Recent Advances in Numerical Weather Prediction

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ABSTRACT

In recent years several application areas, which include reducing loss of life due to severe weather events, agriculture, water resource management, energy, public health; tourism and sports and transportation have posed a challenge to the meteorological community in India. The expectations from the user sectors shall increase along with increased awareness in coming years. Numerical weather prediction (NWP) models now include many complex physical processes and advanced data assimilation schemes. With the availability to high performance computing (HPC) the NWP models now feature very high horizontal and vertical resolutions.

The National Centre for Medium Range Weather Forecasting (NCMRWF) has been a lead centre in India for all weather and climate model related research and operations. NCMRWF currently carries out developmental work on three modelling systems, namely, NCMRWF Global Forecast System (NGFS), NCMRWF Global Ensemble Forecast System (NGEFS) and NCMRWF Unified Model (NCUM). Although the recent advances have reflected in the improved forecast skill in the NWP models, accurate prediction of extreme events is still a challenge. The recent developmental activities at NCMRWF on the next generation weather and climate modelling systems are highlighted in the paper.

Keywords : *Rainfall trend, annual and seasonal variations, extreme events.*

1. Introduction

Weather forecasts from days to season are becoming increasingly important for many applications such as: reducing loss of life and property from high impact weather systems; water resource management; sustainable agriculture; energy; public health; tourism and recreation; adventure sports; transportation; etc.

The relentless increase in computing power over the last few decades has led to a corresponding increase in the resolution operational global NWP models, with resolutions of around 10 km feasible within the next few years. The better understanding of the physical processes coupled with better data coverage (specially coming from satellites) for initializing the models has contributed to a significant improvement in the forecast skill of NWP models.The benefits of the improved forecast skill have accrued to all sectors of Indian economy and society.

In general, the NWP systems of leading global NWP centres are improving by 1 day of predictive skill per decade. These centres have been able to invest adequate resources, both in terms of computing power and manpower. The improvement is generally due to:

1) Better observations
2) Careful use of forecast and observations, allowing for their information content and errors-achieved by variational assimilation
3) Model improvements,
4) Better post-processing techniques.

The National Centre for Medium Range Weather Forecasting (NCMRWF) has been a lead centre in India for all weather and climate model related research and operations. NCMRWF currently carries out developmental work on 3 modelling systems, namely, NCMRWF Global Forecast System (NGFS), NCMRWF Global Ensemble Forecast System (NGEFS) and NCMRWF Unified Model (NCUM).The recent developmental activities at NCMRWF on the next generation weather and climate modelling systems are highlighted in the following sections.

2. Observational Data

A tremendous growth in the volume of observations has been noticed in past few years. With continued efforts of NCMRWF, and with the help of ESSO-IMD and other National and International Meteorological Agencies, NCMRWF is able to sustain the growth in accessing more volume of observational data for assimilation. Volume of data reception both through GTS and Internet Data Service (IDS) has increased manifolds in the recent years as shown in Fig. 1. During the last year, there was about (~10%) increase in the observations received through GTS and this growth is mainly due to reception of Asia-Pacific RARS data and half- hourly reception of INSAT-3D Atmospheric Motion vector (AMV) wind vectors. This year India became partner in the Asia-Pacific RARS community and started getting its data through GTS and also started receiving European RARS (EARS) data through EUMETCAST. With the help of these regional services, NCMRWF is able to receive regional NOAA/METOP ATOVS data with very short time delay (~ 30 min of regional reception) which is very useful for early forecast runs (with ~ 3.00 hrs cut-off) and also an alternative source (Fig. 2) for global NOAA and METOP radiance data. Secondly there is ~90% increase in the IDS (~90% mainly satellite) data during 2014vis a vis those in 2013. It is mainly due to reception of our own INSAT 3D sounder and imager radiance data and also due to reception of NOAA NPP (CrIS and ATMS radiance etc.) data from the new NOAA NDE (NESDIS Data Exchange) server.

Apart from this, NCMRWF also receives about 14 GB of radar observations from 17 Indian Radar stations from IMD through IDS resulting in total volume of data received at NCMRWF to be around ~35GB/day.The characterization of quality of DWR data is essential before assimilating the data into NWP models. The characterization of quality of DWR data is essential before assimilating the data into NWP models.At NCMRWF the quality indices are generated for the effects of beam broadening, beam shielding, attenuation of radar reflectivity in rain and bright band. Fig. 3 shows the sample quality index generated for the Patiala radar.

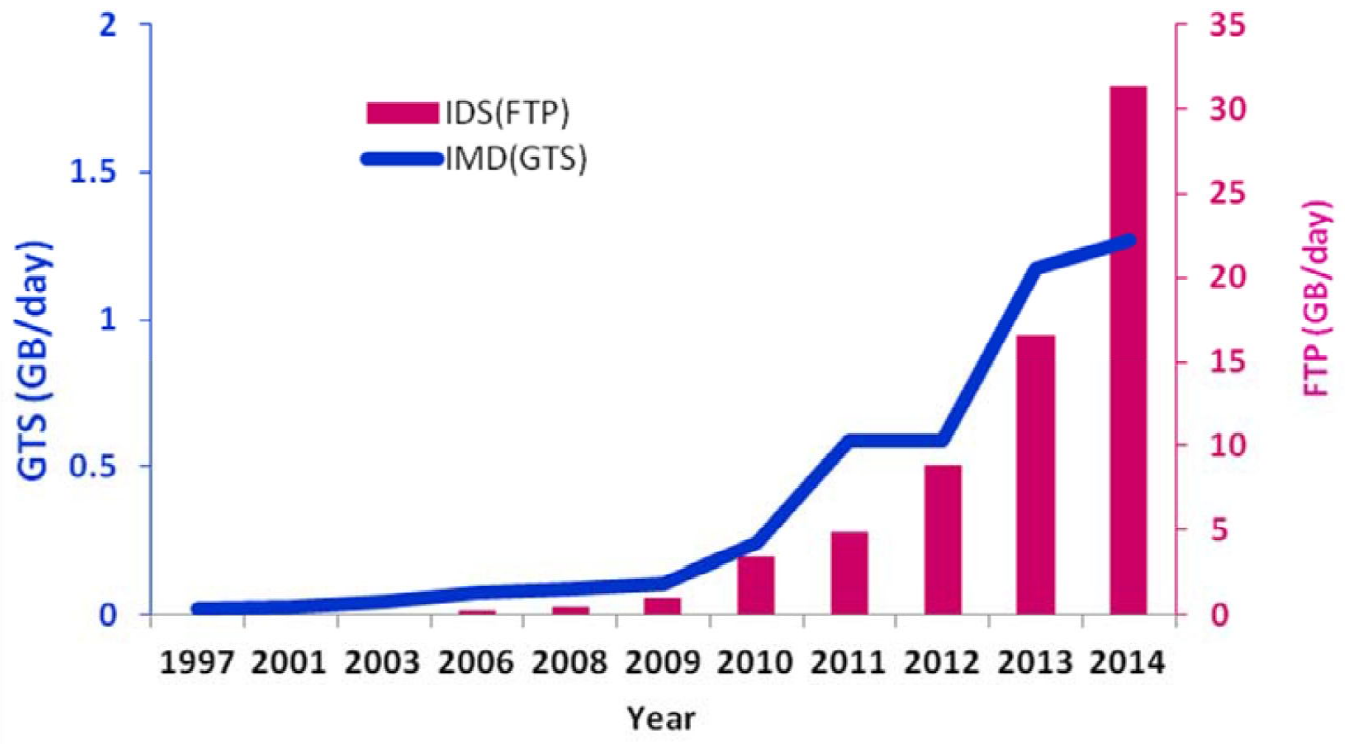

Fig.1 Volume of data received at NCMRWF over the years.

