Implementation of T254L64 Global Forecast System at NCMRWF

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Summary

A new Global Forecast System (GFS) at T254L64 resolution has been implemented at NCMRWF, on the Param Padma (IBM P5 based) and Cray-X1E computer systems. One analysis cycle and seven day forecast run takes about 3 hours on Cray X1E. The new GFS is running in real-time mode since 1st January 2007.

This new higher resolution global forecast model and the corresponding assimilation system are adopted from NCEP, USA. The horizontal representation of model variables is in spectral form (spherical harmonic basis functions) with transformation to a Gaussian grid for calculation of nonlinear quantities and physics. In horizontal it resolves 254 waves in spectral triangular truncation representation (T254), for which the Gaussian grid of 768 x 384 dimensions are chosen. The equivalent horizontal resolution is roughly 0.5 x 0.5 degrees latitude/longitude on the globe. In the vertical 64 layers are kept. Out of these, 15 levels are below 800 hPa, and 24 levels are above 100 hPa. Time step for model integration has been set at 7.5 minutes. The parameterized model physical processes are namely, the gravity wave drag and realistic orography, radiation, cumulus convection (Simplified Arakawa Schubert), shallow convection, large-scale condensation, diagnostic clouds, PBL, air-sea interaction and land-surface processes. The assimilation system is a global 3-dimensional variational assimilation system based on NCEP’s SSI scheme (Parrish et al., 1997). The observation residuals are analyzed in spectral space on sigma surfaces. In the SSI scheme the objective function to be minimized is defined in terms of the deviations of the desired analysis from the first guess field (which is taken as six hour
forecast from the T254/L64 model) and the observations, weighted by the inverse of the forecast and the observational error variances.

In the current implementation only conventional data sets and satellite Atmospheric Motion Vectors (AMV) are being assimilated in GFS. NCMRWF has plans to add other data sets such as satellite radiances, QSCAT winds etc. to the assimilation system in the near future.

This system is running regularly without any interruptions for the last five months. Weather analysis and predictions generated by the system are reasonably good and match well with that produced by other leading NWP centres. NCMRWF is in the process of comparing T254L64 products with that of operational T80L18 model and as well as with NWP products of other leading centres in more objective manner for forthcoming monsoon season. This will enable us to evaluate the skill of T254L64 GFS system in more detailed and comprehensive manner.
Contents

1. Introduction ............................................. 4

2. Observation Pre-processing .......................... 6

3. Global Analysis Scheme .............................. 14

4. Forecast Model ........................................ 19

5. Porting on Cray-X1E .................................. 26

6. Post-processing & plotting ......................... 28

7. Weather Analysis & Prediction: Case Studies .... 29

8. Concluding Remarks ................................. 37
1. Introduction

Global Forecast System (GFS) is the operational numerical weather analysis-forecast system of National Centers for Environmental Prediction (NCEP), USA. This system was acquired by NCMRWF under USAID training programme attended by the first author. The GFS implemented at NCMRWF mainly in Param Padma (IBM P5 cluster) and CRAY-X1E. The report is aimed to give an overview of the various modules of the complete GFS system as installed at NCMRWF.

Fig. 1 depicts the flowchart of the GFS as implemented at NCMRWF. Observation pre-processing and the post processing of model output are presently implemented in PARAM. Where as, the analysis system and forecast model at T254L64 resolution are implemented in CRAY-X1E (grey boxes in Fig. 1). GFS has capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geostationary satellites. But, in the present implementation of GFS, mainly conventional observations and satellite derived atmospheric motion vectors (AMVs) are being assimilated. It is also aimed to add the additional data pre-processing and assimilation modules for various other satellite observations such as radiances, sea surface QSCAT winds etc., in to the currently implemented GFS in near future.

