Mesoscale weather prediction

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There is a growing demand for high resolution mesoscale weather information from sectors like aviation, air pollution, agro-meteorology and hydrology. Mesoscale meteorology is of special importance as local severe weather events cause extensive damage to property and life. Existing observational network and synoptic methods of forecasting cannot predict mesoscale events except in very general terms. They require observations on mesoscale, both in space and time, by means of Doppler radars, lidars, satellites, wind profilers, mesonetwork and aircraft. Mesoscale analysis involves assimilation of data from different sources and sensors. Good quality mesoscale data sets are necessary for the understanding of mesoscale weather phenomenon over the Indian region, developing diagnostic models and conducting mesoscale research and modelling work. The cost of setting up a mesoscale observational network can be prohibitively high and therefore, it is to be conceived as a multi-disciplinary, multi-agency system. This can be achieved by augmenting the existing synoptic network with observational facilities available with other users and participating agencies and developing additional facilities in data-void regions. Mesoscale data assimilation and analysis need to form an integral part of the mesoscale modelling plan at a national level. The proposed Integrated Mesoscale Modelling Programme is an important step in this direction. It is felt that a mesoscale field experiment will give the much-needed boost to the mesoscale modelling effort by creating technical, managerial and scientific expertise in the field of mesoscale meteorology in the country.

WEATHER-related natural disasters are becoming increasingly disruptive both in developed and developing nations. Loss of human lives, social and economic disruption are often caused by severe mesoscale weather events. Some of the high-impact weather phenomena for the Indian region are:

- Extreme precipitation events including cloud bursts and flash floods.
- Development and propagation of mesoscale convective systems, e.g. hailstorm, Nor'westers, dust storms.
- Mountain weather, mountain waves and valley winds.
- Snow/ice storm and blizzards over Jammu and Kashmir, Himachal Pradesh and hills of Uttar Pradesh.
- Intensity and location of rain bands and squall lines associated with the cyclonic storm at the time of land fall.

The demand for high-resolution meteorological information is growing rapidly from the sectors like aviation, air pollution, agriculture, defence, hydrology, out-door recreation and event management. Because of increase-ing population, urbanization and rapid industrialization, risk of natural disasters is also growing. Though the occurrence of severe weather cannot be avoided, improvement in the skill of predicting mesoscale weather events can help in issuing timely warning and taking precautions to minimize the impact of severe weather. Aircraft operations are adversely affected by severe weather. Aircraft accidents can be minimized and delays avoided by issuing timely weather forecasts. It has been estimated that a saving of US $1 billion could be realized by minimizing such weather-related accidents[1]. It is now known that synoptic-scale weather systems in the tropics derive most of their energy through mesoscale systems. The role of the complex topography of the Indian sub-continent in the genesis of sub synoptic and mesoscale systems over different regions has not been fully understood. Therefore, improved understanding of the mesoscale weather phenomenon and its prediction will be of great scientific, social and economic value. The Department of Science and Technology has rightly identified research in Severe Local Storms and Mesoscale Modelling as one of the important challenging thrust areas in Atmospheric Sciences.

Mesoscale

The spectrum of atmospheric motion extends from the mean free path of molecules at the lower end to the cir-

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cumference of the earth at the upper end. Within such a wide range of motion, meteorologists have attempted to classify atmospheric flow according to the physical scale of the apparently coherent structure that appears generally or intermittently in an atmospheric flow. The classification of atmospheric motion in different scales has been guided by three factors: observation of atmospheric phenomena, resolution of observational network and theoretical inferences.

Though the first observational evidence of the mesoscale of atmospheric motion was known to common man in the form cumulus cloud, its recognition in meteorology came much after the synoptic scale. Early work in meteorology in the 19th century and early 20th century focused on large-scale features derived from synoptic charts. The well-known model of extra tropical cyclone by Bjerknes and Solberg[2] was developed during this period. It was in 1930s that aircraft accidents related to thunderstorms and squall lines necessitated establishment of meso networks for better understanding of thunderstorms that escape detection by the synoptic network. The advent of weather radar contributed significantly to the study of thunderstorms and to the success of the Thunderstorm Project[3].

Ligda[4] introduced the term mesoscale for the first time in meteorology on the basis of weather radar observations of sub synoptic scale features. Observational evidence from radars and special surface observation network of the US Severe Local Storm Unit substantiated existence of the mesoscale weather phenomenon propounded by Ligda. Tepper[5] highlighted the importance of meso meteorology as a link between macroscale atmospheric motion and local weather and presented three-fold division of atmospheric flow into macro-, meso- and microscale. Sub synoptic scale studies till the 1960s covered the mesoscale as well. Since then Doppler radar, high-resolution satellite imageries, instrumented aircraft, mesonet data along with increased theoretical understanding and mathematical modelling capabilities contributed significantly to the growth of mesoscale as a distinct separate scale of atmospheric motion. Orlanski[6] classified mesoscale into α, β, and γ sub-scales according to horizontal dimension of the meteorological system. It extends through three orders of magnitude, α (2 to 20 km), β (20 to 200 km) and γ (200 to 2000 km). A recent classification by Fujita[7] consists of two sub-classes meso α (40 to 400 km) and meso β (4 to 40 km). Thus in spite of advancements in meso meteorology no uniformly accepted definition exists. Mesoscale can be descriptively defined as having temporal and horizontal spatial scales smaller than the conventional radiosonde network but significantly larger than individual cumulus clouds. This implies that horizontal scale is of the order of a few kilometres to several hundred kilometres and time scale of 1 to 12 h (ref. 8).

The conventional meteorological observation network is suitable only for the analysis and forecasting of large-scale (synoptic and planetary) meteorological systems. Therefore, the necessity to conduct special field experiments for the understanding of mesoscale weather systems was felt as early as 1940. Some of these experiments are:

- Nor'wester Project at West Bengal in 1941.
- Thunderstorm Project in USA during summer seasons of 1946 and 1947.
- Mesoscale rainfall experiment at Pune in 1964.
- Line Islands Experiment (LIE) in equatorial Pacific in 1967.
- BOMEX in the Barbados area in 1969.
- VIMHEX-1972 at Venezuela in 1972.
- GATE in East Atlantic in 1974.
- Severe Environmental Storm and Mesoscale Experiment (SESAME) in USA in late the 1970s.
- Programme for Regional Observing and Forecasting System (PROFS).
- The Co-operative Convective Precipitation Experiment (CCOPE) in South-eastern Montana in USA in 1981.
- Joint Airport Weather Studies (JAWS) and Classify, Locate, Avoid Wind Shear (CLAWS) at Denver air port in USA.
- Mesoscale Frontal Dynamics Project, FRONTS 87, over the English Channel.
- Convection Initiation and Downburst Experiment (CINDE) in 1987.
- The Winter Icing and Severe Storms Project (WISP) in USA during winter seasons of 1990 to 1994.

