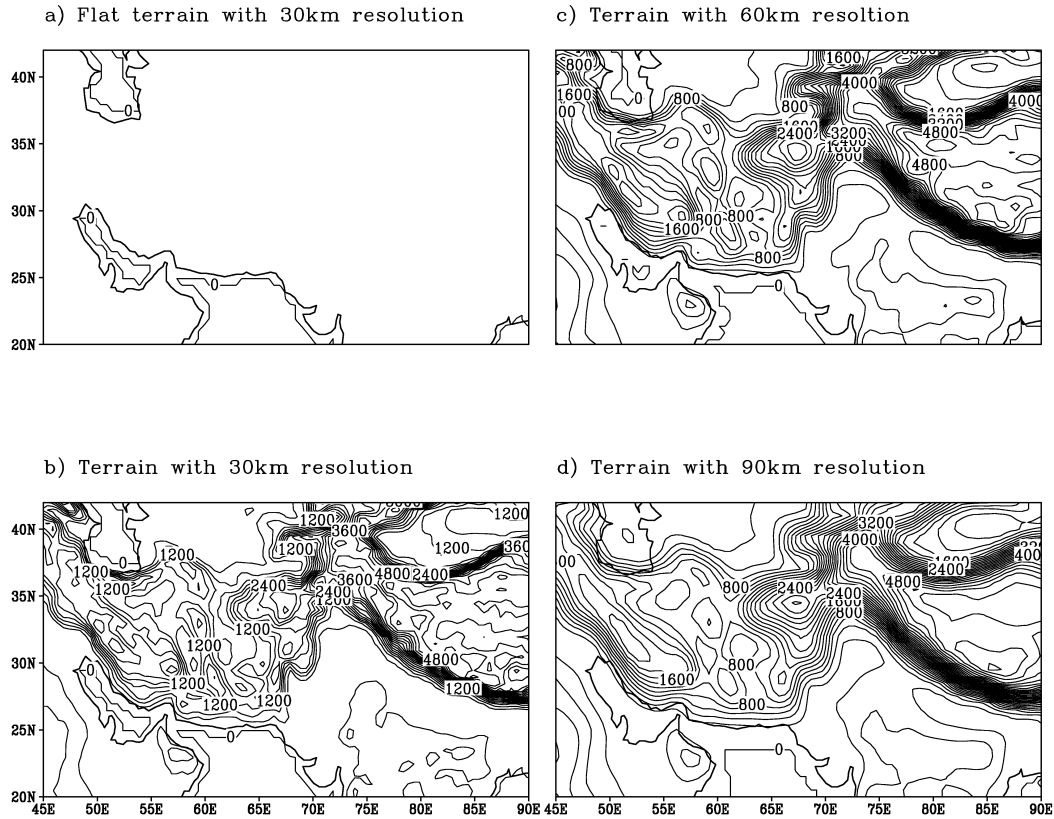
$$\begin{aligned} \frac{\partial p^* T}{\partial t} = & -m^2 \left[\frac{\partial p^* uT/m}{\partial x} + \frac{\partial p^* vT/m}{\partial y} \right] - \frac{\partial p^* T \dot{\sigma}}{\partial \sigma} + T \text{DIV} \\ & + \frac{1}{\rho c_p} \left[p^* \frac{Dp'}{Dt} - \rho_0 g p^* w - D_{p'} \right] + p^* \frac{\dot{Q}}{c_p} + D_T \end{aligned}$$

Water vapor (q_v), cloud water (q_c) and rain water (q_r) are given by the following :

$$\begin{aligned} \frac{\partial p^* q_v}{\partial t} = & -m^2 \left[\frac{\partial p^* uq_v/m}{\partial x} + \frac{\partial p^* vq_v/m}{\partial y} \right] - \frac{\partial p^* q_v \dot{\sigma}}{\partial \sigma} \\ & + q_v \text{DIV} + p^* (-P_{RE} - P_{CON} - P_{II} - P_{ID}) + D_{q_v} \end{aligned}$$

$$\begin{aligned} \frac{\partial p^* q_c}{\partial t} = & -m^2 \left[\frac{\partial p^* uq_c/m}{\partial x} + \frac{\partial p^* vq_c/m}{\partial y} \right] - \frac{\partial p^* q_c \dot{\sigma}}{\partial \sigma} \\ & + q_c \text{DIV} + p^* (P_{ID} + P_{II} - P_{RC} - P_{RA} + P_{CON}) + D_{q_c} \end{aligned}$$

$$\begin{aligned} \frac{\partial p^* q_r}{\partial t} = & -m^2 \left[\frac{\partial p^* uq_r/m}{\partial x} + \frac{\partial p^* vq_r/m}{\partial y} \right] - \frac{\partial p^* q_r \dot{\sigma}}{\partial \sigma} \\ & + q_r \text{DIV} - \frac{\partial V_f \rho g q_r}{\partial \sigma} + p^* (P_{RE} + P_{RC} + P_{RA}) + D_{q_r} \end{aligned}$$



Figs. 1(a-d). Topography with different horizontal model resolution and with flat topography

where

$$\text{DIV} = m^2 \left[\frac{\partial p^* u/m}{\partial x} + \frac{\partial p^* v/m}{\partial y} \right] + \frac{\partial p^* \dot{\sigma}}{\partial \sigma}$$

$$\text{and } \dot{\sigma} = -\frac{\rho_0 g}{p^*} w - \frac{m\sigma}{p^*} \frac{\partial p^*}{\partial x} u - \frac{m\sigma}{p^*} \frac{\partial p^*}{\partial y} v$$

where u , v and w represent three components of the velocity vector, T is the temperature, p is the pressure, and m is the map scale factor. Subscript 0 and superscript prime represent reference-state and perturbation respectively, and other symbols have their usual meanings.

