

# Mesoscale Modeling for Mountain Weather Forecasting Over the Himalayas

## A Workshop Report

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**Severe weather has more calamitous effect in the mountainous region as the terrain is complex, development is poor and economy is fragile. Such weather systems occurring on small spatial-temporal scale invite application of models with fine grid resolution and observations from radars and satellites besides the conventional observations for forecasting and disaster mitigation.**

Weather is a complex phenomenon with no physical boundaries over the globe. It is a result of interplay between various physical processes and scales of motion. The Northwest India and the Himalayan region (Fig. 1) are particularly prone to vagaries of severe weather claiming casualties every year. This region is influenced by western disturbances that originate from extra-tropics and propagate to Indian region during winter season, giving rainfall and chilly weather conditions. These systems severely influence the life over the Himalayas, unsettling normal life by inducing widespread rainfall and at times very heavy snowfall associated with squall winds, hail and severe cold waves. Snow avalanches and land slides result on account of gale winds and heavy rain / snowfall.

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The knowledge about understanding and prediction of weather phenomenon is advanced through analysis of observations and numerical modeling of involved physical processes. The weather phenomena like Norwesters (squall lines which affect the Northeast India during pre-monsoon season), thunderstorms, cloudbursts, windstorms, hailstorms and thunderbolts that have high impact on human life and economy occurring on smaller spatial-temporal scale invite application of regional models with fine grid resolution. The squall that hit Delhi during 27<sup>th</sup> May, 2002 had uprooted around 2000 trees leading to traffic jams, water-logging and electric supply disruption. On 14<sup>th</sup> November, 1986, combined effect of weather and avalanches claimed 70 lives and property worth millions of rupees on Srinagar–Leh highway. On 16<sup>th</sup> January, 1995, Jammu-Srinagar highway was hit by a number of avalanches stranding more than 300 vehicles and 400 personnel in which 67 lives and property worth billions of rupees were lost. The Malpa landslide disaster over hills of

Himachal Pradesh owing to heavy rainfall on 27<sup>th</sup> August, 1997 is still fresh in our memory. During Amarnath pilgrimage in August 1996, 194 people died owing to rough weather. Innumerable incidents of this nature are taking place over hilly areas. To combat the weather induced disasters of this nature and to develop the capacity to predict them, observations and modeling on smaller spatial scale i.e., mesoscale, is necessary.

The year 2002 has been recognized as the International Year of Mountains. The declaration builds on the process initiated at Rio in 1992, which recognised the crucial role played by mountain ecosystems and encouraged governments to ensure sustainable mountain development. In view of the large impact caused by the mountain weather systems on human life and society, a workshop on mesoscale modeling with special emphasis on mountain weather forecasting was jointly organized by the National Centre for Medium Range Weather Forecasting (NCMRWF) of India and the National Center for Atmospheric Research (NCAR) of USA at New Delhi during 29-30 July, 2002 (Table-1 & 2). The workshop was divided into 5 sessions that included (1) Mountain Weather Forecasting, (2) Mesoscale Atmospheric Modeling, (3) Mesoscale Observations and Data Assimilation, (4) Radar and Satellite Applications, (5) Severe Weather Phenomena. The scientists discussed various aspects of mesoscale modeling during the workshop. A panel discussion was held at the end where recommendations were made for improving severe weather forecasts over the mountains, in particular, over the monsoon region (Table -3). A brief summary of papers presented in each session is presented below.

