Improvements in medium range weather forecasting system of India

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Medium range weather forecasts are being generated in real time using Global Data Assimilation Forecasting System (GDAFS) at NCMRWF since 1994. The system has been continuously upgraded in terms of data usage, assimilation and forecasting system. Recently this system was upgraded to a horizontal resolution of T574 (about 22 km) with 64 levels in vertical. The assimilation scheme of this upgraded system is based on the latest Grid Statistical Interpolation (GSI) scheme and it has the provision to use most of available meteorological and oceanographic satellite datasets besides conventional meteorological observations. The new system has an improved procedure for relocating tropical cyclone to its observed position with the correct intensity. All these modifications have resulted in improvement of skill of medium range forecasts by about 1 day.

1. Introduction

The operational global data assimilation and forecast system (GDAFS) of NCMRWF (an adapted version of NCEP GFS system) has undergone various changes in terms of data usage, model physics, resolution and analysis schemes, etc. since 1989 (table 1). The changes were made with an aim to increase forecast skill by incorporating latest advances in model physics, analysis schemes and skill to incorporate new types of datasets into the model. The increase in computing resources at the centre over the years was also an important factor in implementing the abovementioned changes (table 2). A schematic diagram of the entire operational NWP system at NCMRWF is given in figure 1. The meteorological observations from all over the globe and from various observing platforms are received at Regional Telecommunication Hub (RTH), New Delhi through Global

Telecommunication System (GTS) and the same is made available to NCMRWF through a dedicated link. Special arrangements have been made to receive bulk satellite data directly from satellite operators, viz., NOAA-NESDIS, EUMETSAT and ISRO (via ftp access). All data are decoded from their native format and encoded into NCEP Binary Universal Form for the representation of meteorological data (BUFR) format using various decoders and are archived in a special file structure, called BUFR-TANK, for subsequent use. The global data assimilation system (GDAS) accesses the observational database from the BUFR-TANK at a specific time each day (every 6 hours, starting from 0000 hours), four times a day.

The latest major changes that were implemented in May 2011 were significant not only in terms of the improved model physics, but also in the capability of decoding and assimilating more conventional and satellite observations. Figure 1(b)

Keywords. Medium range forecast; data assimilation; numerical weather prediction.

Table 1. *History of global data assimilation and forecasting systems of NCMRWF.*

Model	Analysis scheme	Year	Forecasting range (days)
R40L18	OI	1989	5
T80L18	SSI	1992	5
T170L28	SSI	2005	5
T170L42	SSI	2006	5
T254L64	SSI	2007	7
T254L64	GSI	2008	7
T382L64	GSI	2010	10
T574L64	GSI	2010	10

Table 2. *History of high performance computing (HPC) at NCMRWF.*

Sl. no	HPC (with peak performance)	Period
1	Cray XMP-14 (4 MFlops)	1988–1993
2	Cray XMP-216(16 MFlops)	1993–1998
3	Dec-Alpha cluster (9.6 GFlops)	1999–2011
4	Cray SV1 (28.8 GFlops)	2001–2006
5	PARAM Padma (500 GFlops)	2006–2011
6	Cray X1E (1.1 TFlops)	2006–2011
7	IBM Power 6 (24 TFlops)	2010 onwards

shows increase in the volume of data, in both via GTS and ftp, from time to time. The horizontal resolution of the new GDAFS is now T574 (about 22 km) but vertical resolution is kept same at 64 levels similar to previous version (T382L64). The 64 unequally spaced hybrid sigma-pressure levels are terrain following near the lower levels and constant pressure surfaces in the stratosphere and beyond. There are 15 levels below 800 hPa and 24 levels above 200 hPa. The implementation details of this new GDAFS as well as the preliminary results are given in Prasad *et al.* (2011). The performance of two variants of NCMRWF global analysis forecast systems with resolutions T382L64 and T574L64 in predicting the various components of the Indian summer monsoon during 2011 were evaluated. The salient features of the latest global data assimilation-forecast systems *vis-à-vis* the previous version and the significant results from the same are also presented in this paper.