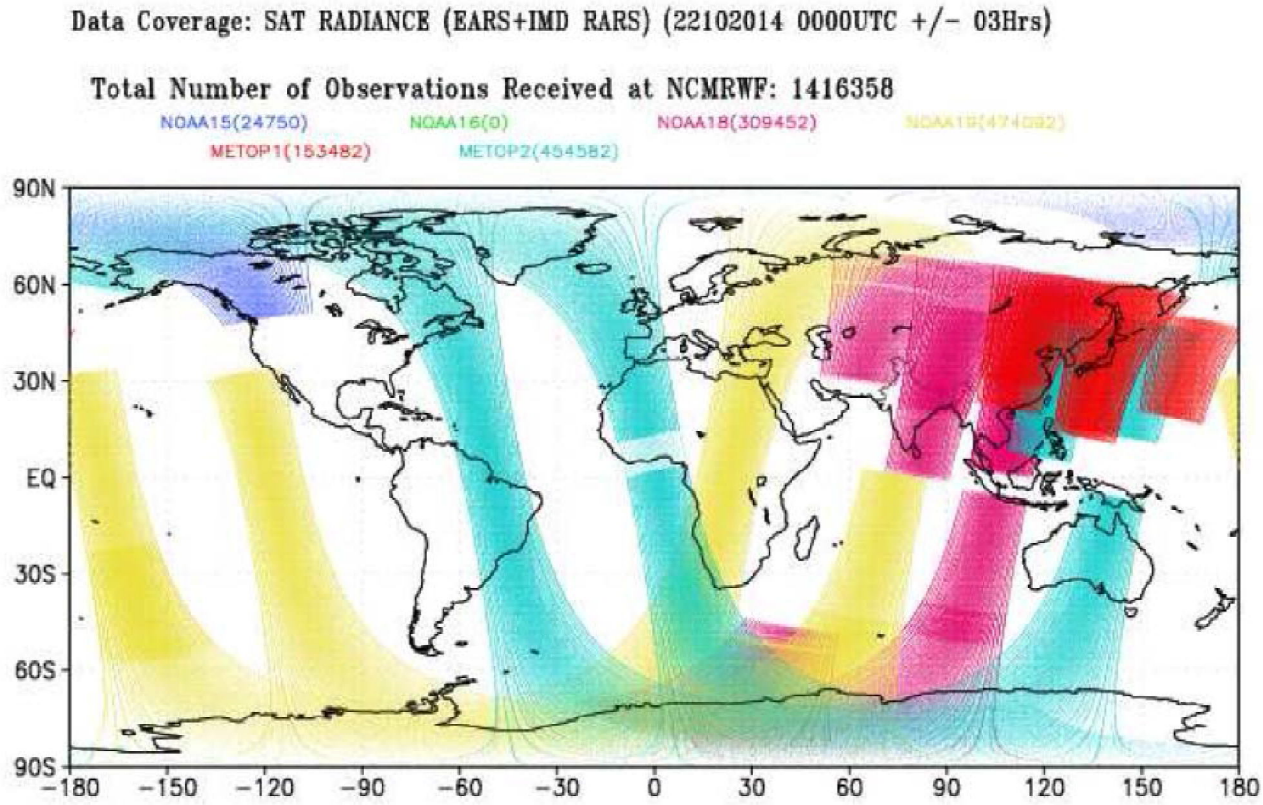

Fig.2 Satellite radiance data coverage on a typical day.

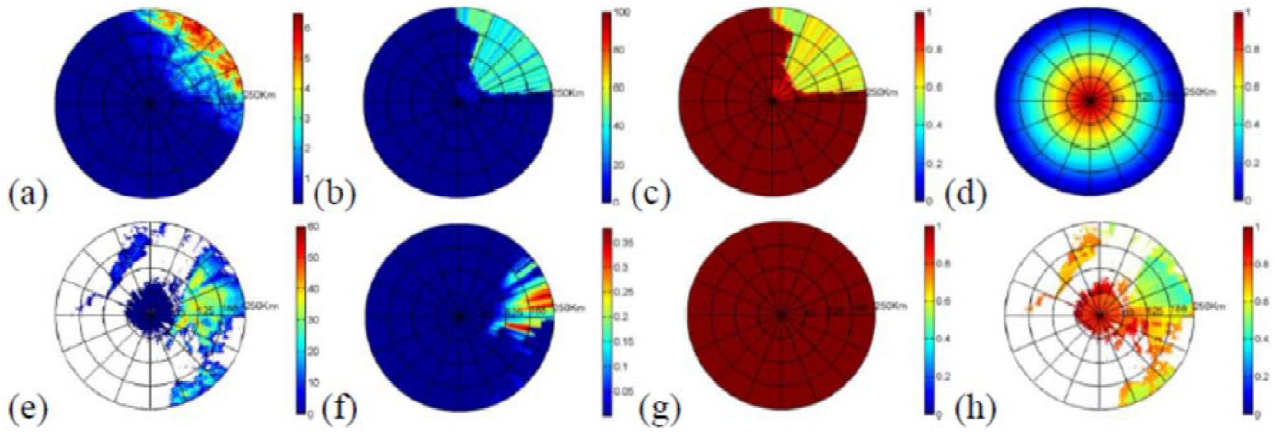

Fig.3 (a) Topography of the place around Patiala, (b) Blockages in the vicinity of the radar, (c) QI of the shielding, (d) Beam broadening QI, (e) Radar Reflectivity (dBz) (16th June 2013 (11:22UTC)), (f) Attenuation of the reflectivity in rain, (g) QI of the attenuation factor and (h) Averaged QI due to all affects.

2.1 INSAT-3D Products

NCMRWF receives the Atmospheric Motion Vectors (AMVs) from different geostationary and polar orbiting satellites through GTS, EUMETCAST, NESDIS viz. AMVs from METEOSAT-7, METEOSAT-10, MTSAT (GMS), GOES-E, GOES-W, NOAA, Aqua and Terra. Continuous efforts are on for the validation and assimilation of AMVs from Indian satellites. AMVs of Kalpana-1 were validated against in-situ observations and short term NWP forecasts for monsoon 2011. It was found that their Root Mean Square Vector Differences (RMSVD)

were higher as compared to that of other geostationary satellites (Das Gupta et al.,2013).

One possible reason was the height assignment of the derived winds using empirical Genetic Algorithm method at the Space Application Centre (SAC), India. Subsequently, AMVs were derived using height assignment based on IR-window and H2O intercept methodalong with modified quality control technique (Dev et al. 2014)which resulted in generation of improved products. Validation of INSAT-3D AMVs against NCMRWF first guess as well as in-situ observations has shown large improvement in the quality of winds. Fig. 4(a) and (b) depict the speed bias density plots for IR lower level AMVs of INSAT-3D and METEOSAT-7 for September 2014.