Mesoscale prediction

Knowledge of meteorology forms the basis of scientific weather forecasting. This knowledge imposes an upper limit to various forecasting techniques[9]. In the region of mesoscale (1 to 12 h), a dip in the knowledge curve (Figure 1) is attributed to the lack of understanding of mesoscale weather processes. The meteorological data available on Global Telecommunication System (GTS) and India Meteorological Department (IMD) channels primarily cater to synoptic analysis and forecasting. These data do not have the required resolution in space and time to resolve and define mesoscale systems. Lack of data on mesoscale is one of the primary reasons for poor understanding of mesoscale weather phenomena over the Indian region. This severely restricts the capability to predict mesoscale events, except in very general terms. Objectively analysed data prepared by National Centre for Medium Range Forecasting (NCMRWF) and IMD are of 1.50 lat./long. resolution which is rather coarse for mesoscale NWP models having resolution of 10 to 50 km (0.1 to 0.5 lat./long.).

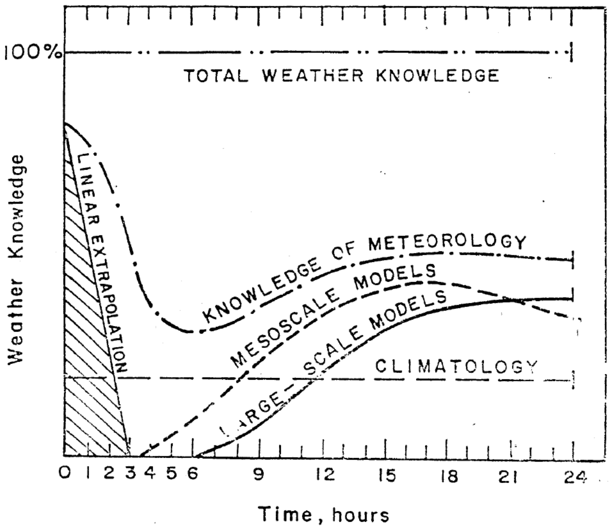

Figure 1. Forecasting skill of different mesoscale short-range forecasting techniques[9].

The mesoscale atmospheric system can be divided into three groups:

1. Those that are primarily forced by surface inhomogeneities (terrain-induced mesoscale systems), e.g. sea and land breeze, valley winds, urban circulations.
2. Those that are primarily forced by instabilities travelling in large-scale disturbances (synoptically-induced mesoscale system), e.g. squall lines and mesoscale cloud clusters.
3. Combinations of the above where instabilities of large-scale features get accentuated and/or persist for longer periods due to orographic features, e.g. heavy precipitation and severe thunderstorm activity at certain locations.

The first group is the least difficult to forecast because the source of mesoscale circulations is geographically fixed with a time scale of 12 h or so. These mesoscale systems do not generally move from the point of their origin and in general do not require detailed spatial resolution, initial, lateral and top boundary conditions for dependent variables. Similar to synoptic scale weather forecasting, mesoscale prediction also consists of three components: (a) observation; (b) analysis and diagnostics; (c) prediction.

Observation

Mesoscale meteorology has immensely benefited from major developments in observational techniques. Weather radars, high-resolution satellite imageries, wind profilers, mesonetworks, automated weather stations and instrumented aircraft have contributed significantly to the growth of mesoscale meteorology. Of these, Doppler radar requires special mention as it promises to be one of the most useful sources of mesoscale information. In addition to having all the capabilities of a conventional radar, Doppler radar can indicate radial velocities of any target volume and hence gives indication of wind flow in the target volume. These may include wind shears, meso cyclones, down burst and cloud top divergence.

Another development from which mesoscale meteorology has immensely benefited is the use of real time digital communication by commercial aircraft for obtaining weather observations. The line of sight VHF telecommunication system, called Aircraft Communication Addressing and Recording System (ACARS), allows very reliable two-way air to ground digital communications. The winds are automatically obtained via the inertial navigation system and the ambient temperature is obtained from the total air temperature probe. The number of air reports received each day is approximately 22,000 (ref. 10) and primarily because of ACARS meteorological data the US has a 3 h operational Mesoscale Analysis and Prediction System (MAPS) update cycle.

The new ACARS meteorological format will provide meteorological data every 100 m during ascent with an option to lower this to 50 m vertical resolution and en-route 3 min sampling interval. At typical aircraft speeds 3 min interval represents 40 km resolution. Water Vapour Sensing System (WVSS) developed by Lockheed Martin installed on B-757 aircraft is in the stage of certification. It is estimated that addition of water vapour information in aircraft atmospheric profile would lead to a 5-fold increase compared to radiosonde[10].

Mesoscale analysis

The all-round developments in mesoscale observation techniques have led to an improvement in the quality and manifold increase in the quantity of mesoscale information. The developments in communication and computers helped meteorologists to process/analyse vast amounts of mesoscale information. Mesoscale data collected from different sources and sensors can be received by a central forecasting office or field forecasting office in near real time. A work station-based interactive processing system provides facility to ingest, process, integrate and analyse various types of data. It allows the forecaster to search for the required information, overlay different types of information for comparison and integration, zoom in areas of interest and loop information to produce animated displays which reveal patterns over time.