2. Forecast model

Rajagopal *et al.* (2007) give a detailed description of the NCMRWF GFS system which was operational from January 2007 at NCMRWF. The forecast model is a primitive equation global spectral model in hybrid sigma-pressure vertical coordinates (Moorthi *et al.* 2001; Environmental

Modeling Centre 2003) for vorticity, divergence, $\ln(P_s)$, virtual temperature and three tracers (specific humidity, ozone mixing ratio and cloud condensate mixing ratio). The model horizontal resolutions are T382 and T574 with 1152×576 (~ 35 km) and 1760×880 Gaussian grid points (~ 22 km), respectively near the equatorial latitudes and employ a reduced Gaussian grid (64 and 18 grid points respectively) as it goes towards either poles.

Time integration is leapfrog for nonlinear advection terms. Semi-implicit method is used for gravity waves and for zonal advection of vorticity and specific humidity. A time split physics adjustment scheme is employed with implicit treatment when possible and damping to simulate subgrid scale dissipation. A digital filter initialization with a 3 h window is used for mass and wind balance and (Asselin 1972) time filter is used to reduce computational modes. The model's time step for T382L64 and T574L64 are 3 and 2 min, respectively. Mean orographic heights on the Gaussian grid are used. Horizontal diffusion is 8th order scale selective for divergence, vorticity, virtual temperature (on quasi-pressure surfaces), specific humidity, ozone and cloud-condensate. Vertical advection of tracers caused computationally generated negative tracers, which are minimized by a positive-definite tracer transport scheme in T574L64 implementation. This change was necessary for the newly implemented GSI which is sensitive to the negative water vapour.

Volume of data reception through GTS (MB/day)

Volume of data reception through FTP via internet(MB/day)

Figure 1. (a) Schematic diagram of the entire operational NWP system at NCMRWF. (b) Showing year-to-year increase of data received at and used at NCMRWF.

The major changes incorporated in the present GDAFS implementation compared to the previous T382L64 are tabulated in table 3. New T574L64 is an upgraded version of NCEP GFS system (Kanamitsu 1989; Kalnay *et al.* 1990; Kanamitsu *et al.* 1991; Moorthi *et al.* 2001; EMC 2003). The physics changes are mainly in radiation, gravity wave drag, planetary boundary layer processes, shallow and deep convection schemes and an introduction of tracer transport scheme in the

vertical (Saha *et al.* 2010). Short wave (SW) routine is changed from RRTM to RRTM1 and invoked every hour. Long wave (LW) computation frequency is 1 h. Stratospheric aerosols (for both SW and LW) and tropospheric aerosols (LW) are added. In stratosphere, for shortwave computation the aerosol single scattering albedo is changed from 0.90 to 0.99. SW aerosol asymmetry factor is changed and the new aerosol climatology (Sato *et al.* 1993) is used. SW cloud overlap is changed from random to maximum random overlap. Time varying global mean CO₂ is used instead of constant CO₂. Treatment of the dependence of direct-beam surface albedo on solar zenith angle over snow-free land surface is based on Yang *et al.* (2008).

Gravity wave drag (GWD) has also been modified to automatically scale mountain block and GWD stress with resolution (Kim and Arakawa 1995; Lott and Miller 1997), using four times stronger mountain block and one half the strength of GWD. Planetary boundary layer (PBL) processes include stratocumulus-top driven turbulence mixing, enhanced stratocumulus-top driven diffusion for cloud top entrainment instability and local diffusion for night time stable PBL. Background diffusion in inversion layer of 2.5 km over ocean is reduced by 70% to decrease the erosion of stratocumulus along the coastal area. Bulk-Richardson number is used to calculate PBL height.

Deep convection parameterization follows modified Simplified-Arakawa Scheme (SAS) (Han and Pan 2010). It eliminates random cloud type, and detrains cloud water from every cloud layer of the height cloud. Finite entrainment and detrainment rates for heat, moisture and momentum are specified. Similar to shallow convection scheme, entrainment rate is given to be inversely proportional to height in subcloud layers and detrainment rate is set to be a constant as entrainment rate at the cloud base. Above cloud base, an organized entrainment is added, which is a function of environmental relative humidity. Intraseasonal momentum background diffusivity is applied for winds only. Convective overshooting increased cloud water detrainment in upper cloud layers.