Step 1 of the flowchart (Fig. 1) depicts the data decoding part. It runs 48 times in a day, half-hourly basis, as soon as data files (known as GTS files) consisting of global meteorological bulletins are received at NCMRWF from regional telecom hub (RTH) of global telecom system (GTS), at India Meteorological Department (IMD), New Delhi. Steps 2-6 of the flowchart mainly consist of observation pre-processing, data assimilation and model forecast. It runs 4 times a day along with each assimilation cycle (0000, 0600, 1200 & 1800 UTC). In all assimilation cycles, except 0000 UTC, forecast model runs up to 9 hours to provide first guess to the next assimilation cycle. At 0000 UTC cycle, forecast model runs up to 168 hour and generates predictions valid for next seven days. Steps 7-8 perform post-processing and plotting of model output. It runs once in a day, along with 0000UTC assimilation cycle.
Fig. 1: Flow depicting the job sequences of GFS installed at NCMRWF
Decoding of meteorological observations from different WMO defined code is the first step of an operational end-to-end numerical weather prediction (NWP) system. Section 2 describes the salient features of the implementation of data decoding procedure and observation pre-processing packages within GFS frame-work at NCMRWF. Implementation details of analysis and forecast packages are described in section 3 & 4 respectively. Porting of analysis scheme and forecast model have been successfully done on Cray-X1E. Related porting issues are discussed in section 5. Post processing and plotting procedure are described in section 6. Few cases studies related with analyses and predictions of some specific weather systems are discussed in section 7. Summary of the implementation is presented in section 8.

2. Observation Pre-processing

Observation pre-processing mainly consists of four major parts viz. (a) decoding, (b) tranjb, (c) gfs_dump & (d) gfs_prep as shown in Fig.1. All these components are described below.

(a) Data Decoding

Decoding of different types of observations is done at NCO (NCEP Central Operations) through LDM (Local Data Manager – an Unidata software). The LDM is used to ingest data received via GTS/other networks into the corresponding NCEP data decoders. An interface is developed at NCMRWF to avoid LDM. It separates out different types of observation bulletins from GTS files and writes them in different output files as per the format in which NCEP decoders expect the input.

NCEP decoders generally use few Unidata GEMPACK libraries such as GEMLIB, CGEMLIB and BRIDGE. So, the first step towards installing the decoders is to build these three libraries in a particular system. Next step is to build the NCEP BUFR library. The decoders listed below in Table 1 have been installed at NCMRWF and each of these decoders is kept in separate sub-directories (viz. decod_dcusnd.fd, decod_dclsfc.fd etc.) under the sub-directory “sorc”. All the decoders mentioned in Table 1 have been compiled using the available make files from the respective sub-directories. All these decoders use various corresponding BUFR table, which are available in
sub-directory named as “fix” ($\text{FIX}$). WMO station-directories used by SYNOP, TEMP etc. are available in sub-directory name as “dictionaries”. In general all these decoders parse observations from different types of WMO codes and write the output in NCEP decoder interface format (i.e. NCEP BUFR).

### Table 1: List of decoders implemented at NCMRWF

<table>
<thead>
<tr>
<th>Type of Observations</th>
<th>Decoder Name</th>
<th>WMO Code Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Upper air sounding</td>
<td>dcusnd</td>
<td>TEMP &amp; PILOT</td>
</tr>
<tr>
<td>2 Land surface</td>
<td>dclsfc</td>
<td>SYNOP &amp; SYNOP MOBIL</td>
</tr>
<tr>
<td>3 Marine surface</td>
<td>dcmsfc</td>
<td>SHIP</td>
</tr>
<tr>
<td>4 Drifting buoy</td>
<td>dcdrbu</td>
<td>BUOY</td>
</tr>
<tr>
<td>5 Sub-surface buoy Obsn.</td>
<td>dcbthy</td>
<td>BATHY &amp; TESAC</td>
</tr>
<tr>
<td>6 Aircraft observations</td>
<td>dcacft</td>
<td>AIREP &amp; AMDAR</td>
</tr>
<tr>
<td>7 Automated Aircraft Obsn.</td>
<td>dcacft</td>
<td>BUFR (ACARS)</td>
</tr>
<tr>
<td>8 Airport Weather Obsn.</td>
<td>dcmetr</td>
<td>METAR</td>
</tr>
<tr>
<td>9 Satellite winds</td>
<td>dcsaob</td>
<td>SATOB</td>
</tr>
<tr>
<td>10 High density satellite winds</td>
<td>dceums</td>
<td>BUFR (winds from EUMETSAT &amp; Japan)</td>
</tr>
<tr>
<td>11 Wind profiler observations</td>
<td>dcprof</td>
<td>BUFR (wind profiler from US/Europe/Hongkong )</td>
</tr>
<tr>
<td>12 Surface pr. Analysis (Aust.)</td>
<td>dcpaob</td>
<td>PAOB</td>
</tr>
</tbody>
</table>