## **Mountain Weather Forecasting**

The importance of the Himalayas on the monsoon circulation over the Indian subcontinent is well known (Desai, 1968; Godbole, 1973; Hahn and Manabe, 1975; Das and Bedi, 1978, Yanai et al., 1992). The Himalayan snow cover during winter is one of the key factors in making long range forecast of the succeeding monsoon rainfall (Vernekar et al., 1995). However, real-time forecasting of severe weather conditions including western disturbances over the mountain regions remain a challenging task. Accurate forecasting of such systems is important for undertaking mountaineering expeditions and avalanche prediction etc. This poses a challenging task especially with sparse data over such regions where there are also problems of communication. To enhance meteorological observations over the western Himalayas, 26 surface observatories and 2 upper air stations have been set up. A mountain meteorology program has been started at NCMRWF, the India Meteorological Department (IMD) and the Snow and Avalanche Study Establishment (SASE) at Manali for the purpose of forecasting, providing training and development of snow climatology etc. Currently, mountain weather forecasting over the Western Himalayas is carried out through a combination of various products viz., regional/ mesoscale model outputs, global model products, in situ observations, and satellite observations along with synoptic conditions by collaborative efforts between NCMRWF, IMD and SASE.

In addition to these techniques, meso-scale modeling can be used as an

aid for site specific avalanche forecast. Snow avalanches are one of the most common weather hazards over the Himalayan range. Avalanche occurrence is as a result of the structural collapse of the snow cover in the upper reaches of the mountainous region. The collapse may occur either by internal factors related to snow metamorphism or the external factors like excessive loading of the snow cover due to snow precipitation, falling of boulders and snow lumps, cornice collapse, explosive waves or seismic activities. Thus to predict an avalanche accurately, an avalanche forecaster is required to keep a continuous record of the weather elements prevailing in the higher reaches which contribute to metamorphism and also the excessive loading of the snow cover due to snow precipitation, cornice formation and its collapse, wind transportation, etc. The information available of the above factors on the synoptic scale is though sufficient for assessment of avalanche danger on a larger scale for a period specific forecast for a general area, however, it is not sufficient for site specific and time specific forecast of an avalanche. This, to a certain extent, can be achieved through meso-scale modelling of various weather parameters.

Some of the meteorological parameters that can be used to assist in forewarning/ forecasting of avalanches are temperature, wind speed/ direction and humidity. Another important parameter that need to be forecast is the type of precipitation (snow, ice, rain) and, if possible to the extent of crystal formation. The forecasts at 10 km resolution in the horizontal and 100 m resolution in the vertical up to 4-5 Km are good enough for making avalanche forecasts. Attempts have been made for point probabilistic

prediction of precipitation and quantitative precipitation forecasting (QPF) in the Northwest Himalayas. Studies based on NCEP and NCMRWF analyses/ forecasts and observations from IMD indicate an accuracy of 80% for 24 h lead time forecast at Sonamarg in the Western Himalayas.

Another important aspect of weather over the Himalayas is the role of Katabatic and Anabatic winds on the mountain slopes. Observations from 1991-2000 during the period January to April shows a high diurnal variation of rainfall in the Assam valley over the Eastern Himalayas. The maximum probable time for its occurrence is between 2100 hrs and 1000 hrs.

### **Mesoscale Atmospheric Modeling**

Mesoscale modeling for real-time forecasting is evolving in India. At NCMRWF, high-resolution mesoscale models such as MM5 and ETA are run on real-time basis for forecasting mesoscale systems viz., the western disturbances, severe thunderstorms, tropical cyclones and heavy rainfall episodes. The MM5 model is run on triple nested domains at 90, 30 and 10 km resolutions using initial conditions from the T80 global model of NCMRWF. For the purpose of mountain weather forecasting, four inner domains at 10 km resolutions are placed over the Northwest Himalayas, Central Himalayas, Northeast Himalayas and the Western Ghat mountains on an experimental basis. Case studies of western disturbances over the Himalayan range and heavy rainfall events associated with active monsoon phase have shown that the model has reasonably good capability of

forecasting severe weather up to 72 hours in advance (Das 2002). However, heavy rainfall events are underestimated for which further studies are required with improvement of physical processes and model resolution. Scarcity of observations over the Himalayan region remain a major issue.