There are many causes for negative water vapour generation in NWP models, the biggest contributor being the usage of vertical central differencing scheme. Removal of this major cause of negative water vapour was affected by a positive-definite tracer transport scheme (Yang *et al.* 2009) in the vertical to replace the central-differencing scheme to eliminate computationally-induced negative tracers. This included the change in parameters 'factqmin and factqmax' in GSI, to reduce negative water vapour and super-saturation points from analysis steps. Modifying cloud physics to limit the borrowing of water vapour that is

Table 3. *Physical parameterization schemes in T382L64 and T574L64.*

Physics		T382L64	T574L64
Surface fluxes	Monin–Obukhov similarity		Monin–Obukhov similarity
Turbulent diffusion	Non-local closure scheme (Hong and Pan 1996)		Non-local closure scheme (Lock et al. 2000) – includes stratocumulus-top driven turbulence mixing
SW radiation	Based on Hou et al. (1996) – no aerosols – invoked hourly		Rapid radiative transfer model (RRTM2) (Mlawer et al. 1997, 1998) – aerosols included – invoked hourly
LW radiation	Rapid radiative transfer model (RRTM) (Mlawer et al. 1997) – no aerosols – invoked 3 hourly		Rapid radiative transfer model (RRTM1)(Mlawer et al. 1997, 1998) – aerosols included –invoked hourly
Deep convection	SAS convection (Pan and Wu 1995)		SAS convection (Han and Pan 2006) – include the effect of convection-induced pressure gradient force in momentum transport
Shallow convection	Shallow convection following Tiedtke (1983)		Mass flux scheme (Han and Pan 2010)
Large scale condensation	Large scale precipitation (Zhao and Carr 1997; Sundqvist et al. 1989)		Large scale precipitation (Zhao and Carr 1997; Sundqvist et al. 1989)
Cloud generation	Based on Xu and Randall (1996)		Based on Xu and Randall (1996)
Rainfall evaporation	Kessler (1969)		Kessler (1969)
Land surface processes	NOAH LSM with 4 soil levels for temperature and moisture (Ek et al. 2003)		NOAH LSM with 4 soil levels for temperature and moisture (Ek et al. 2003)
Air–sea interaction	Roughness length (Charnock 1955) observed SST, thermal roughness over the ocean is based on Zeng et al. (1998) 3-layer thermodynamic sea-ice model (Winton 2000)		Roughness length (Charnock 1955) observed SST, thermal roughness over the ocean is based on Zeng et al. (1998) 3-layer thermodynamic sea-ice model (Winton 2000)
Gravity wave drag and mountain blocking	Based on Alpert et al. (1988)		Based on Lott and Miller (1997), Kim and Arakawa (1995), Alpert et al. (1996)
Vertical advection	Explicit		Flux-limited positive-definite scheme (Yang et al. 2009)

used to fill negative cloud water to the maximum amount of available water vapour so as to prevent the model from producing negative water vapour, the minimum value of water vapour mass mixing ratio in the radiation is changed from $1.0\text{e-}5$ to $1.0\text{e-}20$. Otherwise the model artificially injects water vapour in the upper atmosphere where water vapour mixing ratio is often below $1.0\text{e-}5$.

At NCMRWF, vertical coordinate was changed from sigma to hybrid sigma pressure, reducing some upper air model errors (Sela 2009) in this latest change. The hybrid coordinate system is terrain following in the lower levels and transforming to pure pressure coordinate in the upper levels and is uniquely represented by two values A_k and B_k at the interfaces. The values of $(A_k \cdot 1000.0)$ and B_k are read from an input file. The interface pressure levels (in hPa) can be derived by the relation;

$$IPres_{k+\frac{1}{2}} = (A_{k+\frac{1}{2}} + B_{k+\frac{1}{2}} \cdot P_0) 10.0,$$

where P_0 is the surface pressure in centi-bars (cb).

The layer pressures (Pres), sigma interface (SI) and sigma layer (SL) equivalents for dynamics can be obtained by mathematical manipulations.