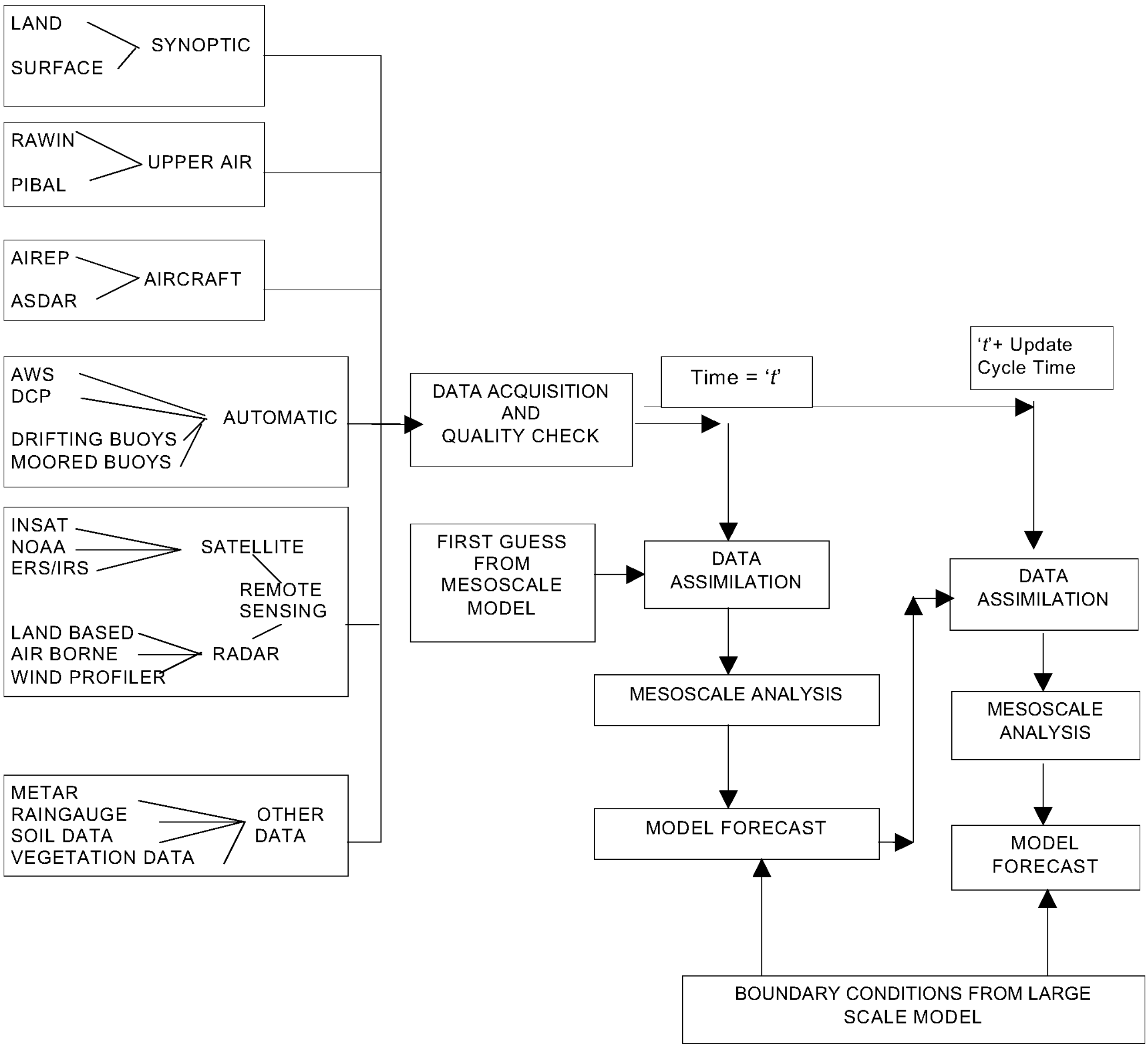

Figure 2. Schematic of mesoscale analysis and prediction system.

Mesoscale analysis is an important pre-requisite for mesoscale research and modelling work. It has evolved as specialized activity involving data acquisition, quality control check, background first guess from the model, data ingest and assimilation. A schematic diagram of the mesoscale analysis system is shown in Figure 2. Today mesoscale analysis with rapid update cycle of one hour is in operational use in USA. MAPS has 40 levels in vertical with explicit treatment of cloud physics with cloud/liquid water, rain water, snow and ice[11]. The one-hour update cycle makes optimum use of high frequency data such as hourly surface observations, profiler and aircraft data.

As on date not a single grid point mesoscale data set is available for the Indian region. There is an urgent need to start work in developing a mesoscale analysis system. The aim should be to generate 50 km resolution data set over data-rich regions. Apart from IMD observatories, data from Indian Air Force, Army and Navy, agriculture department/universities, irrigation department, air pollution centres, state raingauges and all other sources should be augmented. Satellite and aircraft data need to be fully exploited for mesoscale analysis. Assimilation of geostationary satellite sounder data coupled with radiosonde and surface data has been successfully achieved in mesoscale analysis[12].

Mesoscale forecasting

The mesoscale weather phenomenon ranges from microscale turbulence to mesoscale cloud clusters. Depending upon the type of weather elements and their life period, an appropriate observational tool and a good forecasting technique needs to employed. Mesoscale weather forecasting requirements can be broadly grouped into three classes. These are: (a) nowcasting; (b) very short range forecasting and (c) short range forecasting.

Nowcasting: This is based on the ability of the forecaster to assimilate great quantities of weather data, conceptualize a model that encompasses the structure and evolution of the phenomenon and extrapolate this in time. Nowcasts require high resolution of spatial and temporal meteorological data to detect and predict the occurrence of an event. Lack of data of the mesoscale imposes limit on ability to diagnose and predict an event. Nowcasting has benefited from major developments in observational meteorology and computer-based interactive data processing and display systems. Weather radars, automated weather stations, weather satellites, lidars and low level wind shear alert systems have become standard observing tools for nowcasting. The ability of the Doppler radar to sample the pre-storm environment is of great practical value to a mesoscale forecaster. Low-level convergent boundaries may be located from the movement of non-hydrometeoric targets and the detection of the density discontinuities[13]. By scanning at elevation the Doppler radar can provide mean vertical wind shear profile and depth of moist layer in the radar environment. This allows the forecaster to monitor these important phenomena which often provide valuable insight about convective storm and initiation of severe weather.

Very short range forecasting: The focus of nowcasting techniques is on obtaining an accurate picture of the present weather situation and then deducing the future from this state by using the trend of the present weather. The most commonly used practice of trend is linear extrapolation. However, the limits of linear extrapolation become apparent with increasing time on the bounds of the forecast accuracy desired. Zisper[14] estimated the typical time period of valid extrapolation for various weather forecasts (Table 1). Thus for most weather processes relevant to mesoscale forecasting, it is clear that linear extrapolation beyond a few hours is not very useful.

Linear extrapolation loses its predictive value rapidly beyond one hour and becomes inferior to climatology beyond two hours[9]. On the other hand, a large-scale model due to poor representation of local observed state, limited resolution and imperfect assimilation and parameterization schemes does not contribute significantly till 09 h and becomes superior to climatology only after 12 h. Mesoscale models by finer resolution and better assimilation of local weather have been able to reduce the gap showing skill above climatology at $t + 6$ h.

