Heavy rainfall episode over Mumbai on 26 July 2005: Assessment of NWP guidance

A. K. Bohra*, Swati Basu, E. N. Rajagopal, G. R. Iyengar, M. Das Gupta, R. Ashrit and B. Athiyaman

In the present work a qualitative assessment of guidance from NCMRWF operational global and regional Numerical Weather Prediction (NWP) systems in the episode of unprecedented rainfall over Mumbai has been attempted. This also consolidates and examines the predictions that were provided by some of the leading global operational centres. Some hindcast runs were also made with different initial conditions. It reveals that the use of very high resolution global and regional models with advanced data assimilation techniques (4D Var), that optimally utilizes information from satellite observations, could significantly enhance the usefulness of NWP guidance.

ON 26 July 2005, within a span of less than 24 h, Mumbai – the commercial capital of the country – received unprecedented heavy rainfall, with its suburb Santa Cruz recording 94.4 cm of rainfall for the day. There were reports of even heavier rainfall of 104.5 cm near Vihar lake. This torrential rain disrupted life in the metropolis, caused large number of deaths and according to early estimates (as reported in the media), resulted in the loss of more than Rs 10,000 crores. Prior information about the event, a day or even few hours in advance could have helped alleviate the problems the populace and the disaster-management authorities faced. If information could have been provided, say two to three days in advance, it would have helped in better preparation by the disaster-management machinery, thus minimizing life and property loss.

During the last two decades, weather forecasting all over the world has greatly benefitted from the guidance provided by Numerical Weather Prediction (NWP). Significant improvement in accuracy and reliability of NWP products has been driven by advances in numerical techniques, explosive growth in computer power and by the phenomenal increase in satellite-based soundings. However, limitations remain in the prediction of severe weather events which have a very short life, but still cause extensive damage.

In India, the National Centre for Medium Range Weather Forecasting (NCMRWF), Noida uses global and regional numerical models for operationally generating NWP products to provide guidance on weather forecast in medium-range scale (up to a week in advance). Its products are mainly aimed at catering to the agriculture sector. Many other sectors of economy have also found them useful. Even though the NCMRWF NWP system successfully predicted the strengthening of monsoon over the west coast and other parts of the country on 26 July 2005, it could not predict the heavy rainfall event over Mumbai. In this appraisal, we have tried to assess the performance of our NWP system vis-à-vis those of other major global NWP centres in reference to this extreme weather event, to derive lessons for bringing about the desired improvement in the NWP effort in the country.

Heavy rainfall episode over Mumbai

Life in Mumbai was totally disrupted on 26 July due to torrential rains. This extraordinary rainfall event was localized over a region 20–30 km. Santa Cruz in north-central Mumbai recorded an unprecedented 94.4 cm of rainfall on that eventful day. Another nearby weather station at Vihar lake was reported to have received as high a precipitation as 104.5 cm. But, interestingly, Colaba in south Mumbai received merely 7.3 cm. Rainfall (rounded-off to the nearest cm) recorded in different areas of Mumbai over the 24 h period is: Santa Cruz: 94 cm, Bhandup: 81 cm, Dharavi: 49 cm, Vihar lake: 104 cm, Malabar Hill: 7 cm and Colaba: 7 cm (source: India Meteorological Department, IMD).

The event showed very high spatial variability; it is interesting to note that the highest rainfall rates which resulted in heaviest downpour occurred during the six hours between 2:30 and 8:30 p.m. (source: IMD). The Tropical Rainfall Measuring Mission (TRMM) satellite also captured this highly localized rainfall event.

The authors are in the National Centre for Medium Range Weather Forecasting, A-50, Sector 62, Noida 201 307, India.
*For correspondence. (e-mail: akbohra@ncmrwf.gov.in)