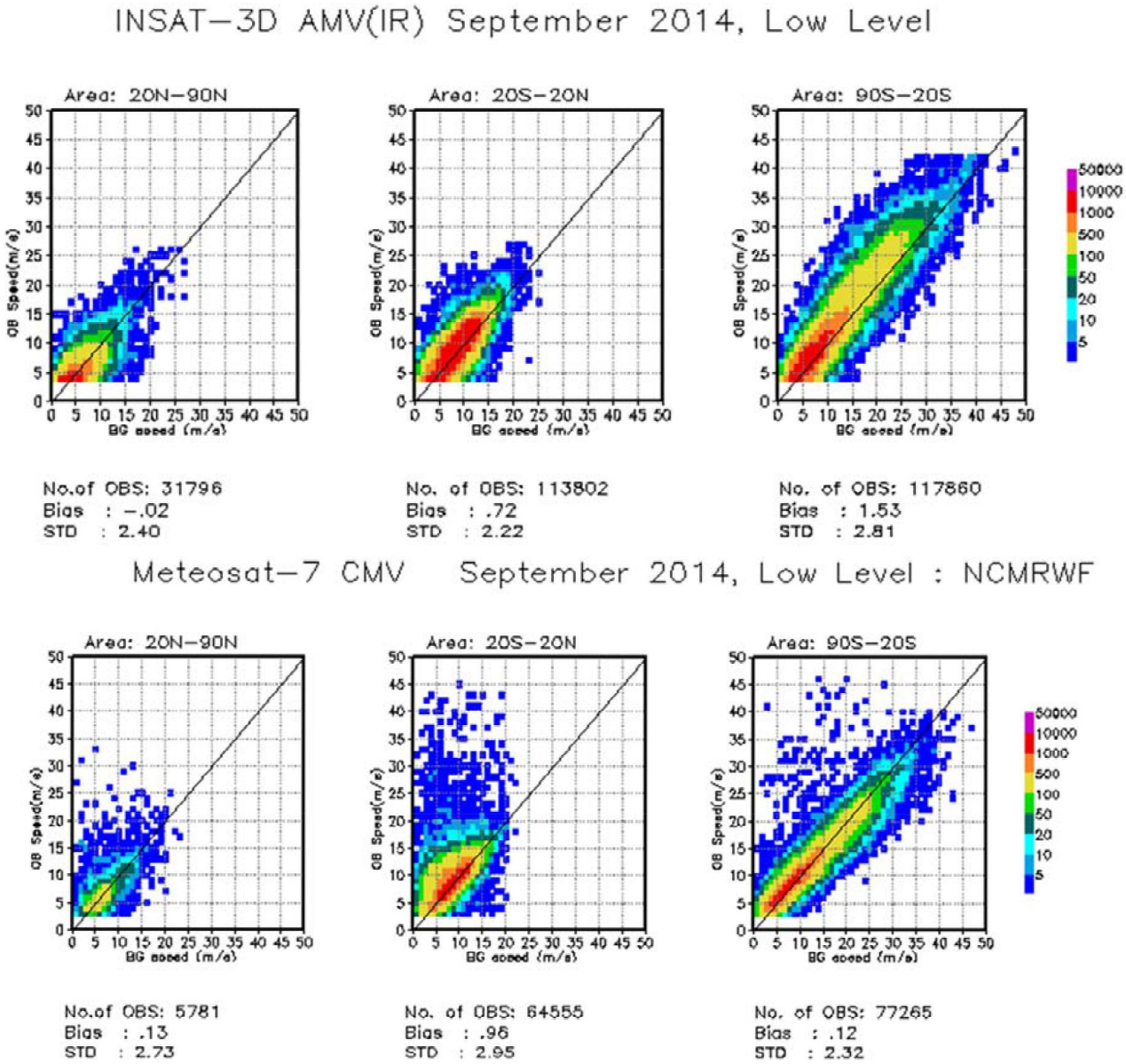

Fig.4 Speed bias density plot of low level IR AMVs for September 2014 (a) INSAT-3D (b) METEOSAT-7.

Further with the joint effort of SAC and NCMRWF, the issues with INSAT-3D radiance products were identified. ISRO recently supplied to NCMRWF the updated Sensor Response Functions (SRFs) of both imager and sounder. Under the MoES initiative, CRTM community recomputed INSAT-3D sensor coefficients based on the updated SRFs Based on NCMRWF feedbacks ISRO has started generating Clear Sky Brightness Temperature (CSBT) radiances from INSAT-3D.

Development works towards assimilation of INSAT-3D sounder radiances data was carried out by NCMRWF and started using the new CSBT radiances. The agreement between model simulated and satellite observed radiances has increased with the improved INSAT-3D CSBT and the global data assimilation system has started accepting the sounder radiance data.

Further, NCMRWF made operational an observation monitoring system for various Satellite sensors health based on various products from its Global Data Assimilation forecasting system. Fig. 5 depicts a comparison of some of these parameters for GOES-15 and that of INSAT-3D sounder. These two sensors are of similar type, the GOES system is operational since a long time where as INSAT-3D sounder is the new addition. It is clear from Fig. 5 that INSAT-3D sounder radiances are now comparable to GOES-15 except at 18 UTC.

2.2 MeghaTropiques Products

Megha-Tropiques (MT) is an Indo-French joint satellite mission for studying the water cycle and energy exchanges in the tropics. It is orbiting the Earth at low orbit (~800 km) and has low inclination (20°) to provide higher satellite repetivity at lower latitudes. It carries four payloads - SAPHIR, SCRAB, Radio Occultation Sounding of Atmosphere (ROSA) and MADRAS, and can measure rainfall, water vapour and radiation.

SAPHIR is a sounding instrument with 6 channels near the absorption band of water vapor at 183 Ghz. These channels provide relatively narrow weighting functions from the surface to about 10 km, allowing retrieving water vapor profiles in the cloud free troposphere. The scanning is cross-track, up to an incidence angle of 50. It is similar to Microwave Humidity Sounder (MHS) on board of NOAA and METOP Series except for the number of Channels (Fig. 6). It also does not have any window channel. The data assimilation system was modified to monitor SAPHIR radiances and a procedure was developed to detect and eliminate deep convective cloudy pixels following Hong et al. (2005). The quality of cloud cleared SAPHIR radiance data was found to be similar to that of operationally used MHS data (Fig. 7). Further, OSEs with SAPHIR radiances clearly demonstrated improvement in relative humidity which varies from 0.1 to 4.5 % in day1 to day4 at 700 and 850 hPa (Singh et al., 2014). On the basis of these experiments, NCMRWF has started assimilating these radiances routinely into its NGFS system.

2.3 Soil Moisture Initialisation

Soil moisture is a key variable which describes the exchange of moisture and heat between the land surface and the atmosphere. So it is important to initialize NWP models with realistic soil moisture. In last few years, satellite derived surface soil

3x3 CSBT product

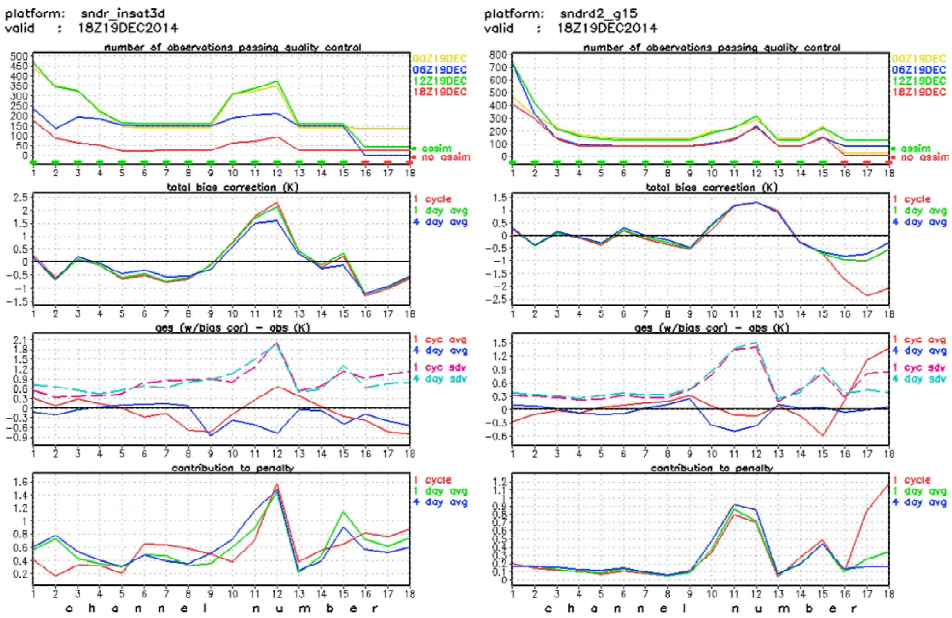

Fig.5 Comparison of GOES-15 and INSAT-3D sounder radiances.

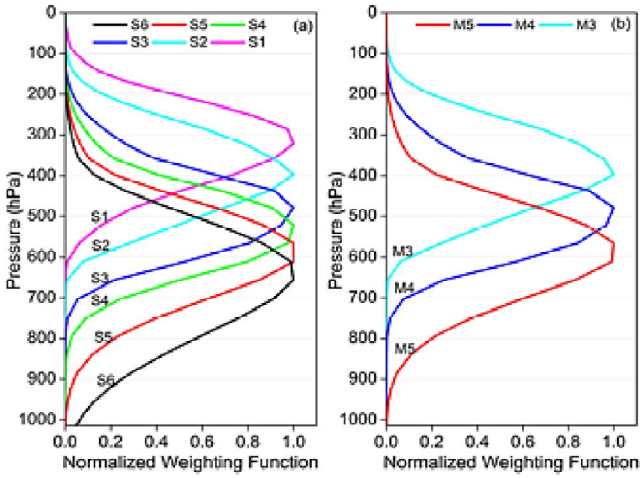

Fig.6 Comparison of Weighting functions of MT-SAPHIR and METOP2-MHS channels.