3. Analysis scheme

The global analysis scheme used at NCMRWF earlier was spectral statistical interpolation (SSI). However from January 2008, SSI system was replaced with grid-point statistical interpolation (GSI). The key aspect of the GSI is that it

formulates the analysis in model grid space, which allows for more flexibility in the application of the background error co-variances and makes it straightforward for a single analysis system to be used across a broad range of applications, including both global and regional modelling systems. In the GSI system many new features are included, such as changes to the observation selection, quality control, minimization algorithm, dynamic balance constraint and assimilation of new observation types.

GSI scheme (Wu *et al.* 2002) is an evolutionary combination of the SSI scheme and the regional ETA 3D-VAR. It replaces spectral definition for background errors with grid point (physical space) version based on recursive filters. This global 3DVAR in physical space is as effective as 3DVAR in spectral space with latitude-dependent structure functions and other error statistics. Diagonal background error covariance in spectral space (in SSI) allows little control over the spatial variation of the error statistics as the structure function is limited to being geographically homogeneous and isotropic about its center (Parrish and Derber 1992; Courtier *et al.* 1998). GSI allows greater flexibility in terms of inhomogeneity and anisotropy for background error statistics (Wu *et al.* 2002). Thus major improvement of GSI over SSI analysis scheme is its latitude-dependent structure functions and has more appropriate background errors in the tropics. The background error covariances are isotropic and homogeneous in the zonal direction. Thus results from initial

Table 4. Differences in the GSI scheme used in T574L64 and T382L64 systems.

New observations assimilated	Improvements in data assimilation system
Inclusion of METOP IASI (Infrared Atmospheric Sounding Interferometer) data	Use of variational qc
Reduction of number of AIRS (Atmospheric Infrared Sounder) water vapour channels used	Addition of background error covariance input file
Assimilating tropical storm pseudo sea-level pressure observations	Flow dependent reweighting of background error variances
NOAA-19 HIRS/4 (High Resolution Infrared Radiation Sounder) and AMSU-a (Advanced Microwave Sounding Unit) brightness temperature	Use of new version and coefficients for community radiative transfer model (CRTM-2.02)
NOAA-18 SBUV/2 (Solar Backscatter Ultraviolet Spectral Radiometer) Ozone, EUMETSAT-9 atmospheric motion vectors	Improved tropical cyclone relocation
Using uniform thinning mesh for brightness temperature data	Change in land/snow/ice skin temperature variance
Improving assimilation of GPS radial occultation data RE-tuned observation errors	
ASCAT (Advanced Scatterometer) winds included	
Korean AMDAR data and more number of aircraft reports	

experiments reported that GSI had a small impact on extra-tropics but it had shown consistent positive impact in tropics (Wu *et al.* 2002). The full details of GSI scheme operational at NCMRWF can be found in Surya and Prasad (2011). Table 4 depicts the major differences in T382L64 and this new implementation.

4. Results and discussions

The two variants of NCMRWF global analysis forecast systems with resolutions T382L64 and T574L64 respectively were run in parallel for the entire monsoon season of 2011. A number of diagnostics have been generated to evaluate the performance of the GFS for the entire monsoon season of 2011.

The forecast errors (defined as the difference between the forecasts and the analyses) of the NCMRWF T574 GFS have been compared with those of the NCEP Operational GFS for June–August (JJA) 2011. The diagnostics of the performance of the NCEP operational GFS have been obtained from NCEP (through personal communication). Figure 2(a and b) shows the day-5 forecast errors of 850 hPa zonal wind of the NCMRWF GFS and the NCEP GFS, respectively. It is seen that the forecast errors from the two systems are similar.

Further, objective verification scores for the both T382L64 and T574L64 forecasts were computed against the radiosonde observations valid at 00 UTC and also against their mean analyses at standard pressure levels as recommended by WMO (WMO-No. 485: Manual on the Global Data-processing and Forecasting System) for the entire monsoon season (June–September) of 2011. The verification scores are computed for analyses against observations, and for forecasts against both analyses and observations.