A special application has been designed at NCEP, which provides user-friendly access to the BUFR files through a series of FORTRAN and
C subroutines in a machine independent BUFR library (called BUFRLIB). These routines allow one to encode or decode data into BUFR using mnemonics to represent the data. The mnemonics are associated with BUFR descriptors in a special version of the BUFR Tables A, B, C and D. When a BUFR file is created, the mnemonic table is read in from an external location and is itself encoded into BUFR messages at the top of the output file. This allows each BUFR file to be “self defined”. No external tables are needed to decode data out of the file. NCO has written a BUFRLIB software user guide ([http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB](http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB)) that provides a detailed explanation of the NCEP BUFRLIB subroutines along with other useful information on BUFR as it is used at NCEP.

Other modules of GFS use various common libraries, which are to be built before proceeding further. The source codes of these FORTRAN libraries are located at /gpfs1/datapro/esmf/lib/sorc (on Param Padma) in the directories listed below:

- bacio
- bufr
- crex
- crtm
- decod_ut
- esmf
- ip
- irsse
- landsfcutil
- sfcio
- sigio
- sp
- w3

These libraries are built by executing make files in each of the source directories. All compilations on Param Padma have been done with FORTRAN flags “–q64 –qstrict”.

(b) **TRANJB**

In decoding step, all the GTS bulletins are decoded from their native format and encoded into NCEP BUFR format using the various decoders. All of the encoded BUFR data are then appended to the appropriate files in the database through a job script named as ‘tranjb’. This script runs as the last step of decoding. It reads BUFR
files and appends each report it encounters into appropriate database (bufr_tank) file. The database files are of the form “$bufr_tank/yyyyymmdd/bmmm/xxsss” where yyyyymmdd is a year-month-day. So, the files are organized by the BUFR type and local subtype and contain information in 24-hour blocks (based on report time). ‘mmm’ is the 3 digit BUFR message type and sss is the 3-digit message sub-type. Since input BUFR files need not contain internal BUFR mnemonic tables needed to read them, the tables are assumed to exist in external files (in ASCII format), which are assumed to be grouped by message type and have the name “bufrtab.mmm”. The BUFR mnemonic tables are assumed to exist in directory $FIX. The respective files related to ‘tranjb’ on Param Padma are:

Script: /gpfs1/datapro/decoders/test/ Tranjb
      /gpfs1/datapro/decoders/test/submit_tranjb.sh
Source: /gpfs1/datapro/esmf/esmf/sorc/dir_bufr_prep
Fix files: /gpfs1/datapro/esmf/fix
Input:/gpfs1/datapro/decoders/tmp
Output: /gpfs1/datapro/bufr_tank

(c) GFS_DUMP

Global data assimilation system (GDAS) of GFS access the observational database at a set time each day (i.e., the data cut-off time, presently set as 6 hour), four times a day and perform a time-windowed (± 3 hours) dump of requested observations. Observations of a similar type [e.g., satellite-derived winds ("satwnd"), surface land reports ("adpsfc")]] are dumped into individual BUFR files, in which, duplicate reports are removed, and upper-air report parts (i.e. AA, BB, CC, DD) are merged.

The dumpjb script is an all-purpose data dump utility for:
   i. Time windowing
   ii. Geographical filtering
   iii. Eliminating duplicates
   iv. Applying corrections to BUFR observation database

Usage: dumpjb yyyyymmddhh <hh><hh> dgrp1 dgrp2 ...dgrpN
(e.g., dumpjb 2007041700 3.0 sflnd dbuoy adpsfc adpupa proflr)