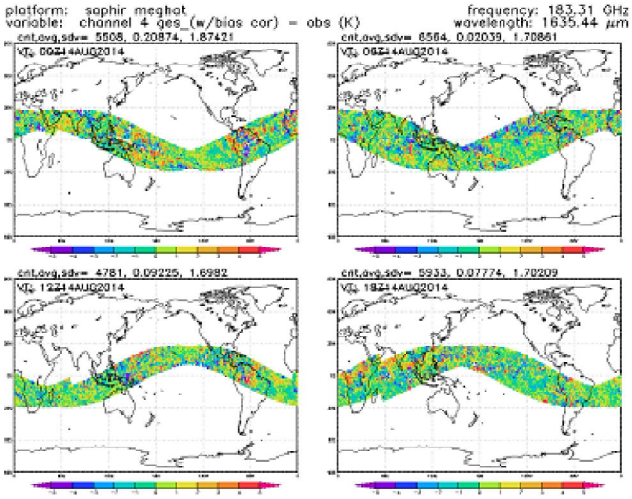

Fig.7 Difference between bias corrected simulated MT-SAPHIR Channel 4 radiance and satellite observed radiance for all assimilation cycles for a day.

moisture information is used by major NWP centres to produce the soil moisture analysis.

A soil moisture assimilation scheme based "nudging technique" is used at NCMRWF for the preparation of soil moisture analysis. The screen level observations of humidity and temperature as well as the ASCAT (Advanced SCATerometer instrument in METOP Satellite) surface soil wetness observations are used for the preparation of soil moisture analysis which is used to initialize the NCUM. Six hourly soil moisture analyses are being prepared at NCMRWF routinely. As soil moisture observations from different sources represent against different independent observations (Fig.8) and it is found to match reasonably well. To further improve the soil moisture analysis of all levels in

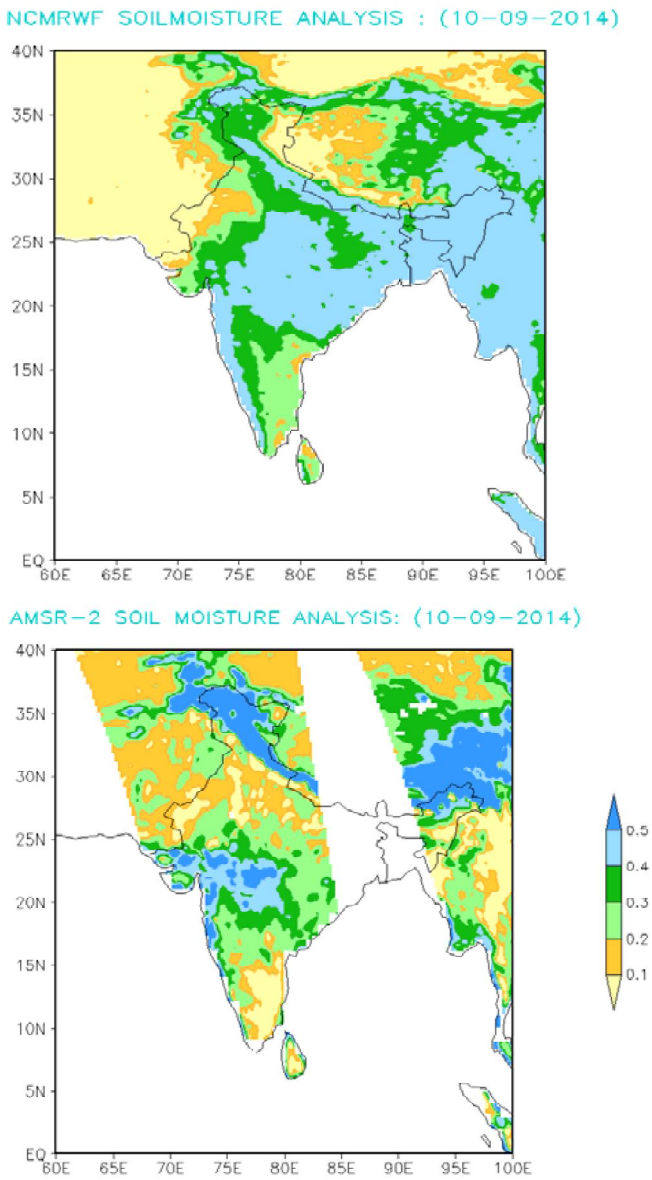

Fig.8(a&b)Surface soil moisture (volumetric content) from NCMRWF analysis and AMSR-2 satellite observation for a typical day over Indian region.

the root zone, an assimilation technique based on extended Kalman filter is being implemented.

3. Atmospheric Modelling

The concept of a Unified Modelling system for seamless prediction of weather and climate has gained in importance and acceptance during the last few years. An Unified Model (UM) with a horizontal resolution of about 25 km and 70 levels in the vertical and the associated 4D-VAR data assimilation system have been successfully implemented at NCMRWF. Regional version of UM at 12 km and 4 km horizontal resolution & 70 vertical

levels has also been implemented and tested for few synoptic cases. More detailed short-range forecasts are provided by this high-resolution regional version of UM which have a more detailed representation of orography and other surface features and are able to represent certain atmospheric processes more accurately.

A Nested UM suite was recently implemented at NCMRWF which is an easily relocatable regional version of UM at a resolution of 1.5 km nested in the global UM. This configuration is tested for various domains namely, Jammu and Kashmir, Madhya Pradesh and Gujarat using orography generated from 90 metre SRTM topography. Fig.9 shows the Himalayan orography for UM global and the high resolution regionalmodel. Fig. 10 displays the day -1, day-2 and day-3 rainfall forecasts valid for 3-5 September, 2014 during the period of J&K floods by UM global and 1.5 km regional models against gridded rainfall analysis at 50 km resolution. The 1.5 km resolution regional model predictions shows better match with the observations in terms of distribution, more details and closer location of rainfall patterns.

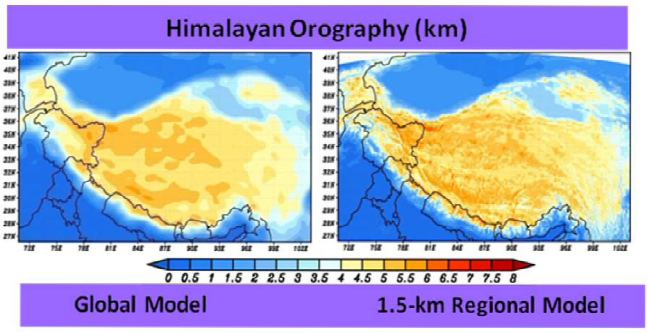

Fig.9 Orography (m) of global UM and 1.5-km Regional UM.

3.1 Probabilistic Quantitative Precipitation Forecast (PQPF)

A 20 member NGEFS system (T190L28) operational since JJAS 2012 at NCMRWF. Rainfall forecasts at each grid based on the ensemble members are expressed in terms of probability of rainfall exceeding different thresholds. PQPF forms a very useful for forecasters in decision making since they provide value addition to thedeterministic model forecasts.