Figures 3 and 4 depict the vertical profile of T574L64 and T382L64 analyses and first guess vector wind fits to radiosonde observation for JJAS (June–September) over the global and global tropics (30°S to 30°N) domains, respectively. The fits include bias and RMSE. The bold lines represent T382L64 and the dotted lines T574L64. The black and red lines represent the analyses and the first guess, respectively. The right panel in the plots gives the count of observation in thousands over the said region used for the comparison. Over the global domain (figure 3), a remarkable reduction in the RMSE values is seen in the T574L64 guess field as compared to the T382L64 guess field, in all levels and more pronounced in the upper levels. This indicates a tremendous improvement in the skill of the short range forecasts (first guess)

Figure 2. Day-5 850 hPa zonal wind forecast errors, w.r.t corresponding analysis for the period June–August 2011. (a) NCMRWF GFS and (b) NCEP GFS.

of the T574L64 model compared to the T382L64. The improvement is due to both changes in assimilation and model physics. The RMSE values in the T574L64 analysis field also show a marginal reduction as compared to the T382L64 analysis field. Similar results are seen over the tropics (figure 4) and other domains (figures not shown) to establish and confirm the improvement in the T574L64 analyses in comparison to the T382L64 analyses.

Figure 5 depicts the anomaly correlation for day-1 to day-10 forecasts of 500 hPa geopotential height from the T574L64 and T382L64 models over the northern hemisphere. In the upper panel, the black and the red lines represent the T382L64 and T574L64 model, respectively. The T574L64 model shows higher values of anomaly correlation throughout the length of the 10 days forecast period. An anomaly correlation of 0.6 (Kalnay *et al.* 1998) is generally regarded as an indication of useful forecast. The T574L64 model is able to retain the value of anomaly correlation of 0.6 for one more day as compared to the T382L64 model,

Figure 3. Global mean vector wind fits to radiosonde observations for 1 June 30–September 2011 at 00 UTC along with the observational data counts.

Figure 4. Same as figure 3, but for global tropics.

Figure 5. Anomaly correlation of 500 hPa geopotential height for day-1 to day-10 forecasts over the northern hemisphere region (upper part of the figure) and anomaly correlation difference of T574L64 forecasts with respect to T382L64 forecasts along with their statistical significance (lower part of the figure).

Figure 6. RMSE of 850 hPa zonal wind over the RSMC region for day-1 to day-10 forecasts (upper part of the figure) and RMSE difference of T574L64 forecasts with respect to T382L64 forecasts along with their statistical significance (lower part of the figure).

Figure 7. Frequency bias score of rainfall computed for day-1, day-3 and day-5 forecasts for the period June–September 2011 from T382L64 and T574L64 models.

thereby indicating an improvement of skill of the forecasts by about 1 day. In the lower panel, the line plot depicts the difference of the forecasts of 500 hPa geopotential height of the T574L64 model from the T382L64 model. The difference values outside the histograms are statistically significant at 95% level of confidence determined by *p*-test. The T574L64 model is found to have significantly higher anomaly correlation at 95% level of confidence compared to T382L64 for all the days of the forecasts.

Figure 6 depicts the RMSE for day-1 to day-10 forecasts of 850 hPa zonal wind from the T574L64 and T382L64 models over the RSMC (Regional Specialized Meteorological Centre (10°S–40°N, 40°–100°E) region of IMD. In the upper panel, the black and the red lines represent the T382L64 and T574L64 model, respectively. The T574L64 model shows lower values of RMSE throughout the length of the 10 days forecast period. In the lower panel, the line plot depicts the difference of the forecasts

of 850 hPa zonal wind of the T574L64 model from the T382L64 model. The difference values outside the histograms are statistically significant at 95% level of confidence. The T574L64 model is found to have significantly lower values of RMSE at 95% level of confidence compared to T382L64 for all the days of the forecasts.

4.1 Indian summer monsoon rainfall

The impact of the new system on the Indian summer monsoon is studied in terms of bias score. The bias score is a measure of the agreement between the forecast frequency and the observed frequency of ‘yes’ events. It is given by the ratio of the frequency of forecast events to the frequency of observed events. The bias score does not measure how well the forecast corresponds to the observations, it only measures relative frequencies. The score values range from 0 to infinity and the score of 1 implies a perfect forecast. It indicates whether

Table 5. Contingency table illustrating the counts used in verification statistics for dichotomous (e.g., Yes/No) forecasts and observations.