3. Data used and numerical experiment

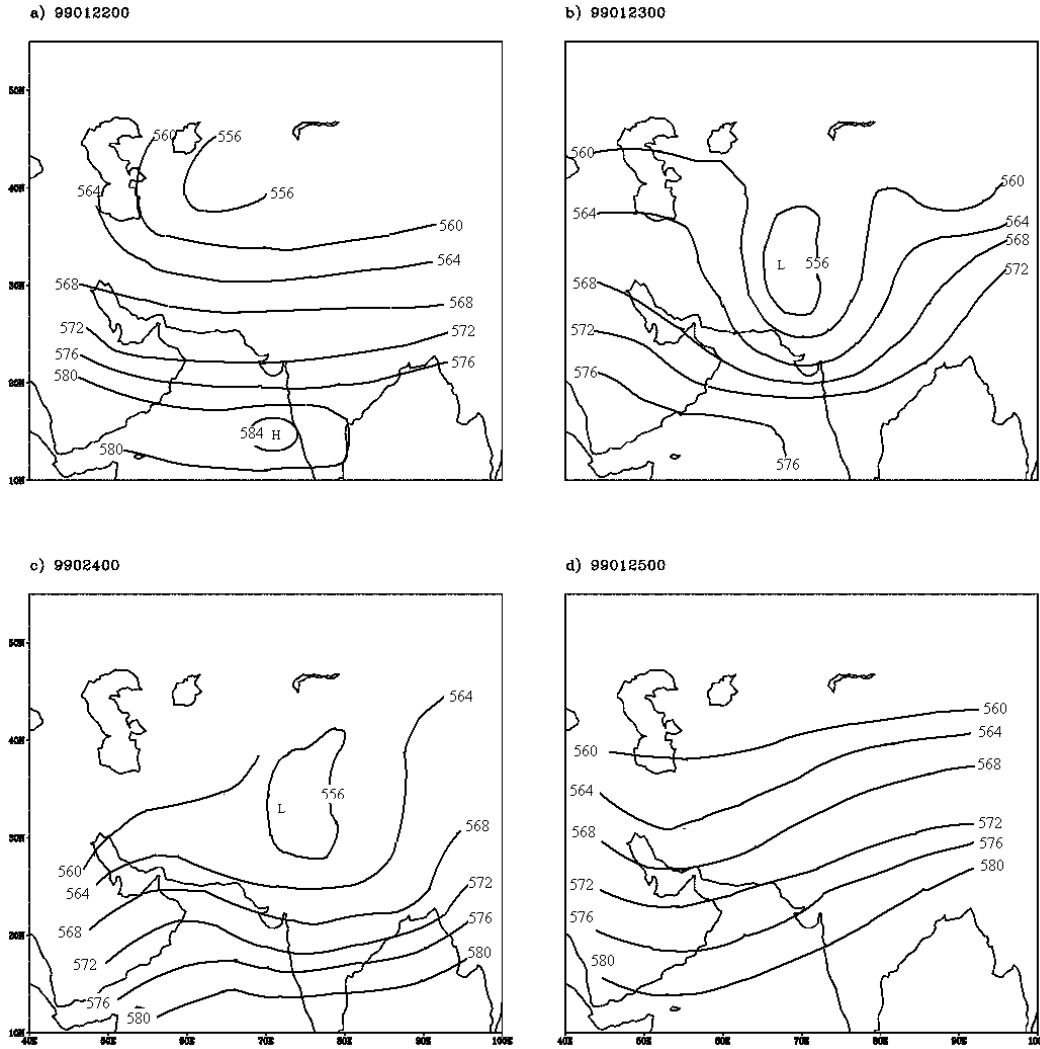
Numerical simulations of active WDs, that affected the western Himalayas is examined. These cases are selected because it gave widespread precipitation over

northwest India including western Himalayas. The domain selected for the study is shown in Figs. 1(a-d).

In first study, role of the planetary boundary layer and cloud convection parameterization schemes in the development of the WD is investigated. Model simulations are made with 60 km horizontal model resolution. Numerical simulation of an active WD that affected the northwestern part of India during 18 to 21 January 1997 is examined. To study the role of physical processes while simulating the WD, a series of eight experiments are performed for producing 24 hour and 48 hour forecast. Following PBL schemes and convection schemes are used.

(i) Two PBL schemes namely Blackadar and Hong-Pan (Hong and Pan, 1996). Hereafter referred as B and M respectively.

(ii) Four convection schemes namely Kuo, Grell, Kain-Fritsch and Betts-Miller (Betts and Miller 1986, 1993). Hereafter referred as KU, GR, KF and BM respectively.