Studies of intense atmospheric vortices particularly, the tropical cyclones over the Indian region have been carried out using the MM5 model by groups working at NCMRWF, the Indian Institute of Technology, Delhi (IITD) and Andhra University, Waltair. Results indicate that the cyclone track and rainfall forecasts by the MM5 model is improved using satellite data in the input analysis. Experiments have been carried out by using synthetic vortex in the input data and four dimensional data assimilation (4DDA) have been conducted. Results indicate that the mesoscale data assimilation, appropriate parameterization of land surface process and meso-network of observations are very important for improving the quality of forecasts.

Another mesoscale model run on real-time basis at NCMRWF is the ETA model. The model is presently run at 32 km resolution using the boundary conditions from the T80 global model. Studies of western disturbances and heavy rainfall events show fairly good forecasts up to 72 hours by using the model (Rajagopal and Iyengar, 2001). Sensitivity studies have also been carried out using two different parameterizations of land-surface processes using a third model, namely a Regional Spectral Model (RSM) at NCMRWF. The first scheme consists of two-layer structure for the soil moisture where as the second scheme has a single-layer soil moisture parameterization.

Results indicated reduction in easterly wind bias at lower levels by using the two-layer soil moisture scheme.

Attempts have been made to simulate severe cyclonic storm over the Bay of Bengal using a Regional Atmospheric Modelling System (RAMS) at the Indian Institute of Tropical Meteorology (IITM), Pune. Initial conditions were prepared from the GEWEX Asian Monsoon Experiment (GAME) analysis. Available RS/RW and surface data were assimilated into the analysis. Results indicated that the predicted track of the cyclonic storm compared well with the GAME analyses and IMD observation till 24 hours by using the RAMS at 50 km resolution.

Attempts have also been made to simulate monsoon depression using an Advanced Regional Prediction System (ARPS) at 50 km resolution over the Indian region by groups working at IITM. The model has also been used to simulate mesoscale circulations and its time evolution over peninsular India by initialising it using vertical profiles of temperature, relative humidity and winds available at Thumba by the group working at Vikram Sarabhai Space Centre (VSSC), Trivendrum.

The rich and complex scale interactions in the tropics make simulation and forecasting of any system a challenge. Both up-scale and down scale energy transfer takes place. Thus, while small-scale (including sub-grid scale) processes play crucial role in monsoon dynamics, the large-scale fields also seem to have significant effects over small (meso-scale) systems. It is, therefore, desirable to employ a global environment for simulation of

meso-scale systems as well. A main drawback of a meso-scale forecast model is that the data for the boundary conditions must be supplied externally. The artificial lateral boundaries in a meso-scale model arises because of its limited domain. This difficulty is often overcome by using simulations from a general circulation model (GCM) to generate the boundary conditions. However, the quality of the meso-scale simulation is then strongly dependent on the quality of the boundary conditions. Attempts have been made to simulate the monsoon by using a variable resolution GCM at the Centre for Mathematical Modeling and Computer Simulations (CMMACS), Bangalore. Preliminary results have shown that with carefully chosen configuration, the variable resolution GCM can be an effective solution for multi-scale modelling from global to monsoon to the meso-scale.

### **Mesoscale Observations and Data Assimilation**

Analysis of very heavy rainfall episodes along the west coast of India shows that such spells occur over an area of 200 x 200 km and may last for one/ two days. The west coast of India has topography rising up to about 800 m known as the Western Ghat mountains. There is clear evidence that deep convection is embedded within the large scale and there are favorable spots in relation to closeness to orography and the horizontal wind shear in the low level jet. These rainfall events coincide with the formation of north-south trough over the coast and some times with an embedded onset vortex in it. Daily rainfall data generated from a high-density mesoscale rain gauge network (25 stations with maximum inter-station distance <100 km)

for the monsoon season (June - September) for the period 1996-2000 were examined. The rainfall reported were from lake catchments along the Western Ghats, in and around Mumbai. A threshold value of 70 mm was used for defining heavy rainfall events. Results indicate that the percentage contribution of precipitation exceeding 70 mm ranged from 29 % to 77 % of the average annual rainfall. The percentages were the largest for gauges located on the Western Ghats and the least for sites located at the foothills of the Ghats. They were moderately large for stations along the coast. These results suggest that different climatic controls influence heavy precipitation over these regions. To understand the nature of mesoscale organization of deep convection along the west coast of India, a field programme called the Arabian Sea Monsoon Experiment (ARMEX) is under implementation. There are 25 institutions/organizations including Indian Air Force and Indian Navy participating in this field campaign. Unfortunately the Monsoon-2002 has not been very active. Only two episodes of heavy rainfall have occurred until the end of July. These episodes were very well predicted by the mesoscale models run at NCMRWF.