Forecast	Observed	
	Yes	No
Yes	Hits	False alarms
No	Misses	Correct rejection

the forecast system has a tendency to underpredict (BIAS < 1) or overpredict (BIAS > 1) events.

$$\text{BIAS} = \frac{\text{hits} + \text{false alarms}}{\text{hits} + \text{misses}}$$

Figure 7 shows bias score computed for day-1, day-3 and day-5 from T382L64 and T574L64 models. The contingency table illustrating the counts used in verification statistics for dichotomous forecasts and observations is stated in table 5. The verification is for rainfall excess of 0.5 cm in a day. Day-1 forecast of both the models are underpredicting over north-west India and overpredicting over Jammu and Kashmir regions. However, T382L64 shows substantial underprediction over north-west parts of India as compared with T574 in day-1 and day-3 forecasts. However, the feature is not apparently visible in day-5 forecasts. T574L64 shows higher skill over eastern and central regions in day-3 and day-5 forecasts.

To further examine the skill of both the models in predicting the rainfall intensities, bias scores are presented in figure 8 for rainfall excess of 3, 4 and 5 cm in 24 hours. For rainfall thresholds starting from 3 cm/day, T574L64 shows higher skill than T382L64 in all day-1 to day-5 forecasts.

4.2 Tropical cyclone relocation scheme

Accurate prediction of tropical cyclones depends on the correct initial analysis of its position and strength. Data scarcity over oceanic region poses limitation on defining the initial position for tropical cyclone accurately. Assimilation of synthetic vortices in case of tropical cyclones were used operationally in NCMRWF since 1994, but the results were not always satisfactory. One of the reasons for this was the erroneous position, structure and intensity of the existing cyclone in the first guess. Often, cyclone in first guess is weak in strength and extends over large area compared to the observed cyclone, and further the model predicted centre is located away from the actual observed position. Thus, adding synthetic observations (cyclone bogus) generally leads to formation of two vortices in the same region, one from the first guess and the other from the synthetic data. The interaction between these two vortices

Figure 8. Frequency bias scores of the rainfall forecasts for different thresholds for both T382L64 (in red) and T574L64 (in blue) models for the period June–September 2011.

often leads to subsequent erroneous prediction. The tropical cyclone relocation scheme (Liu *et al.* 2000) was implemented at NCMRWF in T254L64 system during 2008. This scheme separates cyclone vortex from environmental fields in the first guesses (3-hr, 6-hr and 9-hr forecasts) used for subsequent analysis step, relocates the same to the observed cyclone position according to satellite estimated position reported in Joint Typhoon Warning Centre (JTWC) bulletins. If the predicted cyclone strength in the first guess fields is weaker than that of observed one, then the scheme also adds synthetic wind observations in the vicinity of the cyclone. Figure 9 depicts the track prediction errors of the tropical cyclone over Indian seas in T254L64, T382L64 and T574L64 modelling system during 2007 to 2011. It is clearly seen that the errors in the location of the tropical cyclones in the analysis (initial conditions) have reduced significantly after October 2008 (after the use of tropical cyclone relocation procedure in T254L64). Track errors are further reduced with increase in model resolution to T382 and T574.

Figure 9. Track errors of tropical cyclones in Indian seas, before and after the implementation of the tropical cyclone relocation procedure in October 2008.

5. Summary

The successful implementation of the T574L64 GFS at NCMRWF makes India to be at par with major operational NWP centres. The new GFS represents a significant jump, not only in an improvement in the model physics, but also in the capability of decoding and assimilating more conventional and satellite observations. The comprehensive evaluation of the new system has shown improvements in many metrics. One of the major improvements is in the gain of 1 day in the skill of the forecasts as compared to T382L64. The tropical cyclone track errors have also reduced with increase in model resolution. India is also augmenting its current observational network and also planning to deploy various new observing systems. The upcoming INSAT-3D satellite with atmospheric sounder along with Megha-Tropiques satellite is going to provide a unique opportunity to assimilate direct satellite radiance data from an Indian satellite for improving the initial conditions and the forecasts subsequently.

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