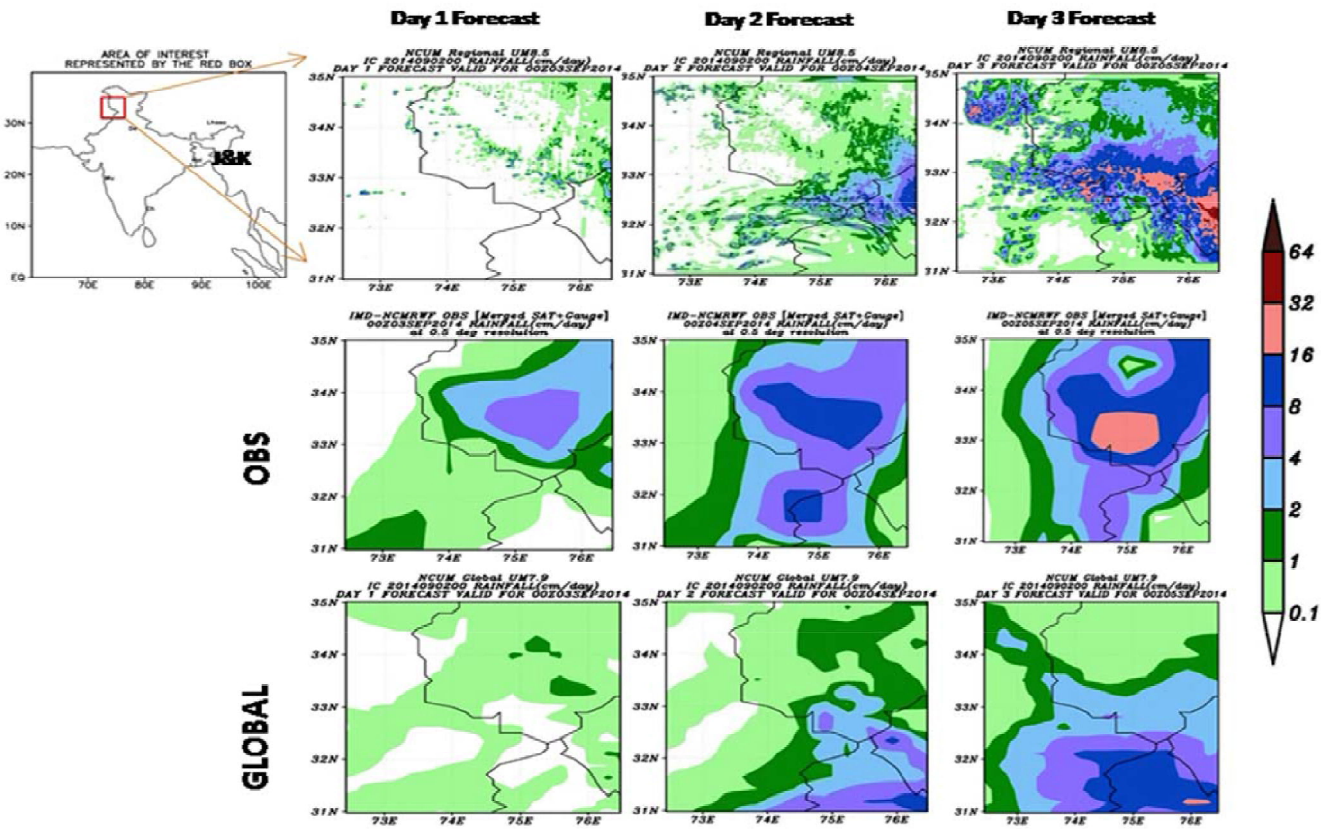

Fig.10 Rainfall forecasts from global UM and 1.5-km regional UM for J&K region (3-5 September, 2014).

Panels in Fig.11 show the ensemble mean rainfall over J&K on 6th September 2014 (top left) and the PQPF plots for three rainfall thresholds 1-2cm/day (bottom left), 2-5cm/day (top right) and 5-10cm/day(bottom right). The high probability (65-95%) of 5-10cm/day rainfall 5 days ahead is predicted in the NGEFS system. Such products are of immense use for the forecasters and disaster managers. These forecasts are also made available to the Bhakra and Beas Management Board (BBMB) for hydrological assessment for potential flood hazard over the river Jhelum river basin.

3.2 Ensemble Based Tropical Cyclone Track Forecasts

Ensemble forecast system can be used for forecasting the tropical cyclone track based on the ensemble members. They produce an ensemble of cyclone tracks, an average track and a map of strike probabilities around the mean track. The tracks (left) and strike probabilities (right) forecast for the recent very severe cyclone 'Phailin' from (4-14 October2013) are shown in Fig. 12.The ensemble member tracks show increasing spread with increasing forecast lead time. Strike probability shows likelihood of the forecast TC being within

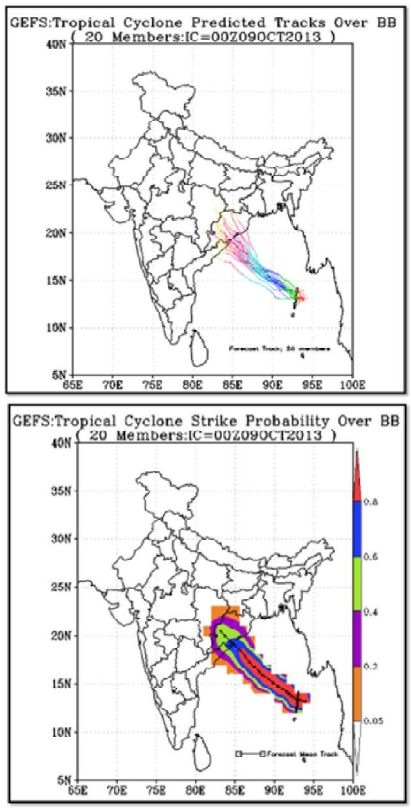

Fig.12 NGEFS ensemble member tracks and strike probability for Bay of Bengal Cyclone 'Phailin'.

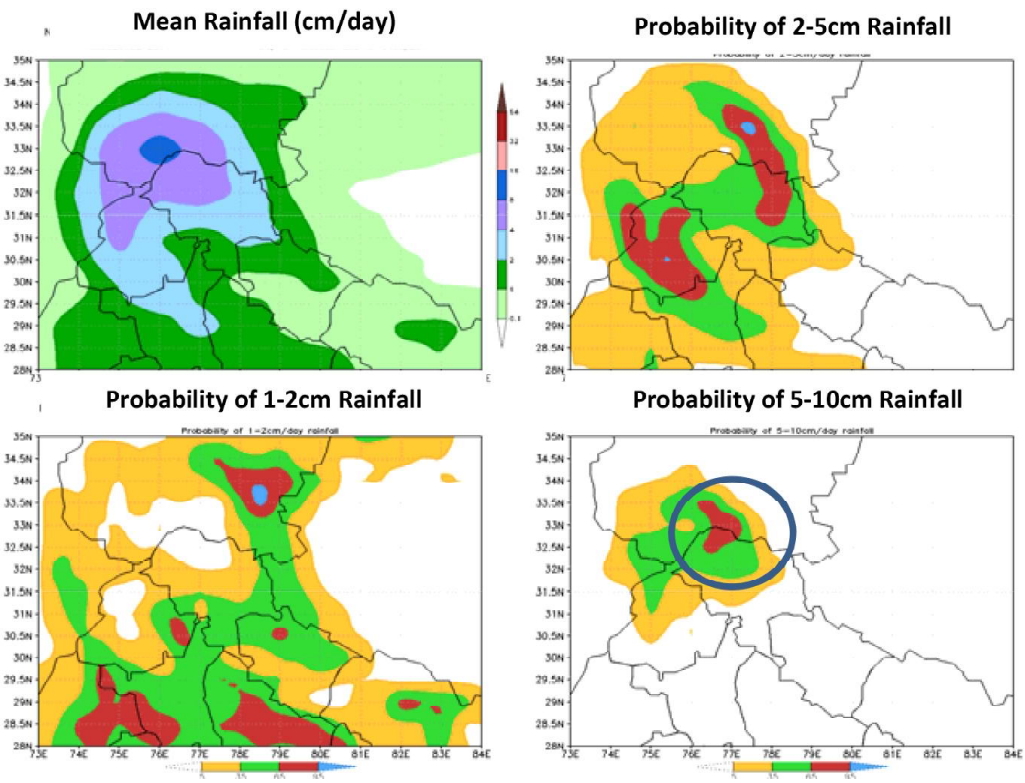

Fig.11 NGEFS ensemble mean rainfall and the forecast probabilities for different rainfall amounts.

110 km of the mean track. The ensemble mean track has lower error compared to the track based on the deterministic model as shown in Fig. 13.

The NGEFS is further improved to provide more real time forecast products using bias correction methods. The calibration (bias correction) of ensemble forecasts is carried out using method of "Moment Adjustment" for MSLP, Geopotential Height, Wind and Temperature at all levels and tested for the period May 2013 to February 2014. The calibrated forecasts show improvement in the forecast in terms of reduced tropical cyclone track errors. On an average, the 24 hour forecast track errors improves by about 49% after the bias correction. Bias correction techniques have been implemented operationally for the NGEFS products.