Prior to ARMEX, another field experiment called the Bay of Bengal Monsoon Experiment (BOBMEX) was organized during July-August, 1999. The MM5 model was used to study circulation characteristics of a monsoon depression during the BOMBEX period (26-29 Jul 1999). Using two global datasets from NCMRWF and the National Center for Environmental Prediction (NCEP)/ NCAR reanalysis separately as first guess, a multiquadric

(MQD) interpolation technique was used for objective analysis at a horizontal resolution of 30 Km. For this purpose, the surface and upper-air observations at regular synoptic hours with additional observations obtained from the satellites (METEOSAT and SSM/I), ORV Sagarkanya and RS/RW data at coastal stations were utilized to improve the mesoscale analysis. A simple data assimilation scheme based on nudging method (Newtonian relaxation) was also employed to put the dynamic constraint during model integration. Results showed that the model was able to simulate the structure of meso-convective organization and the prominent synoptic features associated with monsoon depression using the high resolution analysis. The objective verification and error analysis of different simulations from two reanalysis datasets illustrated that the mesoscale assimilation improved the performance of the model. Investigation of the precipitation intensity and distribution showed that the model responded positively after data assimilation.

Observations are very sparse over the Himalayan region. Analysis of limited observations over the Ladakh region in the Western Himalayas have been carried out based on some special data. Ladakh is popularly termed as a land between Earth and sky at an elevation around 10,680 feet. It is a remote and rugged land situated deep in the Himalayas on the border of Tibet, Sinkiang and Kashmir. Rocky defiles of grotesque proportion, broad valleys cut by lazy rivers, arid expanses of rock merge suddenly with moist, upland meadows with dense shrubs and alpine flowers. Arctic & desert conditions make its climate most peculiar in the world. Based on limited observations, climatology of thundershower,

drizzle/rain/shower, snow/sleet, poor visibility, low clouds, hail and haze have been constructed. Observations indicate that *visibility* reduces to < 800 m at different locations such as in Kargil during September between 0600-1200 hrs; in Thoise from April to May & December between 1500 - 1800 hrs; in Jammu throughout the year between 0600 - 0900 hrs; in Leh during January, February and November between 0600 - 0900 hrs; in Srinagar throughout the year between 0600 - 0900 hrs. Observations show that the maximum occurrence of *low clouds* (< 60 m) is observed over Jammu & Srinagar. Low clouds occur mostly in the months of March and April in Srinagar and during July and August in Jammu between 0900-1200 hrs. Clouds < 60 m are not observed over Leh and Kargil regions. Srinagar & Jammu record the maximum occurrences of *Fog* in a year. Least occurrence is in Leh area. *Fog* Occurs mostly between 0600-0900 hrs in the region. Thoise and Kargil do not experience *Fog*. *Haze* occurs in Jammu and Srinagar throughout the year. Thoise and Leh experience haze in 3-4 months in a year. Haze is observed in Kargil only during winter months, on few occasions. It generally occurs between 0600-0900 hrs in the region. Maximum occurrence of *thunderstorms* is observed in Jammu and Srinagar. Least occurrence is in Leh and Thoise. It mostly occurs in the months of May and July between 0300-0600 and 1500-1800 hrs in the region. It does not occur in Kargil area.