Developed by UK meteorological office, NIMROD addresses directly the gap between nowcasting and NWP model guidance by integrating the systems in a single automated system for forecasting the main weather variable up to 06 h ahead[15,16]. The analyses and forecasts for visibility and precipitation are generated on a 05 km grid and clouds and derived products on a 15 km grid. NIMROD provides forecasts of visibility and clouds in half-hourly steps up to 06 h ahead, which are available within 40 min of data time. The analyses and forecasts of cloud are updated hourly. The precipitation component is based on a 15 min cycle and forecasts are also generated in 15 min interval. The NWP model input is updated every 06 h. The nowcasting and NWP techniques are fully integrated at all stages; all main variables are coupled. Integration of data allows maximum cost-effective utilization of data from radars; satellites, aircrafts, profiles and surface-based observing systems. Full automation of the system has led to reduction in lead times, more frequent updates and improved consistency between the runs. In future with enhanced super computing facilities becoming available, NIMROD will have access to frequent NWP model runs at finer resolution. The results of the NIMROD system show a substantial improvement over NWP, persistence and stand alone nowcasting system till $t + 06$ h.

Short range forecasting: NWP guidance has become the mainstay of short range forecasting of weather phenomena. Over a period of time, the quality and utility of NWP guidance has improved greatly. Today regional models with horizontal resolution between 20 and 50 km with 20 to 40 levels in vertical, and mesoscale models having grid spacing as low as 5 km are operational at many meteorological centres. The distribution

Table 1. Examples of typical linear extrapolation time scales of various mesoscale weather events (Adapted from Zisper[14])

Weather event	Time scale for linear extrapolation validity	Nonlinear predictive capability
Downburst/microburst	~1 to few min	Very limited
Tornado	~1 to few min	Currently very limited
Individual thunderstorm	5 to 20 min	Very limited
Severe thunderstorm	10 min to 1 h	Very limited
Thunderstorm organized on mesoscale	~1 to 2 h	Some
Flash flood rainfall	~1 to few hours	Very limited
Orographic high winds	Few hours	Some
Heavy snow/blizzard	Few hours	Very limited
Low visibility	Few hours	Some

of NWP guidance via World Area Forecast System (WAFS) offers access to digital data sets, which could be used as local diagnostic and forecasting tools. The horizontal and vertical resolution of the data included in the satellite broadcasts have been designed to retain a maximum amount of the information expected from global forecast models. Although at present the mandatory data for the satellite transmission include only winds and temperature aloft, plans are underway to include additional forecast parameters, especially important to a variety of aviation-related forecast problems, including relative humidity, geopotential height, mean sea level pressure and the location and intensity of precipitation, including convection. Global products combined with regional and mesoscale field products processed through a personal computer-based diagnostic and display system at field forecasting offices hold great potential to revolutionize the mesoscale forecasting process and greatly increase the accuracy of mesoscale forecast.

Keeping in mind the requirements of a mesoscale forecaster, NOAA's forecast system laboratory has developed a Local Analysis and Prediction System (LAPS). It produces analysis adjustable grid resolution of 10 km horizontally and 50 levels vertically (i.e. clouds, precipitation, temperature and other meteorological phenomena). Derived fields from clouds analysis include cloud type, cloud liquid water content, cloud drop size and icing severity[17]. The cloud fields that are inputs for the LAPS humidity analysis are used to aid initialization of the forecast modelling components of LAPS. High-resolution local analysis is of immense use in forecasting localized phenomena such as fog, convective clouds and intensity of precipitation. Such a data set enables the forecaster to quickly update the knowledge of local fields and to animate these fields on a personal computer to diagnose local meteorological situation. LAPS was efficiently used to produce high-resolution analysis and forecast using an onsite standard computer platform by the olympic weather support system of XXXVI Atlanta Olympic Games[18]. LAPS integrated all the available data from WSR-88D radar, surface observations from Automated Surface Observing Systems, buoys, and local mesonetwork sites, satellites, profilers and aircraft data and background fields from numerical models[19]. LAPS produced an analysis of standard measured and derived variables at both the surface and upper levels. These were available to the forecaster for further analysis and also as initial conditions for Regional Atmospheric Modelling System (RAMS), the prediction component of LAPS. LAPS is relocatable and resizable so as to be functional at any part of the globe. The US Air Force is making use of LAPS to support operations in 10 global theatres, including Alaska, Asia and tropical regions. Two examples of LAPS-generated products are shown in Figure 3. A 13 h forecast of wind, potential temperature and clouds over East China is shown in Figure 3 *a* and a model convective outlook for continental USA is depicted in the Figure 3 *b*.

Mesoscale modelling

Mesoscale models

The availability of high-power computers has led to the development of a variety of mesoscale models both in research and operational mode. These models fall primarily into three categories: (a) mesoscale non-hydrostatic models; (b) mesoscale hydrostatic models and (c) convective cloud models.

Operational mesoscale NWP is now taking place in USA, UK, France, Japan, Australia, Poland, Austria, Rumania, Hungary and other European countries. With ready access to gridded mesoscale analysis on the Internet for initialization and boundary conditions, mesoscale models are being run in real time at many universities and centres[20] in USA, besides National Centre for Environmental Prediction (NCEP). The Eta model at 32 km horizontal resolution is being run for the entire USA by NCEP twice daily. On an experimental basis, the Eta model has been run once a day on a 10 km grid resolution for portions of the US. In Europe an international project for mesoscale modelling called ALADIN (Aire Limitee Adaptation Dynamique Development International) involves 14 National Meteorological Services[21]. Some examples of current status of mesoscale models in the world are given in Table 2. Mesoscale models by virtue of very high resolution and full microphysics have been able to provide insight into the three-dimensional structure of mesoscale systems taking into account the interaction between different scales of motion. The Regional Atmospheric Modelling System (RAMS) has been able simulate frontal system of 11 January 1987, observed during FRONTS-87 experiment. Using four nested grids and a non-hydrostic version, the model was able to reproduce the frontal structure with an intense low level jet, the temperature gradients marking the frontal discontinuity, the low level cross-front inflow, updrafts just ahead of the front and narrow cold front rain band[22]. In addition to case studies and simulations by research groups, evaluation of the performance of operational mesoscale models for different seasons and locations has been carried out by many workers[23,24].