Synoptic situation

During the period leading to the catastrophic event of 26 July, the monsoon over major parts of the country, particularly over the west coast and peninsular India, was in its active phase. A low-pressure area formed over north Bay of Bengal off Gangetic West Bengal and Orissa coast on 24 July and intensified into a well-marked low as it moved inland. This brought the monsoon trough to the south of its normal position along 20–22°N. There was strong cross-equatorial flow. As the system moved westward, the low-level jet gained strength and strong westerly winds lashed the north Konkan and Goa coasts. This resulted in widespread heavy rainfall over these regions. On 24 July, Panjim and Dabolim reported rainfall of 18 and 16 cm respectively. The next day, many stations in Konkan and Goa reported rainfall of more than 10 cm, including Roha, Mangaon, Panjim and Mapusa which received 45, 25, 22 and 19 cm of rainfall respectively. The rainfall band moved north and large parts of Maharashtra started receiving heavy rainfall. Mahabaleshwar, Kolhapur and Pune received 43, 17 and 8 cm of rainfall respectively, on 26 July. Subsequently, the rainfall belt moved further north towards Gujarat, but in its wake it had devastated Mumbai and many other parts of Maharashtra. Though in the overall strong monsoon conditions, heavy rainfall was expected (and predicted) over Mumbai, the localized nature of the event and the intensity could not be anticipated.

Initially it was suggested that an offshore vortex could be the possible underlying cause. It is, however, not supported by observations. The QuikSCAT satellite surface winds as shown in Figure 1 for 26 July, show strong westerly winds over eastern Arabian Sea along the west coast from Gujarat to north Karnataka, but no offshore vortex is seen.

NWP guidance for the event from NCMRWF system

The NCMRWF has been generating NWP guidance for the agriculture sector using deterministic numerical techniques. It routinely runs a global spectral atmospheric General Circulation Model and generates medium-range forecasts (up to one week in advance) of atmospheric circulation and rainfall. The model has a resolution of about 150 km in horizontal and resolves the vertical thermodynamic structure of the atmosphere using 18 layers (T80L18). The model has been successfully used to provide guidance for forecasting large-scale (synoptic) circulation and rainfall. The initial conditions for the forecast model are provided using a six-hourly intermittent global data assimilation system.

For high-impact weather events, high-resolution products are generated daily up to 72 h using two mesoscale models, viz. Eta (single domain; horizontal resolution 48 km and 38 vertical levels) and MM5 (triple-nested domain; horizontal resolution 90, 30, and 10 km and 23 vertical levels). The initial and lateral boundary conditions for mesocale models are taken from the global model.
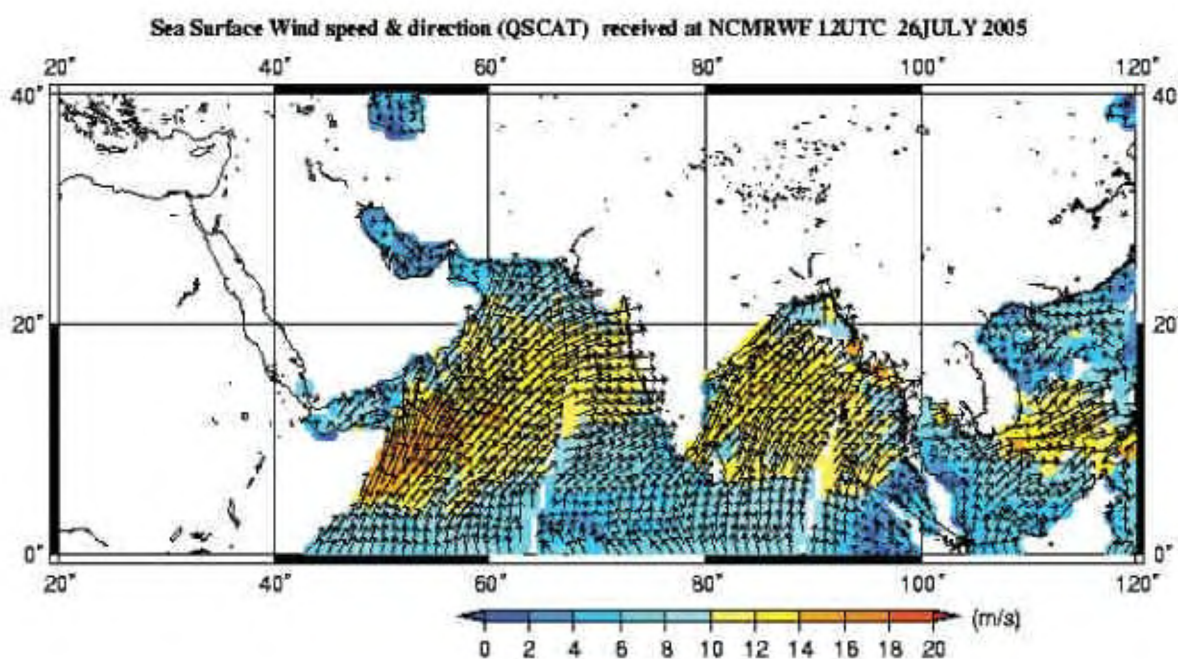