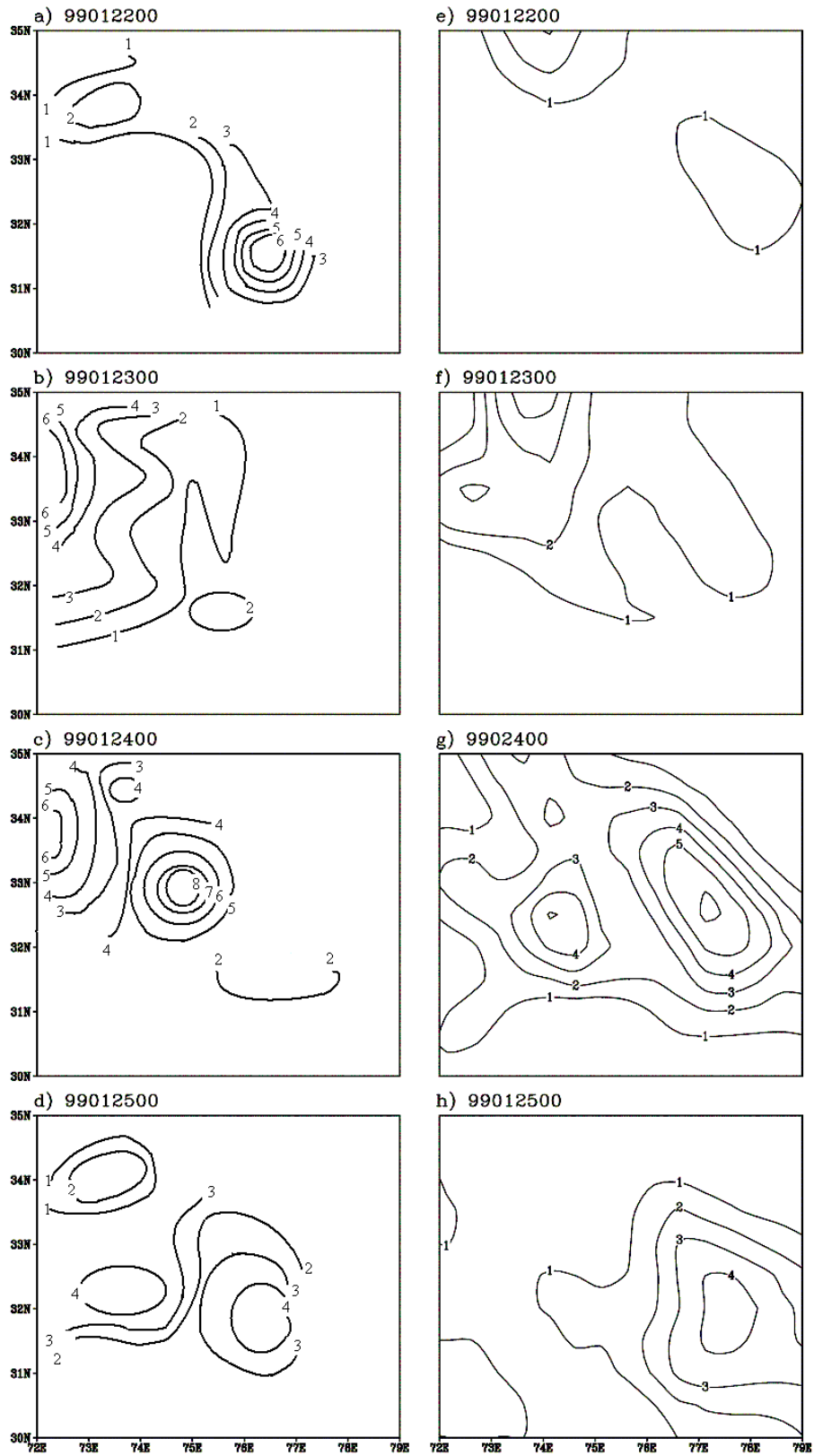
Figs. 2(a-d). Synoptic situations prevailing at 500 hPa during 22 to 25 January 1999

In second study, numerical experiments are made with normal topography and assumed no topography with 30, 60 and 90 km horizontal model resolutions. Numerical simulation of an active WD, that affected the northwestern part of India during 21 to 25 January 1999, is examined. Total six combinations of experiments are carried out under this experiment for producing 24 hour and 48 hour model predictions.