Numerical prediction of thunderstorm

Numerical prediction of thunderstorm is a logical extension of ongoing developments in mesoscale modelling. Access to high resolution data, better assimilation tech-

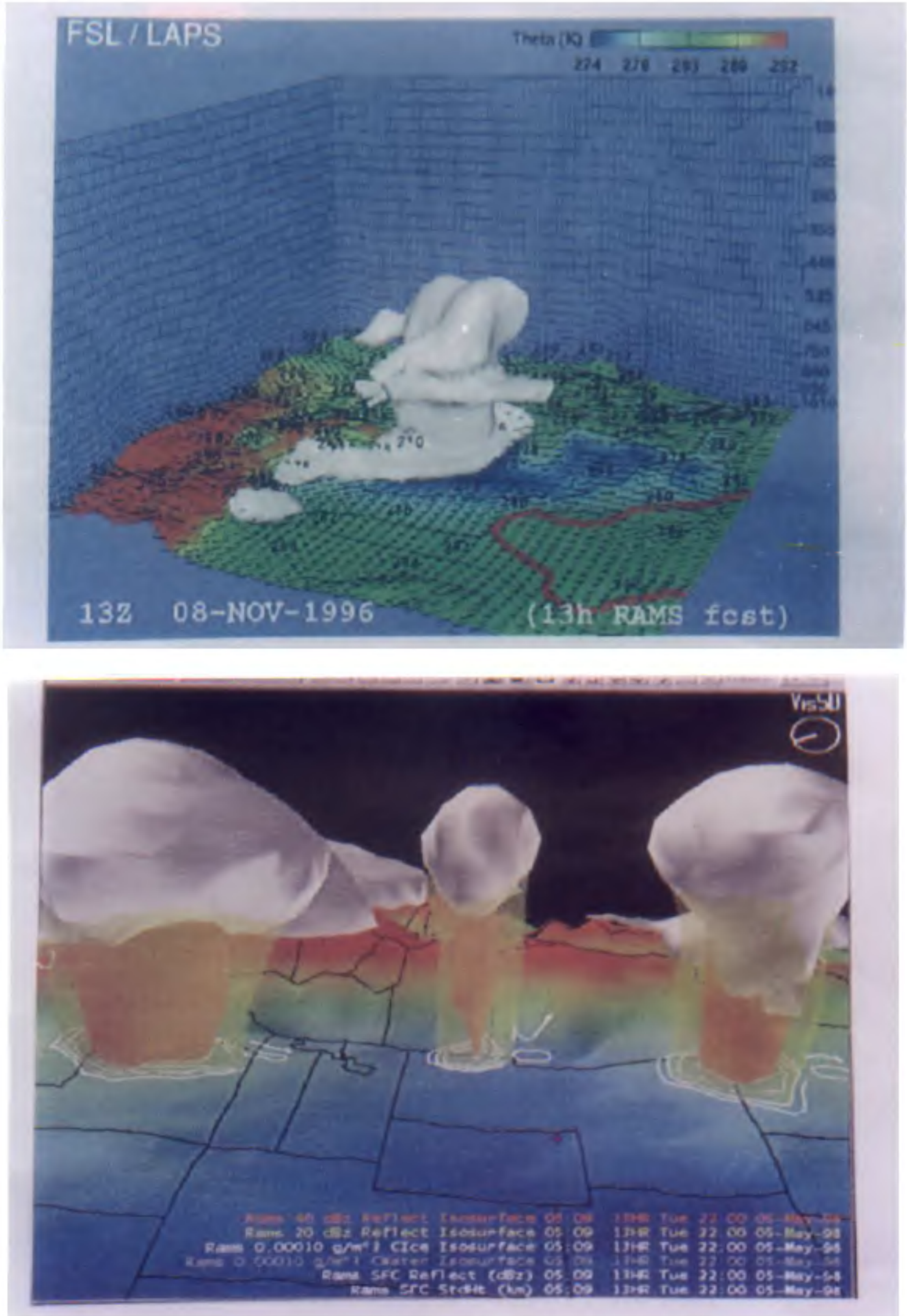

Figure 3. ***a***, A 13 h mesoscale forecast of wind, potential temperature and clouds over East China. Beijing is located near the centre of the domain and the thick line outlines the north-west corner of the East China Sea (FSL annual report 1997–98); ***b***, Mesoscale convective outlook from LAPS for continental USA for 2200 UTC on 05 May 1998. White iso-surfaces depict cloud ice concentration. Model-predicted radar reflectivity is depicted by orange iso-surfaces.

Table 2. Some examples of the current status of mesoscale models

Country and Institution	Model	Horizontal resolution (km)	Vertical levels
USA			
NCEP	Eta-32	32	50
US Navy			
FNMOC	COAMPS	81/27/9	
University of Washington	MM5	36/12/4	33
The Pennsylvania University	MM5	36/12	30
National Severe Storm Laboratory	MM5	29	27
Colorado State University	RAMS	60/20/5/1.25	27
North Carolina University	MASS	45/15	25
University of Oklahoma	ARPS	9/3	43
Japan			
Japan Meteorological Agency	Regional spectral model	20	36
Meteorological Research Institute	Non-hydrostatic model	10	36
UK			
Meteorological office	Mesoscale model	17	
Australia			
Bureau of Meteorology	TLPAS	75	19
University of New South Wales	High resolution model	Variable down to1km	31
France			
Maroc-Meteo	ALADIN	16.6	27
Meteo France	ALADIN	12.7	27
Austria			
National Met Service	ALADIN	14.7	27
Czech Republic			
National Met service	ALADIN	14.7	27
Hungary			
National Met Service	ALADIN	14.7	27
Romania			
National Met Service	ALADIN	12.3	27
Slovenia			
National Met Service	ALADIN	11.7	27
Belgium			
National Met Service	ALADIN	7.0	27

MM5, The Pennsylvania State University/National Centre for Atmospheric Research (NCAR) Mesoscale model – Fifth generation; FNMOC, US Navy's Fleet Numerical Meteorology and Oceanographic Centre; COAMPS, US Navy's Coupled Ocean Atmosphere Mesoscale Prediction System; MASS, Mesoscale Atmospheric Simulation; RAMS, Regional Atmospheric Modelling System; ARPS, University of Oklahoma's Non-hydrostatic Advanced Regional Prediction System; TLAPS, Tropical Limited Area Prediction System; ALADIN, Aire Limited Adaptation Dynamique Development International.