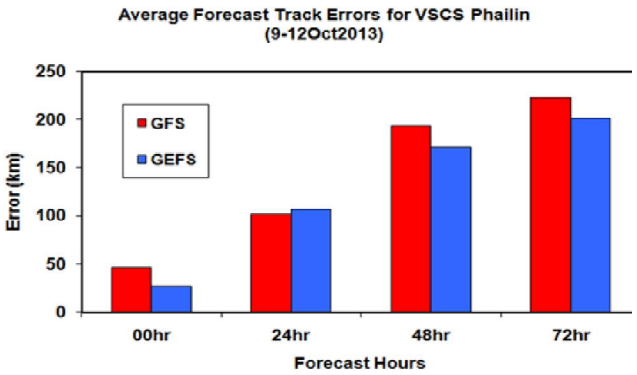

Fig.13 Forecast track error for Bay of Bengal Cyclone 'Phailin".

4. Verification of Model Forecasts

The last 9 year record (2005-2014) of the RMSE (against observations from Indian Radiosonde stations) of the 3-day forecasts of the vector winds at 850 hPa level (Fig. 14) shows that the prediction skill has improved by about 7-8 %. This improvement resulted from periodic increase in the resolution of the model and the capability to assimilate satellite radiances. The most notable feature of the error variation is its seasonal cycle with the winter months having least error and the Southwest Monsoon having the largest error.

Verification of rainfall forecasts is routinely carried out at NCMRWF using the rainfall analysis over India. For spatial verification of rainfall forecasts Contiguous Rain Areas (CRA) technique is adopted. The CRA method is an object-oriented verification procedure suitable for gridded quantitative precipitation forecasts (QPFs). In this framework a weather system is defined as a region bounded by a user specified isopleth (entity) of precipitation in the union of the forecast and observed rain field.

For each entity that can be identified in forecast and observations, the CRA method uses pattern matching techniques to determine the location error, as well as errors in area, mean and maximum intensity, and spatial pattern. The total error can be decomposed into components due to location, volume, and pattern error. CRA method of verification allows one to separate the total error into components due to errors in location, volume and pattern. Fig. 15 presents the CRA verification results for the NCUM Day-1 forecast. The forecast error is mainly due to pattern error (52%) and displacement error (42%) with small contribution (6%) from the volume error.

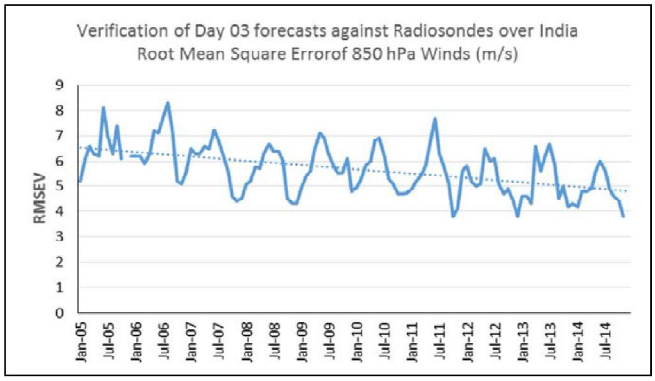

Fig.14 RMSE in the Day-3 forecast vector winds at 850 hPa in the NGFS.

5. Evaluation of Gridded Rainfall Datasets for Monsoon Studies

Various rainfall datasets are being released by reputed research groups at various spatial-temporal ranges. Continuous evaluation of these datasets is required to select the most suitable for our region and goal. Six gridded rainfall data sets, comprise those based solely on gauge observations and those merging gauge data with satellite-derived products, were compared against IMD gridded rainfall data set at seasonal timescale. Various skill metrics were computed for the Indian region during the summer monsoon season (June-September) at all-India and sub-regional scales. The spatial maps of climatological average rainfall in India during the summer monsoon season from different data sets are shown in Fig. 16. In the gauge-based (land-only) category, APHRODITE and GPCC data sets perform better relative to the others in terms of a variety of skill metrics. In the merged category, GPCP data set is shown to perform better than

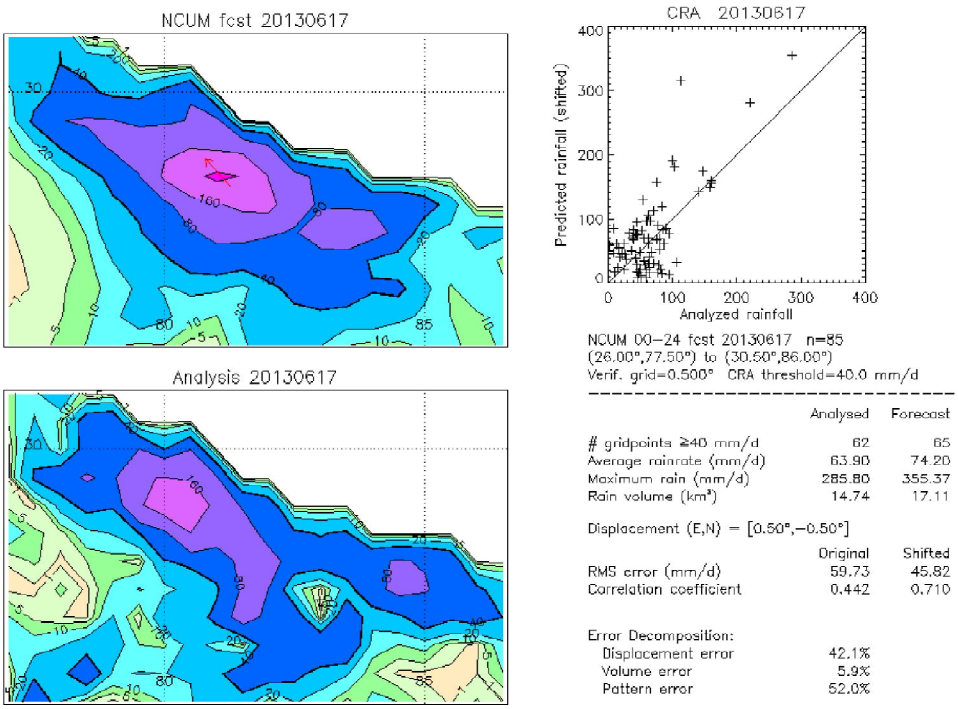

Fig.15 CRA verification of NCUM Day-1 rainfall forecast over Uttarakhand region on 17th June 2013.