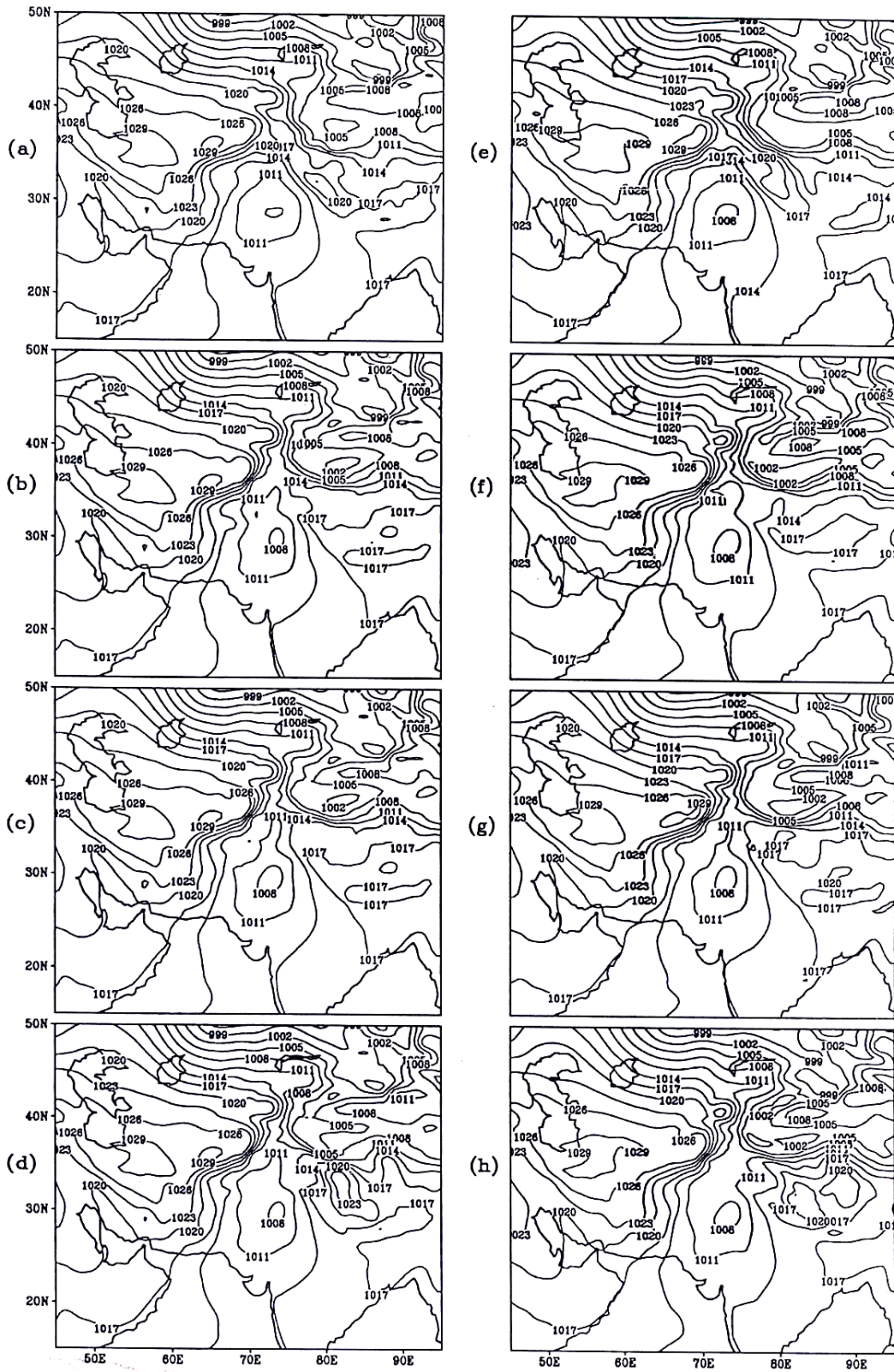
Initial conditions for the model are extracted from NCEP-NCAR reanalysis data sets and interpolated to the model domain. The usual procedure is to use the reanalysis data sets as the first guess in the objective analysis process to enhance them, because interpolation by itself cannot reproduce small scale features that have

already been smoothed out in the large scale reanalysis. As suggested by Sashegyi and Madala (1994) when insufficient data are available on the scale required by the numerical model, the model can be used to provide the time continuity between the observation times and generate the spatial variability on the scales resolved by the model. Hence in this study 12-hour nudging is applied before starting of model integration. During nudging period small scale features are generated by the model physics and are consistent with the large scale data sets used as initial conditions. The boundary layer variables are excluded from nudging toward the observation.

The topography is obtained from United State Geological Survey (USGS). These three numerical



Figs. 3(a-h). 24 hour observed precipitation (cm) and day 1 to day 4 model simulated with 30 km resolution for 22 to 25 January 1999



Figs. 4(a-h). 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-BM (d) Experiment B-KF (e) Experiment M-KU (f) Experiment M-GR (g) Experiment M-KF (h) Experiment M-BM

experiments are conducted with different topographies. In the first experiment the 5 min (9 km) global topography is incorporated for 30 km horizontal model resolution and 10 min (18 km) global topography is incorporated for 60 km and 90 km horizontal model resolution. For assumed no topography, the topography is replaced by a constant value of one meter over the entire domain.

4. Synoptic situations

Two active WDs, from 18 to 21 January 1997 and from 21 to 25 January 1999, are considered for the study. For the sake of brevity WD for case II is presented elaborately.

A WD affected Jammu and Kashmir region from 18 to 21 January 1997. On January 18, WD as an upper air system was seen over Iran and Afghanistan. On the following day an induced low pressure appears over Pakistan and adjoining Rajasthan with a central pressure of 1008 hPa, the main WD having moved northeast towards Jammu and Kashmir. On January 20 the induced low-pressure area moved over Punjab and adjoining areas and becomes unimportant on 21 January 1997 (Figs 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 19th to 0300 UTC on 21st. This WD is considered for studying the impact of model planetary boundary layer and cumulus convection parameterization schemes and its effect on simulating weather parameters.