niques, improved understanding of convective cloud processes and availability of high-speed computers has brought operational NWP of thunderstorm in the realms of reality. The Centre for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma is engaged in developing storm scale NWP system for operational use[25]. The goal is to produce 06 to 09 h forecast in 30 to 60 min for a domain of the order of 1000×1000 km^2. The prediction component of CAPS is a three-dimensional non-hydrostatic Advanced Regional Prediction System (ARPS). It includes data ingest, quality control and objective analysis, a single Doppler radar parameter and retrieval and data assimilation system, prediction model and post forecasting packages. The model has an outer grid at 09 km resolution, and an inner grid at 03 km resolution with 43 vertical levels for both domains. A number of real time operational tests have been conducted since 1993 in collaboration with US National Weather Service, the NOAA Storm Prediction Center, US Air Force, American Air Lines, National Aviation Weather Center and Korean Meteorological Administration. The ARPS has been able to capture the overall structure and to predict explicitly the initiation and evolution of individual convective storms for real time operational application morphology of the intense storm. When dynamical forcing is weak, the skill of the model is reduced. CAPS is planning to increase spatial resolutions more suited for thunderstorm down to 01 km using multiple two-way nesting with the outer grids of 04 and 16 km resolution and to use real time wide band data from several WSR-88D radars. Another operational experiment STORMTIPE-95 (Storm Type Operational Research Model Test Including Predictability Evaluation) using a three-dimensional cloud model was carried out for the north Texas region during the spring of 1995. Grid point sounding obtained from operational numerical prediction models was used to initialize a limited domain cloud resolving the model in an attempt to predict convective storm type and morphology in a timely manner[26]. These experiments have demonstrated the ability of numerical weather prediction models to explicitly resolve individual thunderstorms and their operational use may be possible in the near future[27].

Mesoscale research in India

Mesoscale weather such as severe thunderstorm, strong winds, heavy precipitation and cloud bursts has considerable dependence on local terrain, land–water body contrast, localized sources of moisture and aerosols and local anomalies to synoptic scale forcing. Understanding the mechanism of development, persistence, movement and decay of mesoscale weather phenomena is an essential prerequisite for developing diagnostic models and mesoscale forecasting techniques for the Indian sub-continent. In spite of the availability of limited data in the period prior to the 1970s, Indian meteorologists did pioneer work in mesoscale research specially in thunderstorm research and forecasting. Important among these are Pramanik[28], Nor'wester Project[29], Roy[30], Rao and Mukherjee[31], Asnani[32], Mukherjee and Chaudhary[33].

Radar observations started in India in the early 50s, with radars operating at a wavelength of 3 cm mainly to detect local thunderstorm. During this period a number of radar-based studies by Koteswaram and De[34], Mull and Kulshrestha[35], Mathur and Kulshrestha[36] and many others contributed to thunderstorm research in India. Raghavan *et al.*[37] demonstrated the application of digital radar for the assessment and short period forecasting of precipitation. Based on Runway Visual Range (RVR), surface wind and radar observations at Palam airport, Joseph *et al.*[38] developed a model of the Andhi. In the early seventies, a set of 10 cm radars were set up along the Indian coasts mainly to detect and track cyclones. The wavelength of 10 cm enables long distance tracking (nominally up to about 400 km) free from attenuation of intervening rainfall. These radars provided useful insight about pre-cyclone squall lines, spiral rain bands and rain shields[39], eye wall structure and outer convective activity. With the help of radar observations, Gupta and Mohanty[40] identified secondary convective rings in an intense asymmetric cyclone of Bay of Bengal. Radar pictures depicting secondary convective rings are shown in Figure 4.

The advent of meteorological satellites in the sixties made significant impact on detection and monitoring of severe weather phenomena. The availability of cloud imageries from the Indian geo-stationary satellite INSAT provided an effective tool to detect and monitor tropical cyclones and predict their tracks[41]. The satellite picture of a Bay of Bengal cyclone taken from INSAT is shown in Figure 5. The centre of the storm can be precisely marked with the help of a satellite picture. The INSAT cloud imageries have the capability of observing simultaneously the evolution of clouds from synoptic scale to cumulus scale. The cloud imageries, at an interval of 30 min, are able to capture convective scale interactions which are most vital for initiation of deep convection. Meso-high, a characteristic feature associated with intense thunderstorms is generally seen as an arc-shaped cloud boundary in the satellite pictures. Bhatia and Jain[42] have shown that by observing the interaction of arc clouds with other cloud boundaries with the help of INSAT pictures, one can precisely locate the potential areas of thunderstorm development a few hours in advance. Kalsi and Bhatia[43] studied the devel-

Figure 4. Double eye wall observed in photographs of Cyclone Detection Radar, Chennai at ***a***, 1753 UTC of 07 May 1990; ***b***, 2044 UTC of 07 May 1990; and ***c***, 0041 UTC of 08 May 1990 (range 200 km, range marker interval 40 km) (ref. 40).

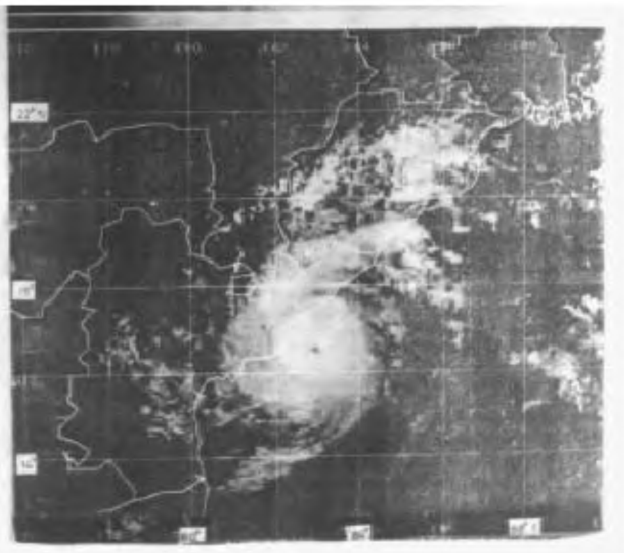

Figure 5. INSAT picture of a severe cyclonic storm off Andhra Pradesh coast in the Bay of Bengal. A distinct eye is observed in the satellite picture.