Figure 1. QSCAT surface winds for 12 UTC of 26 July 2005.

The six-hourly intermittent global data assimilation system (3D-Var) at NCMRWF makes use of the conventional *in situ* observations such as surface observation from land and ocean (SYNOP/SHIP, BUOY), temperature, moisture and wind observations at different vertical levels of atmosphere (TEMP and PILOT) and observations from aircraft. It also uses satellite data such as cloud motion vectors from geostationary satellites (INSAT, GOES, GMS and METEOSAT) and derived temperature and moisture profiles from polar-orbiting NOAA satellite. Though volume of conventional data assimilated over the Indian region is comparable to those assimilated at other leading NWP centres of the world, satellite data assimilated are only 10% of those at other centres. In addition, the other centres use satellite-derived radiance directly, whereas in India derived temperature and moisture profiles are still being used.

Since April 2005, due to some technical problems, temperature and moisture profiles (ATOVS) derived from the NOAA (15 and 16) satellites have not been assimilated, which could have resulted in deterioration of the analysis, especially over the data-sparse oceanic regions.

The NCMRWF operational global model prediction of 24 h accumulated rainfall amount for the period ending at 3 UTC of 27 July (made one day in advance) shows rainfall of only about 2 cm over Mumbai, with a 4 cm core region much south of Mumbai. It is further seen that the prediction skill deteriorates as the lead time increases (Figure 2).

A high-resolution global model (T170L28), equivalent to about 75 km in horizontal, that is run regularly but in experimental–operational mode at NCMRWF, did predict higher rainfall with a core of 8 cm; but again it was much south of Mumbai (not shown here). These models did predict the large-scale monsoon rainfall reasonably well.

The NCMRWF mesoscale models also failed to predict the high rainfall. The Eta model predicted 4 cm of rain and MM5 model predicted only 2 cm of rain. These models take the boundary and initial conditions from the NCMRWF operational global model. At present, there is no separate data assimilation system for mesoscale models. In addition, there are no additional observations that could be made use of. Thus the only added feature in these mesoscale models is the better resolution of orography.

Guidance from other major global NWP centres

Limitations of the NCMRWF operational NWP system mainly arise from the use of coarser resolution models and ingestion of much less data compared to other major global NWP centres. In view of this, it was interesting to study the potential of various models from some of these centres, in predicting the very heavy rainfall episode over Mumbai. Requests were made to the Meteorological Office, UK (UKMO); Japan Meteorological Agency (JMA), Tokyo; National Centres for Environment Prediction (NCEP), USA and European Centre for Medium Range Weather Forecasting (ECMWF), UK for their products for the relevant period. All the centres made their products available promptly. Details of resolution of the operational models and data assimilation technique(s) used at these centres are shown in Table 1.

All forecast models contain unknown parameters. These parameters may be the initial conditions of a model, its boundary conditions, or other tunable parameters which have to be found for a realistic result. Four dimensional variational data assimilation, or '4D-Var', is a method of estimating this set of parameters by optimizing the fit between the solution of the model and a set of observations which the model is meant to predict. In this context, the procedure of adjusting the parameters until the model 'best predicts' the observables is known as optimization. The 'four-dimensional' nature of 4D-Var reflects the fact that the observation set spans not only three-dimensional space, but also a time domain. The 4D-Var method supersedes the simpler and less expensive '3D-Var', in which no proper account is made of the time for which an observation is made.