In the second case study, another WD that affected the northwest India from 21 to 25 January 1999 is undertaken to see the impact of horizontal model resolution and topography. During this period most of the northwest India remains covered with intense multilayered low and high level clouds. On 21 January 1999 a trough at 500 hPa was observed extending from Afghanistan to northwest India associated with a low pressure at surface over northwest India. On 22 January 1999 the low on the sea level persisted at the same location with associated upper air circulation up to 700 hPa and trough aloft extended up to 300 hPa. Precipitation amounts varying between 2 cm day⁻¹ to 6 cm day⁻¹ were recorded at number of places in northwest India. On 23 January 1999, at 0000 UTC the pressure trough persisted at the same location, but pressure gradient steepened considerably over the region. The associated upper air cyclonic circulation also strengthened and could be seen extending up to 500 hPa and trough aloft up to 200 hPa. The upper air cyclonic circulation and the associated trough tilted westward with height. On this day, precipitation amounts varying between 2 cm day⁻¹ to 6 cm day⁻¹ were recorded at a number of places in northwest India. On 24 January 1999

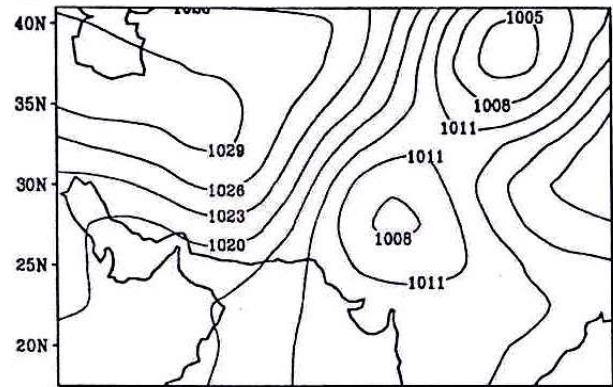


Fig. 5. Reanalysis of sea level pressure with contour interval of 3 hPa at 0000 UTC on 19 January

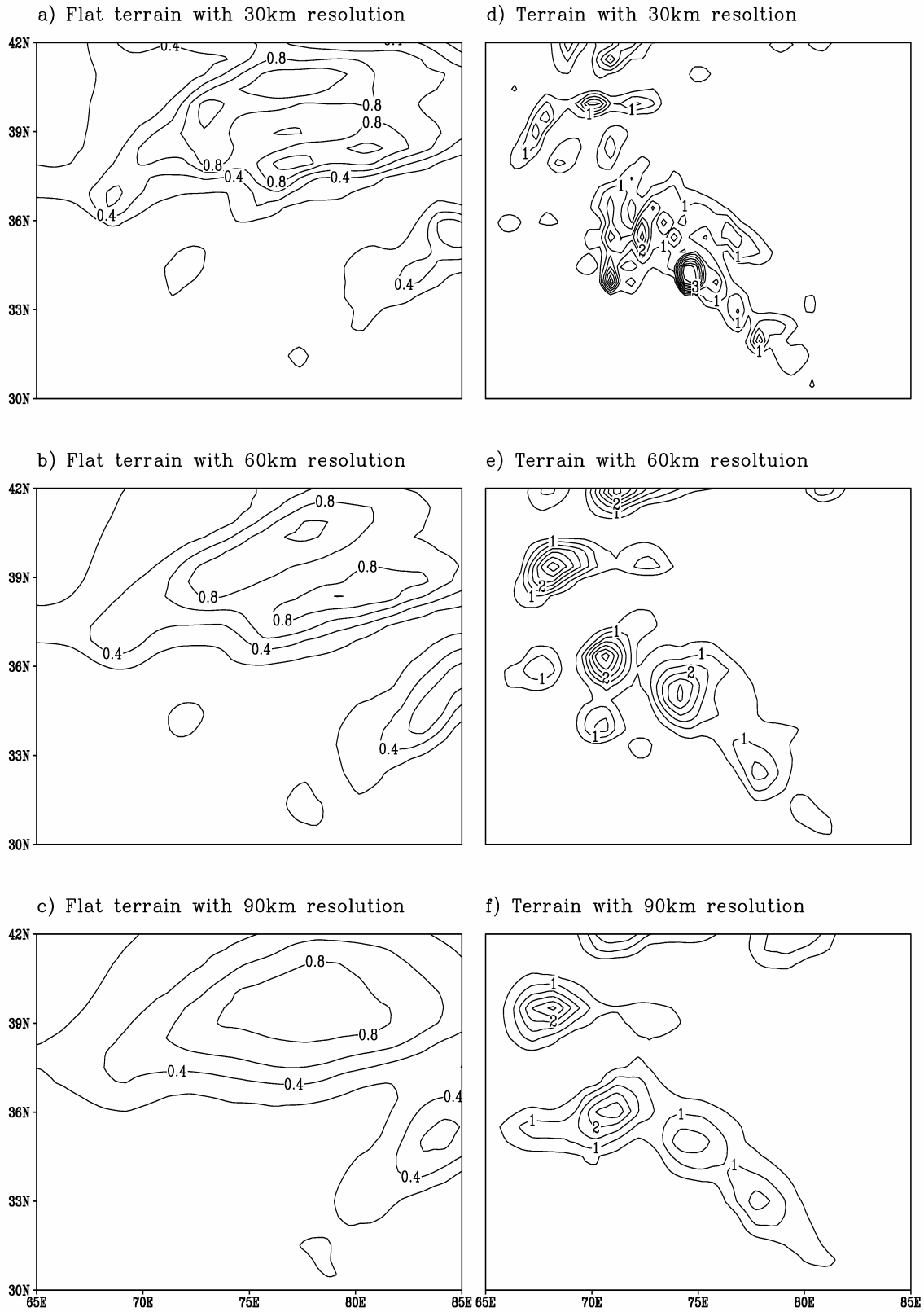
low pressure area moved over to Rajasthan and the steep pressure gradient to the north of it could still be observed over northwest Indian states. The associated cyclonic circulation extended up to 500 hPa and trough aloft up to 200 hPa. The trough was located close to 70° E. On this particular day the precipitation amount varying between 2 cm day⁻¹ to 9 cm day⁻¹ were recorded at many places over northwest India. On 25 January 1999 the low pressure area over Rajasthan weakened considerably and moved east northeastwards. The associated upper air trough was noticed between 700 hPa and 200 hPa. The precipitation amounts varying between 2 cm day⁻¹ to 4 cm day⁻¹ were recorded at a few places in northwest India. On 26 January 1999 the trough became very feeble. Synoptic weather information associated with the WD at 500 hPa is depicted in Figs. 2(a-d). The observed 24 hourly precipitation amounts as recorded by India Meteorological Department (IMD) at 0300 UTC from 22 January 1999 to 25 January 1999 over northwest India are shown in Figs. 3(a-d).