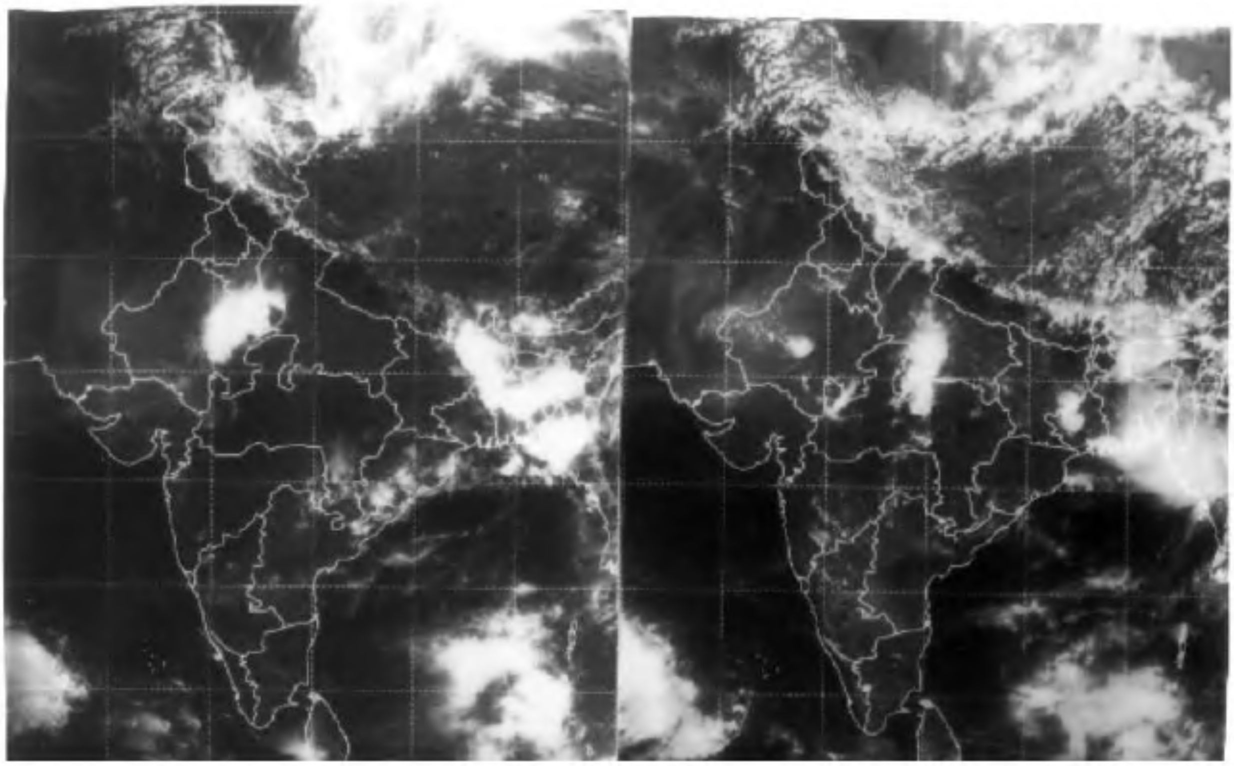

Figure 6. INSAT visible picture of a mesoscale convective complex at ***a***, 03 UTC on 01 June 1991; and ***b***, 09 UTC on 01 June 1991.

opment of thunderstorm complexes in a weakly forced environment with the help of INSAT imageries. The capability of INSAT pictures in detecting mesoscale convective complex and its subsequent movement is brought out in Figure 6. An intense mesoscale convective complex was observed over Delhi and adjoining east Rajasthan at 03 UTC (Figure 6 *a*). Its eastward movement to central Uttar Pradesh and weakening is clearly seen in the INSAT picture of 09 UTC (Figure 6 *b*). Kalsi[44] confirmed the existence of a double eye wall structure in an intense cyclone with the help of satellite and radar observations.

Attempts were made by several workers[45–47] to apply simplified versions of mesoscale models for local circulation over the Indian region. During the 1980s, modelling groups at IMD, the Indian Institute of Tropical Meteorology (IITM) and the Indian Institute of Technology (IIT), Delhi carried out evaluation of multilevel Limited Area Models (LAM) for short-range prediction over the Indian region[48,49]. Turbulence Kinetic Energy (TKE) Closure in a high-resolution LAM over monsoon trough region was tested by Tyagi *et al.*[50] and Potty *et al.*[51,52]. Simulation studies with respect to cyclonic storm have also been attempted[53,54].

However, mesoscale research and forecasting in India could not keep pace with developments of the post-1970 period, specially in respect of mesoscale observational techniques (Doppler radar, wind profilers, meso-network), mesoscale analysis and mesoscale NWP. In India, even today operational mesoscale weather forecasting continues to be based on synoptic methods. While significant progress has been made in long-range forecasting, monsoon meteorology, satellite meteorology, tropical cyclone surveillance and medium range NWP, similar progress has not taken place in the field of mesoscale meteorology, mesoscale modelling and severe weather forecasting.

In the recent past there has been definite revival of interest in mesoscale research in our country. A number of research groups are actively engaged in mesoscale modelling work at IMD, IITM, Indian Institute of Science (IISc), IIT and other universities and research institutions. A major transition in mesoscale research is taking place, one in which mesoscale modelling and research is spreading from a handful of national centres to a number of institutions across the country. It has become possible because of the availability of modestly priced single and multiprocessor workstations and easy access to mesoscale models. IMD conducted an advanced refresher course on mesoscale systems and circulations with special emphasis on tropical cyclones at Pune between 20 April and 4 May 1996. A national seminar on NWP with emphasis on boundary layer modelling and mesoscale modelling was held at

Jadavpur University in December 1998. In this seminar, a wide variety of papers related to mesoscale modelling in India were presented. This included the study of heavy rainfall zones over coastal Kerala with Eta model[55], numerical simulation of a Bay of Bengal cyclone using NCAR MM5 mesoscale model[56], effect of synthetic data on prediction of the track of cyclones over the Bay of Bengal by a high resolution LAM[57] and simulation of mesoscale features of the south-west monsoon by nested grid mesoscale LAM[58]. Other papers covered objective analysis[59,60], initialization[61], use of remote sensing[62,63], effect of topography[64–66], sea breeze simulation[67], role of surface fluxes[68] and parameterization of convection[69]. However, for want of mesoscale analysis no major progress could be made in developing mesoscale diagnostic models for the Indian region and modellers have not been able to critically evaluate the performance of various mesoscale models.