Compared to the other centres, resolution of the analysis-forecast system at NCMRWF is seen to be much coarser both in the horizontal and vertical directions. At NCMRWF, a
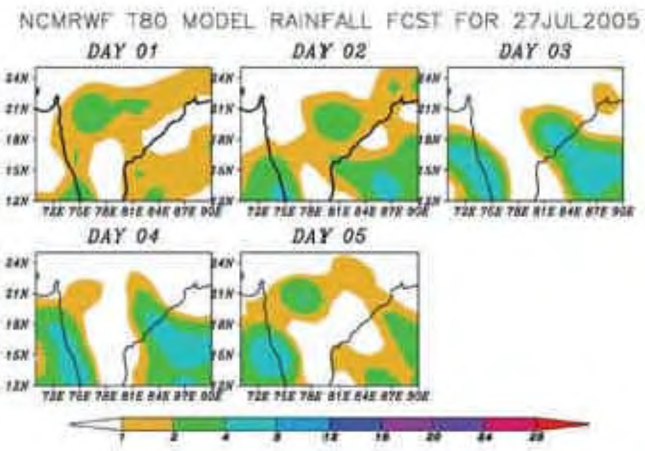

Figure 2. Five-day rainfall forecasts from NCMRWF global model for 24 h period of 26–27 July 2005.

Table 1. Resolution of operational models, and data assimilation techniques at various centres

Forecast centre (country)	Model resolution – horizontal resolution/ no. of levels in vertical	Data assimilation
ECMWF (Europe)	40 km/60	4D-Var
Meteorological Office (UK)	60 km/38	4D-Var
NCEP (USA)	35 km/64	3D-Var
JMA (Japan)	60 km/40	4D-Var
NCMRWF (India)	150 km/18	3D-Var

3D-VAR system is in use for data assimilation as against the 4D-VAR system in most of the other centres. NCMRWF currently uses derived products from the satellites, whereas the others centres assimilate satellite radiances directly instead of derived products.

Global data coverage giving details of various types of observations that were ingested in the assimilation system for preparing initial conditions for 00 UTC of 26 July 2005 was received only from UKMO. Comparison with global data coverage at NCMRWF revealed that UKMO ingested more types of satellite data (ATOVS, AIRS, and SSM/I radiances) than NCMRWF.

Figures 3 and 4 show winds at 850 and 700 hPa levels respectively, from NCMRWF and other centres. The NCMRWF analyses show much weaker monsoon flow over the Arabian Sea compared to the other centres. Also, the core of the low-level westerlies over eastern Arabian Sea in the NCMRWF analysis is at a lower latitude compared to other analyses. However, the location and strength of the depression over Orissa and its neighbourhood are more or less the same in the analyses from all the centres. The monsoon trough location is also similar.
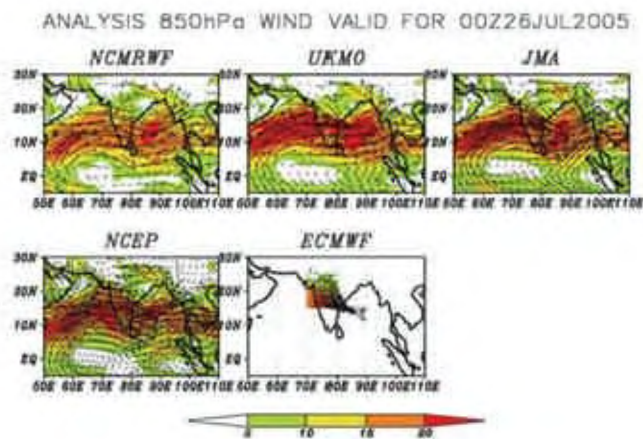

Figure 3. Analysis of winds at 850 hPa from NCMRWF, UKMO, JMA, NCEP and ECMWF for 00 UTC of 26 July 2005.
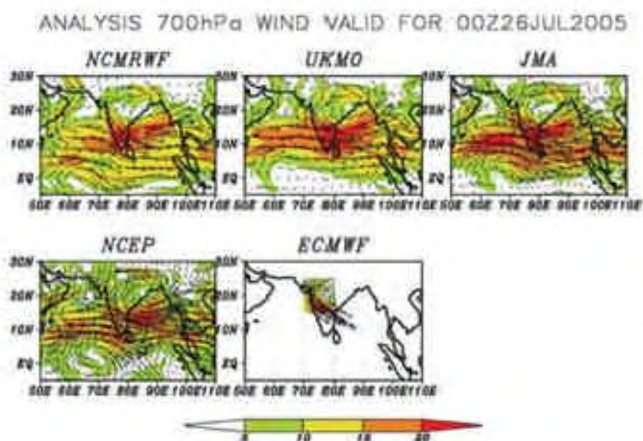

Figure 4. Same as in Figure 3, but for 700 hPa level.