5. Results and discussion

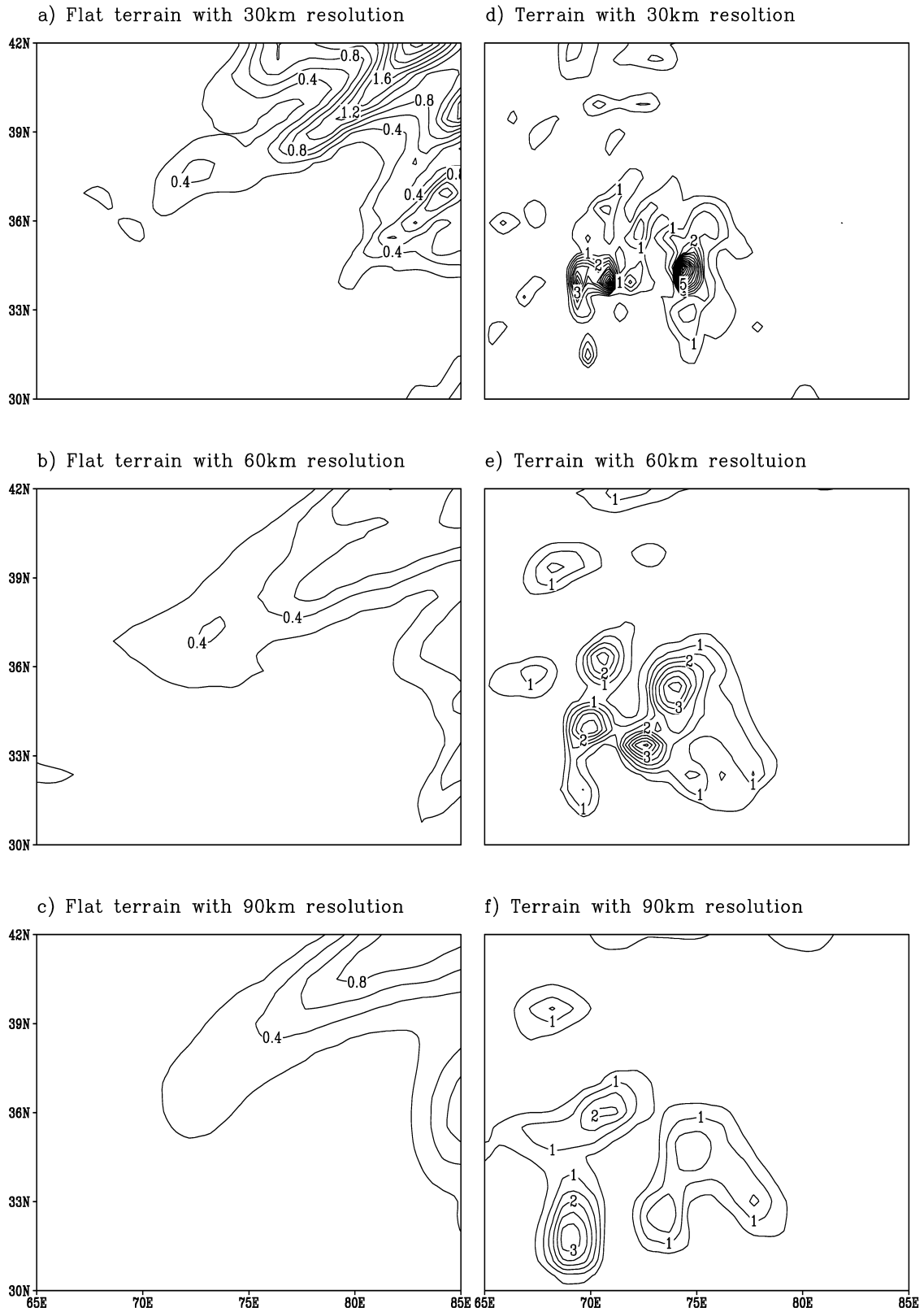
5.1. Role of planetary boundary layer and cloud convection parameterization schemes