Integrated mesoscale modelling programme

It is now widely realized that reliable forecasting of atmospheric and oceanic mesoscale processes can provide cost-effective solutions for better resource management, planning and crisis management. Mesoscale forecasting requirement covers a wide range applications from aviation to coastal zone management, defence to industrial risk analysis, air pollution to severe weather alert and forest fire to mountain meteorology. In view of societal and strategic value of an effective mesoscale forecasting system, a discussion meeting on issues in mesoscale modelling was held at CSIR Centre for Mathematical Modelling and Computer Simulation, Bangalore during 6 and 7 August 1999. The major recommendation of the discussion meeting was that a nationally coordinated and integrated programme would lead to an effective and versatile Mesoscale Forecasting System (MFS) for India. To cater to the needs of diverse users, an Integrated Mesoscale Modelling Programme (IMMP) has been conceived[70] with the following objectives:

1. To develop an effective mesoscale forecast system by integrating model development, observation programmes, database management and assimilation methodology.
2. To develop the MFS into a versatile modelling platform by making it adaptable to diverse geographical, agricultural, industrial and other environmental conditions.
3. To identify, model and integrate diverse user needs to the MFS through a user interface to make it a modelling platform of global standard.
4. To develop a resource sharing, coordinated modelling programme for optimum participation by various groups in the country.
5. To develop, enhance and maintain an integrated manpower development programme in the area of mesoscale modelling for continuous upgradation of skill and performance.

The major scientific issues of the IMMP include process modelling, model physics, model development/evaluation, data generation and assimilation, mesoscale dignostics and forecast methodology. Initiation of a multi-component pilot project and integrated computing network were two important recommendations of the meeting.

Need for mesoscale analysis

Mesoscale analysis is an important prerequisite for worthwhile mesoscale modelling and forecasting work. There is an urgent need to initiate a time-bound programme to prepare mesoscale analysis of at least of 50 km resolution for the Indian region. This could be achieved by augmenting the analysis carried out at IMD and NCMRWF by assimilating INSAT data, HRPT data of polar orbiting satellites, aircraft reports, synoptic and asynoptic data from the Indian Air Force, Navy, Army, DRDO, Agriculture universities/colleges, pollution centres, and the irrigation department. The costs and logistics of obtaining mesoscale observations over the entire country by a single agency can be staggering.

Table 3. List of some of the observational facilities and resource agencies

Facility/service	Resource agency
Weather radar/Doppler radar	IMD, National Airport Authority
Met surface observatories	Participating agencies
Radiosonde and pilot balloon observations	IMD, IAF, Indian Navy, DRDO
Half hourly INSAT data	IMD
HRPT data of NOAA satellites	IMD, SAC, NRSA
IRS, ERS data	ISRO, NRSA, SAC
Sodar	IITM, NPL
Aircraft data	IAF, NRSA, airlines
Micro Met towers	DST, IISc, IITM, Agriculture universities
Automatic weather stations, DCPs	IMD, DRDO, Industries
Radiation data	IMD Radiation observatories
Ship observations	Indian Navy, NIO, Shipping liners
Topography	Director General of Survey
Aerosol concentration	Air pollution centres
Soil characteristics, vegetation details	Agriculture Department, Soil Survey Department
Rainfall data	Synoptic observatories, irrigation, agriculture and other rain gauges
NWP model background analysis	IMD, NCMRWF
Mesoscale model evaluation	IMD, IITs, IISc, IITM and other institutions

Mesoscale information is operationally useful for agrometeorology, aviation, defence, hydrology and air pollution. Therefore, a multi-disciplinary and multi-agency framework of mesoscale observatories needs to be developed to augment the existing synoptic observatories of IMD. Such an arrangement will benefit from the strengths and resources of different agencies and promote multi-disciplinary research and cooperation in mesoscale meteorology. IMD, NCMRWF or any other institution should be identified and designated as a nodal agency to formulate, coordinate and implement a national plan of mesoscale data collection, analysis and dissemination.

In order to develop high quality and high resolution (10 km or less) mesoscale data sets, the proposal of a mesoscale field experiment needs serious consideration. Gangetic West Bengal and adjoining Orissa and Chhota Nagpur regions provide ideal settings for a mesoscale field experiment. This region has superior logistics, communication and organization set-up compared to north-east India. Such a field experiment will provide the much-needed data set to study:

(a) Formation of Nor'westers and associated severe squalls and lightening;
(b) PBL processes associated with eastern end of monsoon trough, lows and depressions;
(c) Cumulus convection during weak, normal, active and vigorous monsoon conditions;
(d) Heavy rainfall events;
(e) Role of topography in the initiation of convection;
(f) Aerosols concentration and its role in the formation of clouds;
(g) Dispersal of air pollutants;
(h) Role of soil moisture and wet ground in the mesoscale surface energy budget.

The planning and successful performance of a mesoscale field experiment is a great challenge for the Indian meteorological community. It requires coordination and optimum utilization of scientific, technical, managerial and organizational resources available with different agencies at the national and state level. Some of these are listed in Table 3. Indian meteorologists have successfully planned and conducted MONTBLEX[71] and BOBMEX field experiments and participated in various international experiments, viz. International Indian Ocean Experiment (IIOE), Indo-Soviet Experiment (ISMEX), Monsoon 77, Monsoon Experiment (MONEX) and the recently held International Indian Ocean Experiment-INDOEX[72]. With experience and expertise gained from these experiments, Indian meteorologists will be able to plan and conduct the mesoscale field experiment with success. Such a field experiment will provide the much-needed high quality mesoscale data sets and develop technical, scientific and managerial expertise in mesoscale meteorology.

Conclusions

Mesoscale analysis modelling and prediction can be viewed as an integrated system. No worthwhile mesoscale research and modelling work can be carried out without good quality mesoscale data sets for the Indian sub-continent. Mesoscale modelling the world over has immensely benefited from easy access to gridded mesoscale analysis on the Internet, availability of modestly priced high power workstations and free exchange of mesoscale models. Today a wide variety of mesoscale models are functional at national meteorological centres in operational mode and at universities for research and development. One of the reasons for slow progress in mesoscale modelling in India can be attributed to the non-availability of mesoscale data sets. Therefore, mesoscale analysis needs to be taken up on a high priority and it must form an integral part of the mesoscale modelling effort at a national level. It involves on the one hand, augmentation of existing observational network and on the other, assimilation of satellite, radar, aircraft and other asynoptic data. For this IMD, NCMRWF or any other institution should be designated as a nodal agency to formulate, coordinate and implement a comprehensive plan of mesoscale data acquisition, assimilation and analysis. The proposed IMMP is an important step in this respect. It is felt that a mesoscale field experiment will provide good mesoscale data and will also help in developing scientific, technical and managerial expertise in the field of mesoscale meteorology in the country.

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