Figure 5 shows NCMRWF rainfall analysis using rain-gauge data and quantitative precipitation from TRMM data[1]. Figures 6–8 show the day-1, day-2 and day-3 rainfall forecasts for the 24 h period of 26–27 July 2005 from different centres, namely NCMRWF, UKMO, JMA, NCEP, and ECMWF. In the day-1 forecasts, i.e. when the models are run with initial condition of 26 July 00Z, the UKMO model showed 20–24 cm rainfall near Mumbai, which was the highest among the various models and also closest in terms of location. The JMA and NCEP models showed
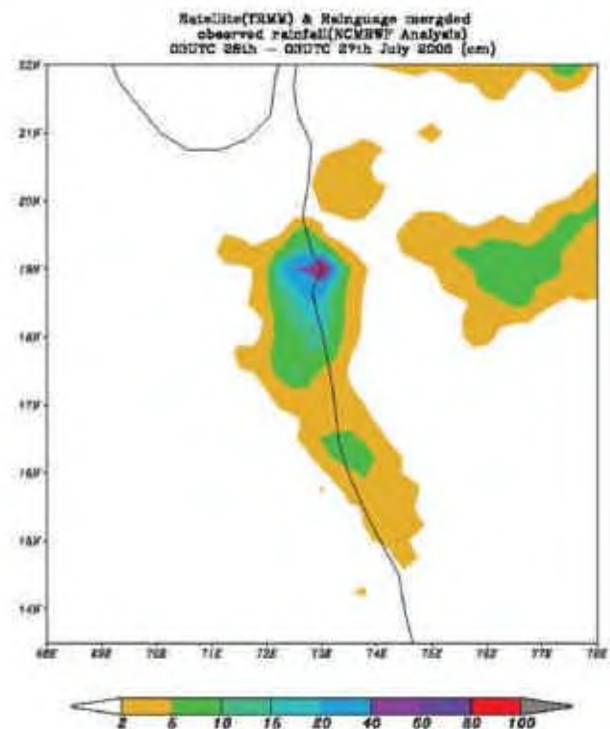

Figure 5. Observed rainfall (24 h accumulated) as obtained from NCMRWF rainfall analysis for 03Z of 27 July 2005.
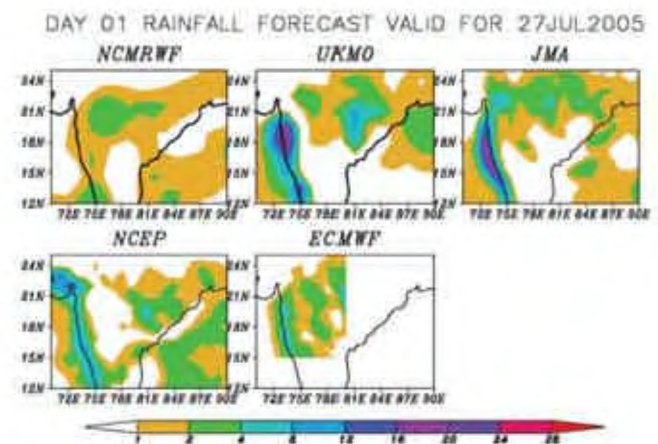

Figure 6. Day-1 rainfall forecast for 24 h period of 26–27 July 2005 from NCMRWF, UKMO, JMA, NCEP and ECMWF models.

16–20 and 12–16 cm of rainfall respectively. However, their locations were to the south and north of Mumbai respectively. The ECMWF model showed only 4–8 cm of rainfall near Mumbai. As mentioned earlier, NCMRWF showed the least amount among all the models and also had a core located much south of Mumbai. Similarly, in the day-2 forecasts, i.e. when the models are run with initial condition of 25 July 00Z, the UKMO model showed 28–32 cm of rainfall near Mumbai, which was the highest among the other models and also closest in terms of location. In the day-3 forecasts, i.e. when the models are run with initial condition of 24 July 00Z, the UKMO model again showed higher rainfall compared to the other models, as shown in Figure 8. Although the magnitude was less (12–16 cm), nonetheless it was higher compared to the other models and also closest in terms of location.