### **Radar and Satellite Applications**

One of the major problems of mesoscale modeling is the paucity of data at very high spatial resolution. The present day operational observing

system comprising of surface, radiosonde, satellite derived cloud drift wind data and satellite soundings are well below the scales required by mesoscale models. Mesoscale analyses therefore have increasing reliance on additional new and high resolution satellite based data and other remote sensing observing systems such as radars capable of monitoring and recording the atmospheric state. In addition, increasing use is made of proxy data such as moisture profile and adiabatic heating from infrared imagery and tropical cyclone bogus data. Present day space technology is able to circumvent these problems to some extent.

One of the most remarkable applications of radar technology is the meteorological observation of the atmosphere. Detection of precipitation by radar has allowed analysis of structure of the precipitation and provided information on intensity, rain rate, vertical extent and drop size distribution etc. After the advent of Doppler Weather Radar (DWR) it became possible to measure the velocity fields in a weather system. DWR is a class of Pulse Doppler Radar systems which provides quantitative, geo coded digital information on prevailing weather over 1000's of square kilometers around the radar on convenient colour graphic synthetic video displays to facilitate quick analysis and forecasting, including nowcasting. DWR are now used in operational meteorological arrays in many countries particularly as part of mesoscale observing systems. The polarimetric DWR makes it possible to observe microstructure of hydrometeors.

Recently, IMD has begun to replace the existing cyclone detection radars with state-of-art DWR. Three DWR have been installed at Chennai, Kolkata

and Sriharikota (SHAR) on the east coast of India for detection and monitoring of cyclonic storms as part of IMD's plan for induction of Doppler technology in its radar network. Among these, the DWR at SHAR is indigenously developed by the Indian Space Research Organization (ISRO) and the other two have been purchased from a German company. With the induction of DWR technology in IMD and the expansion programme envisaged to cover the entire coastline and areas prone to storm activity, the cyclone warning and short range forecasting capability is expected to go up further. The facility is expected to provide useful support to numerical-dynamical modelers. While the wind field measurement in a cyclonic storm with the DWR would provide a direct estimate of the intensity of the system, particularly near the coast at the time of landfall, the availability in real time of data and imagery in composite form through networking would make the process of cyclone warning more efficient. Aviation forecasting and storm warning will get a boost with the availability of various hydrological and wind products derived instantaneously.

Besides the DWR, a mesosphere-stratosphere-troposphere (MST) radar has been operational in India at Gadanki (13.47<sup>0</sup>N, 79.4<sup>0</sup>E). Several field campaigns have been carried out to study the deep convective systems over Gadanki using the MST radar since 1996. Data collected during all these campaigns have been analyzed to explore various aspects of mesoscale convective systems, such as radar reflectivity, height-time structure of vertical velocity structure, weak echo regions (WER), height structure of

tropical tropopause and troposphere - stratosphere exchange (TSE). Two important physical processes *viz.* tropopause weakening and gravity wave triggered by tropical mesoscale convective systems (TMCS) have been examined to get an idea of TSE related dynamical processes. The convective storms are generally followed by stratiform type of precipitation. The height-time structure of vertical velocity during these two types of precipitating events can help in distinguishing such systems. The composite height profiles of vertical velocity in convective and stratiform precipitation indicate height-time structure of diabatic heating. Co-located L-band radar observations at Gadanki are used to classify the observed precipitating systems into convective and stratiform regions and thus a composite height profile of vertical velocities in the respective regions are obtained. Results from these studies can be used for preparing initial conditions and verification of outputs simulated by mesoscale models.

Shortly three geo-stationary satellites namely INSAT-2E, METSAT & INSAT-3A will be available over Indian Ocean region. VHRR onboard these satellites gives information on cloud motion vectors, cloud cover, outgoing long wave radiation, precipitation etc. CCD payload onboard INSAT-2E/ INSAT-3A had additional features of cirrus cloud detection, vegetation monitoring and also for continuous monitoring of meso-scale systems. Microwave radiometers onboard DMSP and TRMM satellites give the water vapour content and the precipitation rates. The input of water vapor information and the assimilation of rain rates have significantly improved the meso-scale forecasts. Scatterometers provide surface wind vector over oceans