In this study, non-hydrostatic version of MM5 (Grell *et al.*, 1994) is used to simulate a WD that affected northwest India from 18 January 1997 to 21 January 1997 with different planetary boundary layer and cloud convection parameterization schemes. To study the role of physical processes while simulating the WD, a series of eight experiments are performed for producing 24 hour and 48 hour forecast with the combination of two planetary boundary layer schemes and four cloud convection schemes.

Experiments with Blackadar scheme for planetary boundary layer and KU, GR, KF and BM schemes for



Figs. 6(a-f). Precipitation (cm) after 24 hour forecast valid at 0000 UTC on 22 January 1999 over flat and normal topography with different resolution



Figs. 7(a-f). Precipitation (cm) after 48 hour forecast valid at 0000 UTC on 23 January 1999 over flat and normal topography with different resolution

TABLE 1
Precipitation (cm day⁻¹) through various experiments at Sonamarg

	SASE (Observation in we)	90 km resolution	60 km resolution	30 km resolution	PPM
Day1	0.40	0.353	0.319	0.363	0.37
Day2	0.35	0.433	0.440	0.458	0.35
Day3	0.43	0.537	0.642	0.670	0.43
Day4	0.40	0.460	0.468	0.490	0.37

cloud convection are referred to as B-KU, B-GR, B-KF and B-BM respectively. Similarly, using Hong-Pan scheme for planetary boundary layer and cloud convection schemes as earlier, the experiments are referred as M-KU, M-GR, M-KF and M-BM respectively. For verification purpose, the 24 hour model output of sea level pressure in the above eight experiments, valid at 0000 UTC on 19 January 1997 is compared with corresponding verification analysis. The 24 hour model simulated sea level pressure with the eight experiments is presented in Figs. 4(a-h) and the corresponding verification analysis is depicted in Fig. 5. 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 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-BM experiment [Fig. 4(h)] is 73.5° E and 29.8° N which is closer to the position of the system as seen in the reanalysis map (Fig. 5) at 73.7° E and 27.8° N compared to the other experiments. Therefore, M-BM experiment is closest to the actual position of the system as seen in corresponding verification analysis.

5.2.1. Role of horizontal model resolution and topography on simulated meteorological fields

Using the above mentioned best physics option, *i.e.*, M-BM experiment, the impact of horizontal model resolution and topography on the evolution of the WD and associated precipitation is investigated. In this study, role of topography and horizontal model resolution on precipitation field is presented. WD from 20 January 1999 to 25 January 1999 is simulated for present study. Simulations are made with different horizontal model resolution with assumed no topography and normal topography, so that comparison can be clearly made out.

The horizontal model resolution at 30, 60 and 90 km with assumed no topography and normal topography is considered. Topography with these resolutions is shown in Figs. 1(a-d). Model simulation with 30 km resolution results in more intricate topography as compared with 60 km horizontal model resolution and 90 km horizontal model resolution. The simulated precipitation field at the

end of 24 hour and 48 hour period *i.e.*, ending at 0000 UTC of 22 January 1999 and 23 January 1999 are presented. It is clearly noticed that with assumed no topography simulation produces less precipitation, Figs. 6(a-c). The precipitation increases with increasing horizontal model resolution too. Moreover precipitation with assumed no topography is more towards north-northeast as compared to the precipitation produced in the model with normal topography. Also, precipitation produced by the model with normal topography shows northwest to southeast orientated band with a few pockets of heavier precipitation along the Himalayan ranges [Figs. 6(d-f)]. On day 2, model could able to simulate higher precipitation amount [Figs. 7(a-f)]. The precipitation produced in 30 km horizontal model resolution shows intense pockets. Moreover the precipitation pattern nearly remains anchored to the same location in all the three resolutions. Comparison with actual precipitation (Fig. 3) shows that though the magnitude of precipitation amount differs, but orientation of precipitation distribution is well simulated. The model with finer resolution, 30 km, is able to estimate affects of mesoscale forcings on precipitation over the selected domain in better manner.