Thus, the UKMO model was quite consistent in predicting heavy rainfall near Mumbai. Rainfall predictions in the other models reduced with increasing lead time. The NCMRWF model however did show improved intensity and location in the day-3 forecast. This is perhaps due to

model spin-up. The initial imbalance in the thermodynamic state of the model atmosphere results in adjustment of fields as they approach dynamical and physical equilibrium. This initial adjustment phase is commonly referred to as spin-up. In the ECMWF model also (not shown), increase in rainfall with maxima of 40 cm, at longer forecast range is seen, though locations are northwest of Mumbai (A. Simmons, pers. commun., 2005).

Simulation experiments with mesoscale models using initial and lateral boundary conditions from UKMO

The operational analysis and subsequent rainfall forecasts from UKMO operational global model were found to be most consistent and closest to the realized rainfall. To see whether the difference in predicted rainfall amounts could be attributed to differences in models or it resulted from the initial conditions, a few hind-cast runs of the NCMRWF mesoscale models using initial and boundary conditions from the UKMO model were made.

Eta model runs

Figure 9 shows the day-1 forecast rainfall (cm) by the Eta model (horizontal resolution 48 km and 38 levels in the vertical) using initial and lateral boundary conditions based on the global model outputs of NCMRWF and UKMO respectively. Model runs based on UKMO outputs suggest improvement in the rainfall amounts all along the west coast, particularly over the Mumbai region. The model run with NCMRWF global output shows rainfall of over 4 cm in the Mumbai region, with the core of maximum rainfall exceeding 8 cm, located much to the south of Mumbai. The model run with UKMO global outputs shows enhanced rainfall activity, with maxima between 8 and 16 cm all along the west coast.
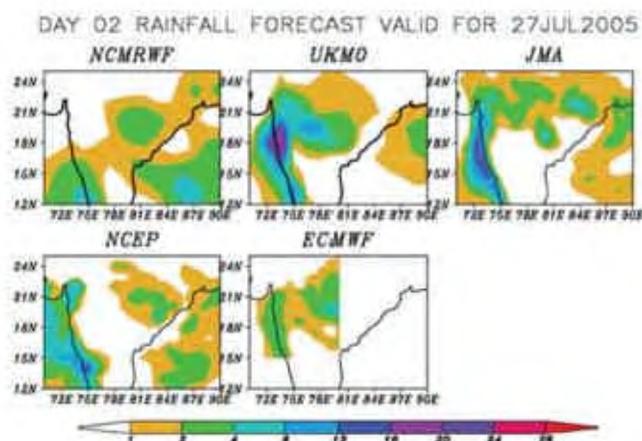

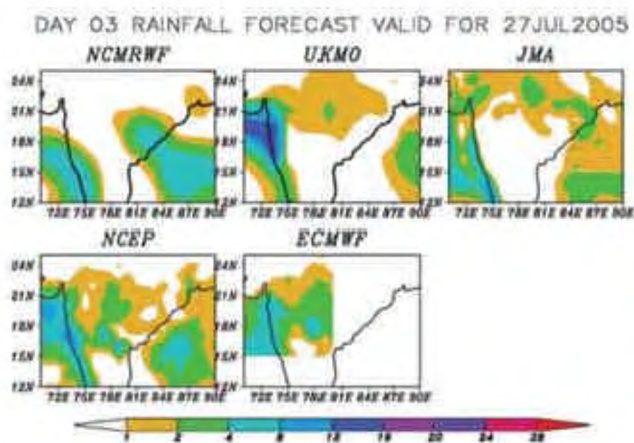**Figure 7.** Same as in Figure 6, but for day-2 forecasts.