and are important input to the meso-scale models. The prediction of movements of tropical cyclones have been found to be significantly improved with the use of scatterometer data. A recent input for meso-scale modeling is from MODIS (Moderate Resolution Imaging Spectroradiometer) onboard Terra/Aqua satellites of NASA. Efforts in receiving this data in India is currently under progress. This has the possibility of very high resolution humidity profiles. Radiometer & Sounder onboard Megha-Tropique (to be launched in the year 2005) will provide high resolution and frequent data coverage over tropics. A sensor called GIFTS (Geostationary Imaging Fourier transform Spectrometer) is presently under active investigation. This would provide humidity and temperature with very high vertical and horizontal resolution.

Increasing efforts are being made at NCMRWF to generate and study the high resolution satellite data bases to use in the planned future mesoscale analyses system. The advanced satellite data sets from SSM/I, Quikscat, TMI, ATOVS, AIRS and India's own satellites MSMR, INSAT and METSAT are now being actively studied and archived. Some of these data sets are already being used operationally in the NCMRWF global data assimilation and Forecasting system.

### **Severe Weather Phenomena**

Both free and forced motions occur in nature. The latter result from the direct influence of the boundaries of the system whereas the former result from the natural instabilities of flows with much larger scales. Mesoscale circulations are forced by the heterogeneity of the earth

surface. The small-scale variations in the characteristics of the land surface and the adjoining water-bodies of different extent present sufficient complexity that can be resolved only by fine-scale numerical simulations. Earlier efforts have been directed towards answering the question: "Can mesoscale be treated as a finite number of free and forced waves interacting with each other and the mean flow, or a continuous spectrum of eddies whose interactions are studied statistically?" Waves and eddies transfer energy between cumulus and cyclone scale, but intermittent mesoscale phenomena convert potential energy to kinetic energy on the mesoscale. The mesoscale convective complexes (MCCs) have been studied in great detail, nevertheless, mesoscale weather forecasting continues to remain a challenging problem. The Council of Scientific & Industrial Research (CSIR) has recognized it as a problem where inter-institutional cooperation is essential and therefore launched an ambitious project on "Mesoscale modelling for monsoon related predictions. Among the devastating weather systems that cause loss of life and properties over the Indian subcontinent are the tropical cyclones, western disturbances causing land slides and snow avalanches, severe thunderstorms causing lightning, cloud burst and flash floods.

The Orissa Super cyclone of 29-30 October 1999 resulted in loss of more than 10,000 life, damaged 1828532 houses, 1810091 hectares of agriculture land and significant infrastructure destruction affecting one third population of the state. The storm, classified a Super cyclone with winds of over 250km/h (160mph), destroyed communications and cut road, rail and air links over the eastern state. The Super cyclone wiped out everything in its path.

Due to lack of adequate data coverage over the ocean, the intensity of the cyclonic storms are poorly represented in the available global analysis/reanalysis. Most of the global analysis/reanalysis have large initial positional error too. An improved high-resolution analysis was prepared for simulation of the Orissa super cyclone using the MM5 modeling system. The analysis was carried out by the group working at IITD ingesting satellite observations (METEOSAT, SSM/I, MSMR) and station surface and upper air observations over India with the NCEP reanalysis as the background field. The improved analysis was used to integrate the model (MM5) for producing 5-day forecast of the storm from 00 UTC 26<sup>th</sup> October to 00 UTC 31<sup>st</sup> October 1999. Several important fields including sea level pressure, horizontal wind and rainfall were examined and compared with the verification analysis/ observations. The tracks of the storm obtained from model simulations were also compared with the best-fit track obtained from IMD. Results show that the mesoscale analysis improved the prediction skill of the model both for track and intensity of the cyclonic storm.