5.2.2. Sensitivity studies of area averaged precipitation

Precipitation sensitivity is studied by considering the difference in precipitation rates among the domain with three different horizontal model resolution and the two topography experiments. Area (65° E to 80° E and 30° N to 40° N) averaged precipitation for 24 hour during the entire 96 hour model integration of the model is examined. The area averaged maximum and area time averaged values of simulated precipitation are given in Table 1. It is found that more precipitation is simulated as the domain becomes finer and as the topography resolution becomes higher. Further, area averaged maximum and area time averaged precipitation rates get larger as the domain becomes finer. Secondly, less precipitation was simulated with assumed no topography as compared with normal topography as gradient becomes smaller. It shows that model resolution and topography gradient play very important role in prediction of precipitation due to WD. As precipitation estimation mainly depends upon horizontal moisture convergence

and vertical velocity and since horizontal convergence and vertical velocity are stronger in finer domains, hence more precipitation was simulated over finer domains. Further, as topography is better presented in finer domains, location and structure of topography barrier lead to generate realistic location specific precipitation. Since orographic gradients are larger in finer domains, hence better precipitation results are simulated in finer domains. Even though, it is very difficult to say whether the effect of model resolution or topography is large as both are closely related to each other. However, the ratios of the finer resolution mean and the coarser resolution mean in these experiment are computed, *i.e.*, 1.028 and 1.220. On comparison these value suggest that the effect of topography plays more important role that the model resolution. Further, these precipitation rates are compared with the NCEP reanalysis data sets and it is found that fine resolution simulated rates are much closer to with these and also to the IMD and Snow and Avalanche Study Establishment (SASE), Manali, realtime observations.

6. Conclusions

Simulation results indicate that the distribution and the rate of simulated precipitation due to WD over northwest India is highly sensitive to the correct model physics, horizontal model resolution and topography. Study of planetary boundary layer and cloud convection parameterization scheme shows that combination of Hong-Pan and Betts-Miller scheme is better among other possible combinations of schemes. Sensitivity results show that this combination gives closer resemblance to the real synoptic weather situations. Further, precipitation prediction does vary with horizontal model resolution. This emphasizes the fact that integration of finer scale topography is needed for more precise prediction of precipitation. It could be missing in the model due to its coarse horizontal resolution, and, also, coarse resolution cannot represent subgrid processes in the model.

Over the western Himalayas, meso scale modeling system, using appropriate planetary boundary layer scheme and finer horizontal model resolution, can simulate meteorological fields satisfactorily. Introduction of detailed/fine topography in the model produces more realistic results.

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References

- Anthes, R. A. and Warner, T. T., 1978, "Development of hydrodynamic models suitable for air pollution and other mesometeorological studies", *Mon. Wea. Rev.*, **106**, 1045-1078.
- Anthes, R. A., Kuo, Y. H., Hsie, E. Y., Low-Nam, S. and Bettge, T. W., 1989, "Estimation of skill and uncertainty in regional numerical models", *Quart. J. R. Met. Soc.*, **115**, 763-806.
- Betts, A. K. and Miller, M. J., 1986, "A new convection adjustment scheme", Part II : Single column tests using GATE wave, BOBMEX, ATEX and Arctic air-mass data sets, *Quart. J. R. Met. Soc.*, **112**, 693-709.
- Betts, A. K. and Miller, M. J., 1993, "The Betts-Miller scheme", The representation of cumulus convection in numerical models, (ed. Emanuel, K. A. and D. J. Raymond), *Amer. Met. Soc.*, p246.
- Dudhia, J., Gill, D., Guo, Y. R., Hansen, D. and Manning, K., 1998, "PSU/NCAR Mesoscale Modeling system Tutorial class notes and User's Guide : MM5 modeling system version 2", Available on the World Wide Web (URL:<http://www.mmm.ucar.edu/mm5/doc.html>).
- Dudhia, J., 1993, "A nonhydrostatic version of the Pan State-NCAR mesoscale model : Validation tests and simulation of an Atlantic cyclone and cold front", *Mon. Wea. Rev.*, **121**, 1493-1513.
- Giorgi, F. and Marinucci, M. R., 1996, "An investigation of the sensitivity of simulated precipitation to model resolution and its implication for climate studies", *Mon. Wea. Rev.*, **124**, 148-166.
- Grell, G. A., Dudhia, J. and Stauffer, D. R., 1994, "A Description of fifth generation Pan state/NCAR Mesoscale Model (MM5)", NCAR technical note, NCAR/TN-398 + STR.
- Hong, S. Y. and Pan, H. L., 1996, "Nonlocal boundary layer vertical diffusion in a medium range forecast model", *Mon. Wea. Rev.*, **124**, 2322-2339.
- Kallos, G. and Kassomenow, P., 1994, "Effects of selected domain in mesoscale atmospheric simulation and dispersion calculations", In air pollution modeling and its application. (edited by S. V., Crying and M.M. Millan), Plenum Press, New York.
- Kalsi, S. R., 1980, "On some aspects of interaction between middle latitude westerlies and monsoon circulation", *Mausam*, **38**, 305-308.
- Kalsi, S. R. and Haldar, S. R., 1992, "Satellite observations of interaction between tropics and mid latitude", *Mausam*, **43**, 1, 59-64.
- Krishnamurthy, T. N., 1990, "Monsoon prediction at different resolutions with a global spectral model", *Mausam*, **41**, 234-240.
- Pisharoty, S. and Desai, B. N., 1956, "Western Disturbances and Indian weather", *Indian J. Met. Geophys.*, **7**, 333-338.
- Sashegyi, K. D. and Madala, R. V., 1994, "Initial conditions and boundary conditions", Mesoscale modeling of the atmosphere, (Ed. Pielke, R. A. and Pearce, R. P.), *Amer. Met. Soc.*, 1-23.