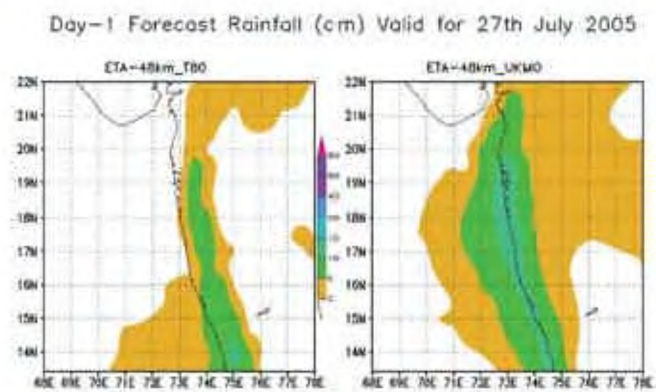**Figure 8.** Same as in Figure 6, but for day-3 forecasts.

Figure 9. Day-1 rainfall forecast for 24 h period of 26–27 July 2005 from Eta model with initial and boundary conditions from NCMRWF and UKMO model.

MM5 model runs

Figure 10 shows the 24 h total rainfall (in cm) from MM5 model run using initial and boundary conditions based on the global model outputs of NCMRWF and UKMO respectively.

The model run at 30 km resolution based on NCMRWF global outputs shows a broad contour of 2 cm rainfall over the region, but it has completely failed to capture the localized heavy rainfall over Mumbai. The model run with UKMO global outputs captures the localized heavy rainfall over Mumbai, with predicted amounts over 32 cm, which is still much lower than that realized. The high resolution (10 km) MM5 simulation shows rainfall maxima (Figure 11) exceeding 80 cm, though the location is somewhat to the west of Mumbai.

These runs of high resolution regional models revealed that the prediction of circulation features (not shown) as well as rainfall amount and location improved significantly when advanced 4-D Var and a high resolution global model were used to prepare initial and boundary conditions.
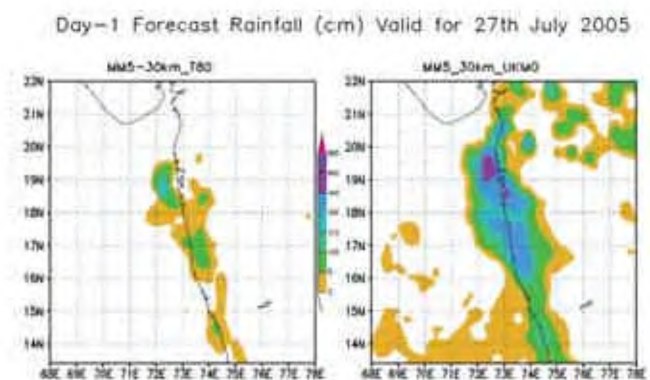

Figure 10. Day-1 rainfall forecast for 24 h period of 26–27 July 2005 from MM5 model with initial and boundary conditions from NCMRWF and UKMO model.
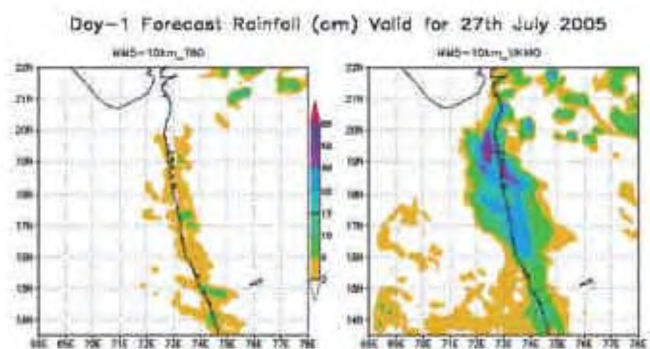

Figure 11. Same as in Figure 10, but with a higher resolution (10 km).

UKMO SAM run

NCMRWF and UKMO are jointly assessing the performance of their models over the Indian monsoon region during 2005. Prediction from the 17 km regional Southern Asia Model (SAM) of UKMO was found to be much poorer than the global model. This may be because the UKMO had upgraded the 4-D VAR in its global model, and the global analyses were far superior to the regional model analyses which still used 3-D VAR. Although the regional analyses had the benefit of detail at the surface, this was considered to be of secondary importance beyond 12 h. The regional model thus was re-run from an interpolated 00 GMT 26 global analysis. The re-run was impressive and added value to the global product with peak values in excess of 80 cm. The 24 h prediction of rainfall from the UKMO regional model SAM is shown in Figure 12 (B. Stuart, pers. commun., 2005).