The Orissa super cyclone was also investigated by two different models used at IMD for regional weather and cyclone prediction. The first model is a limited area model (LAM), which includes a synthetic vortex generation capability for tropical cyclones (TC). The LAM is a semi-Lagrangian, semi-implicit, multilayer primitive equation model on sigma coordinates. The model has horizontal resolution of  $0.75^{\circ} \times 0.75^{\circ}$  lat/ long and 16 sigma levels in the

vertical. The second model adapted from NCEP for hurricane forecasting is a quasi-Lagrangian model (QLM). The QLM is a multi-level fine mesh model with horizontal resolution of 40 km and 16 sigma levels in vertical with variable domain depending on the centre of the vortex. In this model a more complex vortex circulation defined by an analytical expression is added after the objective analysis but before the model initialisation. Results from the LAM and QLM show that the track prediction errors in both the models are of comparable magnitude. The 24hour model forecast error was about 80 km in both models.

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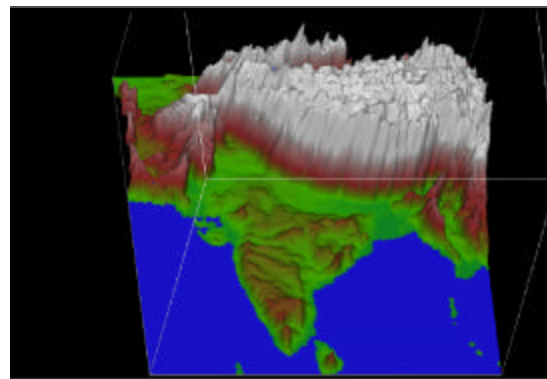


Fig. 1: Topography over the Indian region

**Table 1****Workshop speakers, affiliations and presentation titles**

<b>Speaker</b>	<b>Affiliation</b>	<b>Title talk</b>
Robert Gall	NCAR	The Observing system Research & Predictability Experiment (THORPEX) & Weather Research Forecast (WRF) model
H. R. Hatwar	IMD	Development of mountain meteorology over western Himalayas
S. S. Sharma	SASE	Mesoscale modeling as an aid for site specific avalanche forecast
Someshwar Das	NCMRWF	Mountain Weather Forecasts Over the Indian Region Using MM5 Model
H. R. Hatwar	IMD	Prediction of Western Disturbances and associated weather over Western Himalayas
V. J. Kirubhanidhi	IAF	The role of katabatic and anabatic winds in the weather over Assam with special reference to Tezpur air field
A. P. Dimri	SASE	Point Probabilistic Prediction of Precipitation and Quantitative Precipitation Forecasting in NW Himalayas
U. C. Mohanty	IITD	Mesoscale modelling of intense vortices over India
D. V. Bhaskar Rao	AU	Numerical model experiments of weather disturbances over India using a mesoscale Model
A. R. Kellie	NCAR	Super Computing Division of NCAR
P. Goswami	CMMACS	Variable Resolution GCM: A Promising Tool for Monsoon to Meso-scale simulations
S. S. Vaidya	IITM	Simulation of Tropical systems over Indian Region using Mesoscale Models
E. N. Rajagopal	NCMRWF	Mesoscale Forecasts with Eta model over Indian Region
Radhika Ramachandran	SPL/ ISRO	Numerical Simulations Over Peninsular India during Monsoon Seasons using a non-hydrostatic mesoscale model
Saji Mohandas	NCMRWF	Sensitivity of land surface parameterization on RSM forecast
N. V. Sam	IITD	Surface Fluxes and Related Convective Activity during MONEX- 79: A Single Column Experiment
Soma Sen Roy	IMD	Analysis of thermodynamics of atmosphere over NW India during a western disturbance as revealed by model analysis
S. Raghavan	IMD	Radar Observations of Mesoscale Phenomena and Tropical Cyclones
A. R. Jain	NMRF	Study of Tropical mesoscale convective systems over Gadanki using MST Radar and co-located L-band radar
G. Viswanathan	RDC/ ISRO	Indigenous development of Doppler weather Radar in India
P. C. Joshi	SAC/ ISRO	Satellite data for Mesoscale studies in the context of Indian Scenario
Krayn Sawyer	NCAR	Introduction to UCAR
V. S. Prasad	NCMRWF	High Resolution Satellite Data Sets for Mesoscale Applications