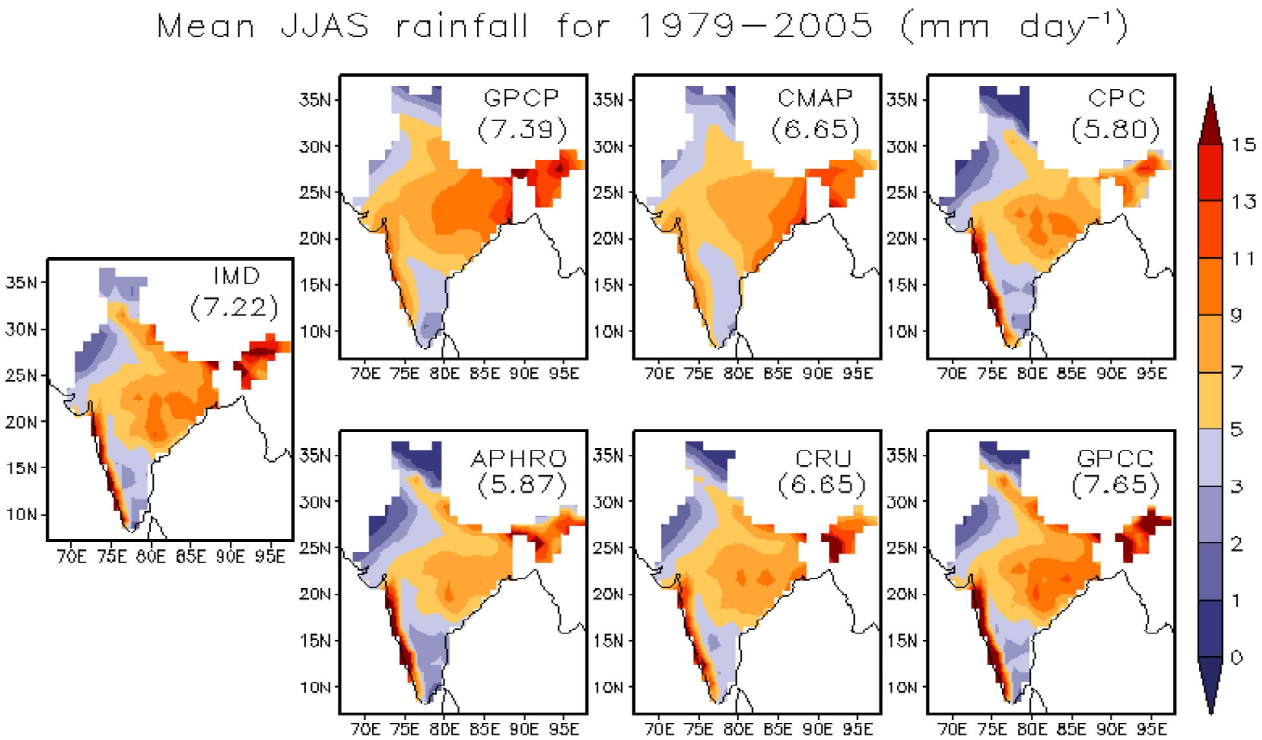

Fig.16 Spatial distributions of mean seasonal rainfall during the JJAS southwest monsoon averaged for the period 1979-2005. All-India mean values are given in the parentheses.

CMAP for the Indian monsoon. However, there are significant differences among data sets indicating uncertainty in the observed rainfall in the region which is crucial when evaluating model simulations.

The TRMM Multi-satellite Precipitation Analysis (TMPA) research monitoring product is one of the most widely used high-resolution merged precipitation products for various hydro-

meteorological applications which takes advantages of the rich constellation of microwave and infrared satellite-borne sensors along with available rain gauge data over land. The TMPA research version precipitation monitoring product version 7 (V7) was released in December 2012 after retrospective processing of the various inputs with the new V7 algorithm and supposed to be better than existing version 6 (V6) product. These two successive versions of the TMPA-3B42 research monitoring product, V6 and V7, were evaluated at daily scale over India during the southwest monsoon with gauge-based data for 1998 to 2010 period. The bias between V7 and V6 and between both versions and the gauge-based data are shown in Fig. 17. Over typical monsoon rainfall zones, biases were improved by 5-10% in V7 over the regions of higher rainfall like the west coast, northeastern, and central India. Different skill metrics at all-India scale and over typical sub-regions within India showed an overall improvement of the monsoon rainfall representation in V7. In general, results indicated that V7 is considerably improved over V6 over India and can be used for the monsoon studies and numerical model output verification.

6. Coupled Modelling for Seamless Prediction

NCMRWF in collaboration with Met Office, has implemented the HadGEM3AO (N96L85O1L75) based coupled model and is being further developed for Indian/monsoon conditions. The atmosphere component UM has a horizontal resolution of 1.875o x 1.25o and has 85 layers in the vertical going up to 85 km. The Ocean component NEMO is configured at 1 o x 1 o resolution, but near equator its resolution is 0.33 o. It has 75 layers in vertical, with 35 layers in upper 300 mts (1 m near surface). For Sea-Ice, the CICE model of Los Almos Lab, USA is integrated to the coupled system. The coupled system will be upgraded to N216L85O25L75 higher resolution on the new HPC. In collaboration with Met Office/NCOF NEMOVar Ocean initialisation scheme is also being implemented at NCMRWF. This coupled model has been adopted by MoES as part of the 'National Monsoon Mission' to enhance the skill of monsoon prediction from days to season in a seamless context. Fig. 18 shows the mean rainfall from the hindcast runs done at NCMRWF. The GA3.0 having better physical parameterisation processes has reduced rainfall biases compared to older GA2.0 version in UM.

7. New Applications

7.1 Visibility Forecasts

Forecast of fog and visibility over most parts of Indo-Gangetic plains are becoming increasingly important in the winter season. High frequency of occurrence of dense fog and reduced visibility has significant socio-economic impacts. The life cycle of fog is mainly controlled by different

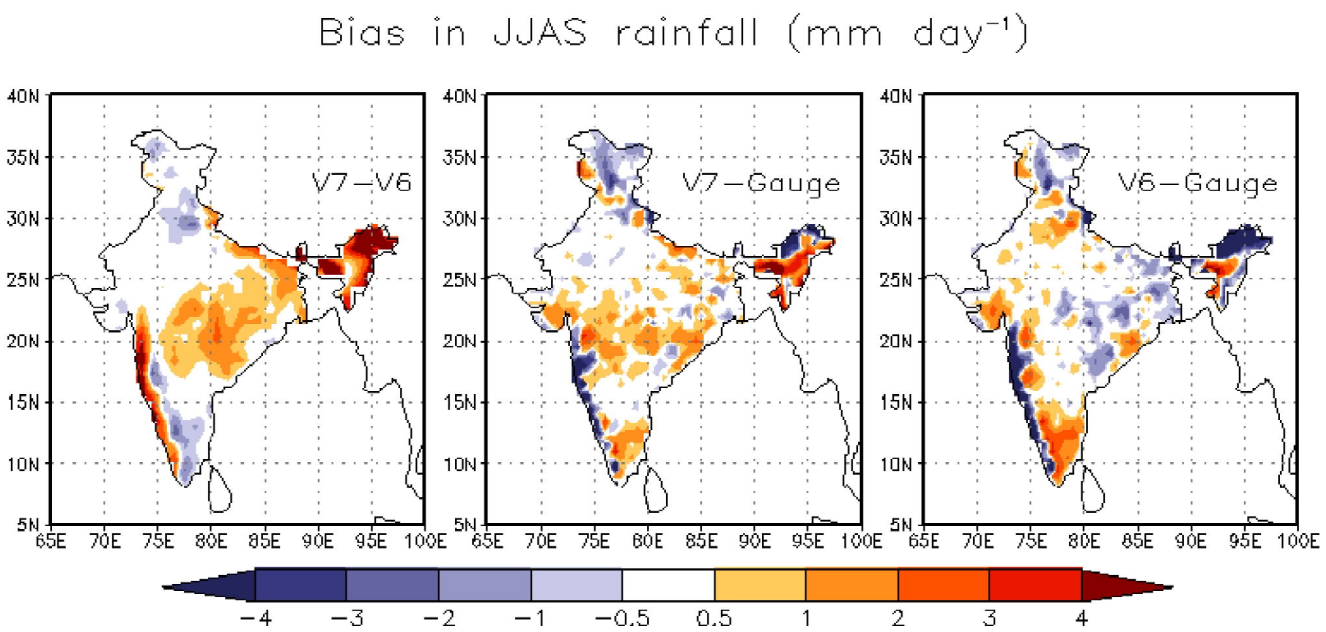

Fig.17 Spatial distributions of bias over India during the southwest monsoon season for the period 1998-2010 from daily IMD rain gauge-based observations and TMPA-3B42 V6 and V7 rainfall products.

meteorological factors and the microphysical/ chemical properties of the particulate matter present in the atmosphere. The present day numerical weather prediction (NWP) models of high spatial resolution are able to forecast situations that are favourable for the occurrence of fog events with reasonable accuracy few days in advance. In the NCUM, determination of atmospheric visibility mainly depends on two crucial factors; one is the relative humidity and second is the aerosol concentration (Clark et al. 2008). The model visibility is being verified against surface visibility observations from meteorological airport reports (METAR) (Fig.19). Visibility products are also being verified against visible and IR based fog products from INSAT-3D.