Performance appraisal and planned initiatives

From the above exercise, it is evident that the present-day state-of-the-art NWP systems are able to provide useful guidance for forecasting very high rainfall events. Some of the NWP systems like UKMO may even predict the events like the unprecedented 26 July rainfall over Mumbai. It is now an established practice in the developed world that the NWP guidance is preferred for forecasting weather on all temporal ranges and spatial domains. All major centres deploy significant human and computing resources to continuously improve the NWP system by increasing resolution, including more physical processes and feedback mechanisms in the models as realistically as possible, and also making an all-out effort to maximize utilization of information content from all conventional and non-conventional observations through the use of advanced data-assimilation techniques. Though huge resources are deployed, given the critical requirements of accurate weather forecast for various sectors of economy, the cost–benefit ratio has been found to be highly favourable.
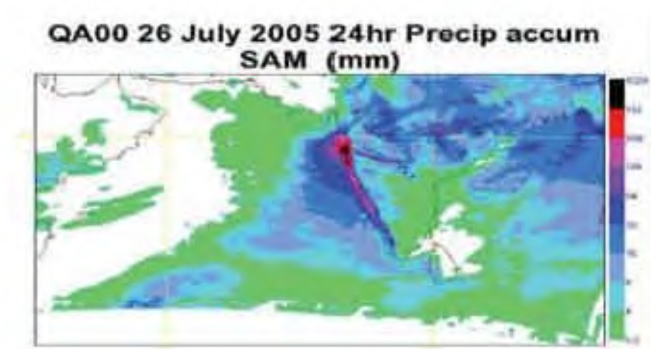

Figure 12. Day-1 rainfall forecast for 24 h period of 26–27 July 2005 from UKMO South Asia Model.

Monsoon is the life line of the Indian economy. The country also experiences a number of other extreme weather events round the year. In India, even though useful experience has been gained in running the global NWP system and providing guidance to the forecasters, progress has been rather slow for various reasons. There is dearth of skilled scientific manpower in the field. Lack of adequate computing resource has been another major handicap. Quality of observations and their availability in near real-time for efficient use in NWP has also been a major concern in the context of poor performance of the NWP guidance, particularly in the case of extreme weather events.

Even though monsoon prediction and other extreme events over the Indian region still remain challenging problems for the operational and research community, the state-of-the-art NWP systems used at major NWP centres are capable of providing useful guidance. There has been an explosive growth in recent years in the availability of satellite data, and optimum utilization of these data in NWP is a major area of research. Particularly, use of direct radiances from satellites in 4-D VAR framework has proved to be a major contributing factor for significant improvement in NWP guidance in recent years. NCMRWF is developing a collaborative programme with NCEP to carry out R&D work in satellite data assimilation and land surface data assimilation.

UKMO and NCMRWF are jointly diagnosing the performance of their models over the Indian region during monsoon 2005. The two organizations are seriously considering prospects of working as strategic partners in improving the prediction capability over the Indian monsoon region, for tropical cyclone track and intensity prediction, use of satellite and other non-conventional data, seasonal prediction and climate variability and change research.

Summary

A qualitative assessment of guidance from NCMRWF operational global and regional NWP systems in the episode of unprecedented rainfall over Mumbai has been attempted. The NWP guidance in this case was of limited help, if any. An examination of products from other major global NWP centres has also been made. It revealed that the use of very high resolution global and regional models with advanced data assimilation techniques (4-D Var), could significantly enhance the usefulness of NWP guidance.

Development of a state-of-the-art NWP system for our region calls for (i) good quality data of adequate density and advanced data assimilation techniques, (ii) very high resolution global and regional models, (iii) ability to receive in near real-time all observations, including the voluminous satellite data, (iv) capability to use direct radiances from satellites, (v) very high computing power and (vi) deployment of more skilled scientific manpower.

1. Mitra, A. K., Das Gupta, M., Singh, S. V. and Krishnamurti, T. N., *J. Hydrometeorol.*, 2003, **4**, 769–781.