R. M. Saxena	IAF	A satellite study of western disturbances over northwest India during winter months
D. R. Sikka	ICRP	Mesoscale Weather Disturbances over India during Different Seasons
Ananda K. Das	IITD	Mesoscale Assimilation and Comparative Study of Circulation Characteristics of a Monsoon Depression
G. Srinivasan	IMD/ DST	Daily Rainfall Characteristics From a High Density Raingauge Network
O. P. Madan	IITD	Contrast in Meteorological fields of surplus and significant winter seasonal precipitation over Western Himalayas
R. M. Saxena	IAF	Mesoscale climatology of Ladakh area
O. P. Sharma	IITD	Mesoscale circulations forced by topographic heterogeneity
M. Mandal	IITD	Mesoscale Analysis and Tropical Cyclone Forecast: A Case Study
Y. V. Rama Rao	IMD	Cyclone Track Prediction with IMD limited area model and quasi-Lagrangian limited area model
P. K. Mohanty	BU	A study on the role of mesoscale phenomena on the incidence of wet and dry conditions over Orissa
K. Srinivasan	SASE	A Case study of western disturbance using MM5 model
M. R. Sakya	NMS	Weather Forecasting in Nepal

**Table –2: Acronyms of Affiliations**

AU	Andhra University, Waltair, India
BU	Berhampur University, India
CMMACS	Centre for Mathematical Modeling and Computer Simulations, India
DST	Department of Science & Technology, India
IAF	Indian Air Force
ICRP	Indian Climate Research Program
IITD	Indian Institute of Technology, Delhi
IITM	Indian Institute of Tropical Meteorology, Pune
IMD	India Meteorological Department
ISRO	Indian Space Research Organization
NCAR	National Centre for Atmospheric Research, USA
NCMRWF	National Centre for Medium Range Weather Forecasting, India
NMRF	National MST Radar Facility, India
NMS	Nepal Meteorological Service
RDC	Radar Development Cell, India
SAC	Space Application Centre, India
SASE	Snow & Avalanche Study Establishment, India
SPL	Space Physics Laboratory, India
VSSC	Vikram Saravai Space Centre, India

**Table – 3**

**Key issues and Recommendations**

<b>Issues</b>	<b>Recommendations</b>
What it takes to make a better weather forecast over the mountains?	<ul style="list-style-type: none"> <li>➤ Input observations at very high resolution</li> <li>➤ A mesoscale model of high resolution (&lt; 1 - 10 km) with appropriate physics</li> <li>➤ Appropriate 3D/4D variational data assimilation system</li> </ul>
How to generate better initial conditions for mesoscale forecasting over the Himalayas?	<ul style="list-style-type: none"> <li>➤ Set up mesoscale network of automatic weather stations along the entire Himalayan belt</li> <li>➤ Install Doppler Weather Radars covering the Himalayan range</li> <li>➤ Utilize satellite observations over the region.</li> </ul>
How to increase accuracy of forecasts over the Himalayas?	<ul style="list-style-type: none"> <li>➤ Conduct sensitivity experiments with the physical processes</li> <li>➤ Examine the forecasts at different resolutions in horizontal and vertical</li> </ul>
Do we understand the physical processes over the mountains?	<ul style="list-style-type: none"> <li>➤ Conduct special field experiments at suitable locations to study severe storms, cloud microphysics and other mesoscale convective complexes</li> <li>➤ Study air flow, mass and moisture fields over and around the mountain ranges under various synoptic conditions, Western Disturbances and Norwesters</li> <li>➤ Study the precipitation patterns and orographic contributions at different altitude ranges during summer and winter seasons</li> </ul>
What are the dynamical effects of mountains on the weather systems?	<ul style="list-style-type: none"> <li>➤ Study dynamic and physical processes associated with orographically forced thunderstorms</li> <li>➤ Improve understanding of mountain waves, lee cyclogenesis, gravity wave drag and, parameterization of sub-grid scale orography in NWP models</li> </ul>