7.2 Dust Forecasts

Mineral dust is a major constituent of airborne particles in the atmosphere. Dust forecast models are designed to predict the atmospheric cycle of mineral dust. Since forecast of airborne dust is very important especially over the north western part of the country, it is required to have the numerical prediction capability of dust. Dust forecast models are becoming integral part of the advanced numerical weather prediction (NWP) models and NCMRWF Unified Model has the dust forecast scheme (Woodward 2001, 2011). Numerical prediction of dust started at NCMRWF in 2013. Dust forecast from NCUM is verified against various space and surface based observations for all seasons over Indian region. Dust forecast is mostly useful in the pre-monsoon season over Indian region since the dust load as well as its temporal variability is high during this period. Dust forecasts over western, central and eastern part of India verified separately. Forecast of Dust aerosol optical depth (AOD) is mainly compared against the observations since AOD is the commonly measured parameter from both satellites (from CALIPSO, MODIS, MISR, OMI etc.) and ground based (AERONET) measurements. The comparison results shows that the model dust forecast has good skill over the western part of the country in the pre-monsoon season (Table-1 & Fig.20). Vertical distribution of dust concentration in the forecast is studied with the help of CALIPSO

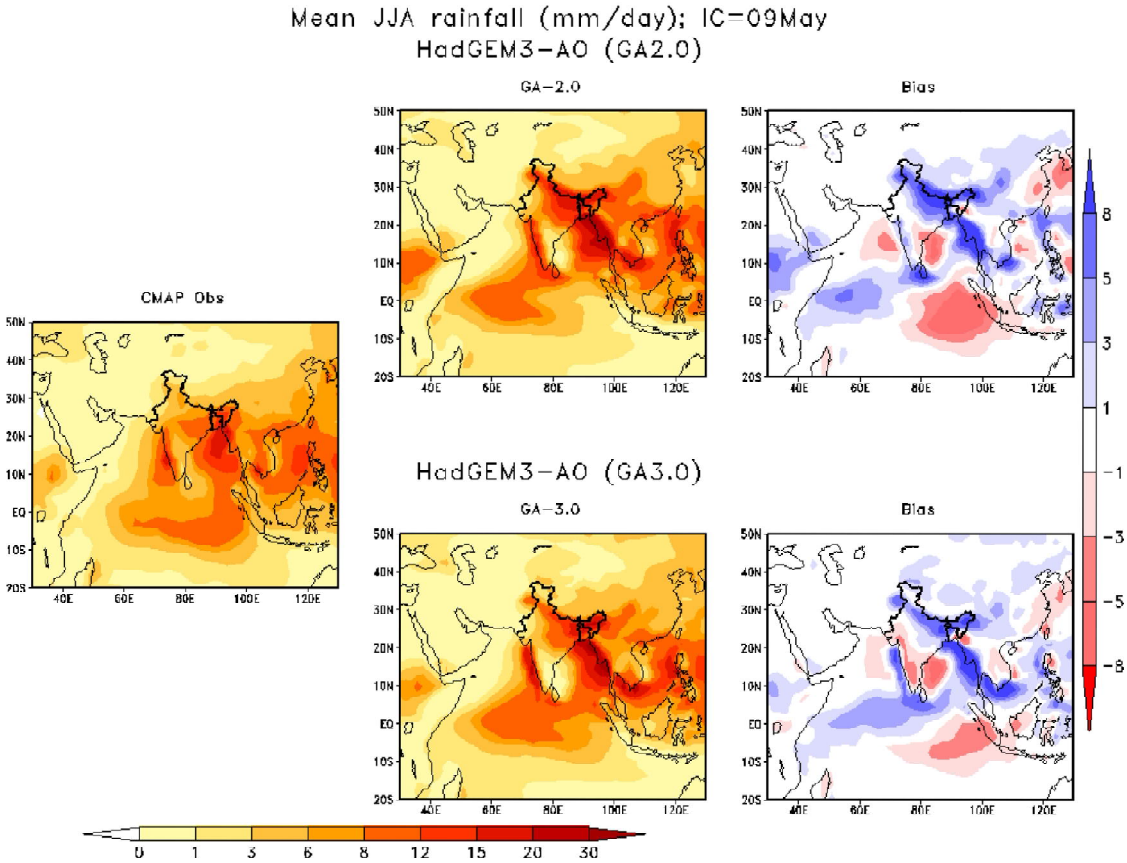

Fig.18 Mean Monsoon JJA rainfall and biases from coupled model,.

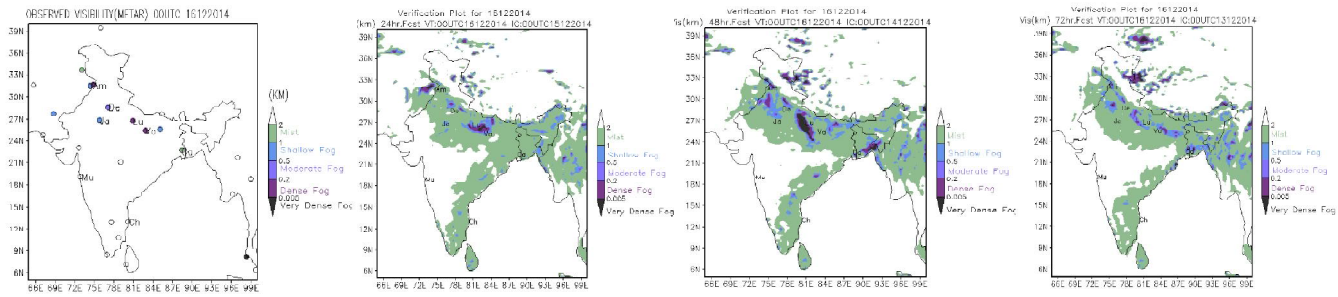

Fig.19 24, 48 and 72 hr forecast of visibility from NCUM valid for 00 UTC16 December 2014 and corresponding METAR visibility observations.

TABLE-1
NCUM day-2 forecast and CALIPSO satellite observations of dust AOD over north western part of the country during April-May, 2014

Time period	Mean Bias Error (BE)	Root Mean Square Error (RMSE)	Willmott's index of agreement *(d)*	Correlation Coefficient (CC)	Data points (N)
April 2014	0.1417	0.1734	0.6561	0.7033	5115
May 2014	0.0434	0.1780	0.6676	0.7071	5494

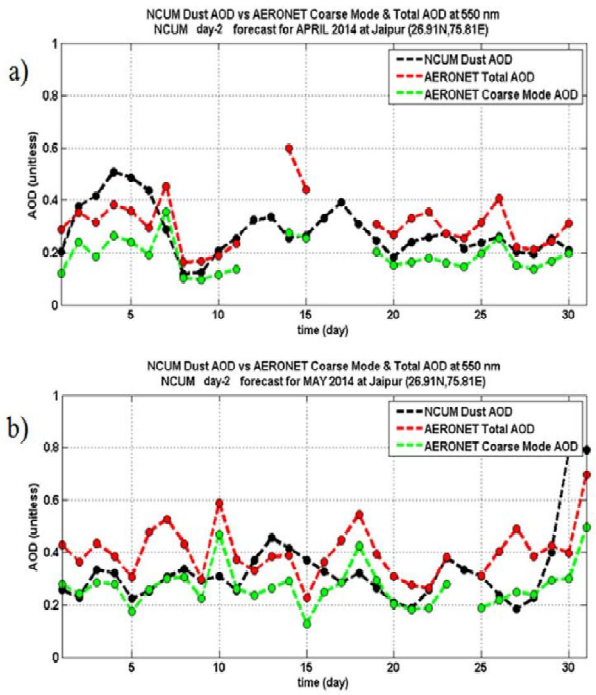

Fig.20 NCUM day-2 forecast of dust AOD at 550nm and corresponding AERONET observations of total and coarse mode AOD at 550 nm at Jaipur during (a) April and (b) May, 2014.

measurements. This also indicates that the model has reasonably succeeded in forecasting the vertical distribution of dust even in case of extreme events.

8. Future Plans

During this year, with the commissioning of the 350 TF HPCS at NCMRWF, the horizontal resolution of the deterministic model (NCUM) will be upgraded to 17 km. A higher resolution ensemble prediction system (33 km and 44 member) based on NCUM will also be implemented. There are also plans to implement hybrid ensemble 3D and 4D Variational data assimilation systems. High resolution models require correspondingly high resolution wind and moisture data for initialisation, which radar networks are well placed to deliver. Assimilation of DWR data into regional UM will be undertaken. A high resolution coupled model will be implemented to enhance the skill of monsoon prediction from days to season in a seamless context.

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