The script is driven by script parameters, which specify the time window and the list of data to dump. Data to dump is indicated by mnemonic references to individual data type and/or groups of data types. ‘dumpjb’ script calls the various programs to perform different
dumping tasks, which are briefly described below (more details of which are available at [http://www.emc.ncep.noaa.gov/mmb/data_processing/data_dumping.doc/document.htm](http://www.emc.ncep.noaa.gov/mmb/data_processing/data_dumping.doc/document.htm)):

i. bufr_raddate – Accepts a real date and hour increment from standard input and writes a real incremented date to standard output. It is useful for computing endpoints of a time window given a centre point and radius.

ii. bufr_dumpmd – Dumps data from the bufr_tank files which falls within the supplied time window, by looking only at the message date in BUFR section 1 header records.

iii. bufr_geofil – Geographically filter BUFR database dump files by using a lat/lon box filter

iv. bufr_dupcor – Performs duplicate checking and trimming of non-profile data types (e.g., aircraft)

v. bufr_dupsat – Performs duplicate checking and trimming of all satellite data types (e.g., radiances, sounding, winds, retrievals)

vi. bufr_dupsst – Performs duplicate checking and trimming of SST date types

vii. bufr_dupmrg – Performs duplicate checking and trimming of upper-air types (e.g., RAOB, PIBAL, DROP).

viii. bufr_dupmar – Performs duplicate checking and trimming of all marine types and surface land METAR.

ix. bufr_duprad – Performs duplicate checking and trimming of all radar data types (e.g., radial wind, reflectivity)

x. bufr_dupcor – Performs duplicate checking and trimming of all other data types (aircraft, profiler, VAD winds, surface synoptic land)

xi. bufr_dupair – Processes any combination up to 5 dump files containing aircraft (bufr message type 004) reports in AIREP format (subtype 001), PIREP format (subtype 002), AMDAR format (subtype 003), E-ADAS (European AMDAR, subtype 006) and/or Canadian AMDAR (subtype 009), performing a cross subtype duplicate check between different types. 
xii. bufr_edtbfr – Applies real-time interactive QC flags, generated from either a ‘reject’ list maintained by NCEP/NCO or from decisions made by NCO SDM, to all types of surface land (BUFR message type 000), surface marine (BUFR message type 001), upper-air (BUFR message type 002), aircraft (BUFR message type 004) or satellite derived wind (BUFR message type 005).

xiii. bufr-quipc – Applies real-time interactive QC and duplicate flags generated by NCEP/OPC to surface marine ship, buoy, tide gauge data (BUFR message type 001, sub-types 001-005)

xiv. bufr_chkbfr – Checks a list of BUFR files to determine whether they contain any data or not.

xv. bufr_combfr – Concatenates individual BUFR files into a single BUFR file. It also generates 2 dummy messages at the beginning of the combined dump file, which contain dump centre time and the dump time (as discussed in step i). Currently the maximum number of files that can be combined is 100.

The outputs of gfs_dump are then passed into gfs_prep (PREPBUFR) processing steps. The respective files/directories related to ‘gfs_dump’ on Param Padma are:

Script: /gpfs1/datapro/esmf/gfs_jobs/gfs_dump.sh
Source: /gpfs1/datapro/esmf/esmf/sorc/dir_bufr_prep
Fix files: /gpfs1/datapro/esmf/fix
Input:/gpfs1/datapro/decoders/tmp
Output: /gpfs1/datapro/bufr_tank


(d) GFS_PREP : PREPBUFR processing & Quality Control

The "PREPBUFR" processing is the final step in preparing the majority of conventional observational data for assimilation into the
analysis. This step involves the execution of series of programs designed to assemble observations dumped from a number of decoder databases, encode information about the observational error for each data type as well the background (first guess) interpolated to each data location, perform both rudimentary multi-platform quality control and more complex platform-specific quality control, and store the output in a monolithic BUFR file, known as PREPBUFR.

The background guess information is used by certain quality control programs while the observation error is used by the analysis to weigh the observations. The structure of the BUFR file is such that each PREPBUFR processing step which changes a datum (either the observation itself, or its quality marker) records the change as an "event" with a program code and a reason code. Each time an event is stored, the previous events for the datum are "pushed down" in the stack. In this way, the PREPBUFR file contains a complete history of changes to the data throughout all of the PREPBUFR processing. The most recent changes are always at the top of the stack and are thus read first by any subsequent data decoder routine. It is expected that the data at the top of the stack be of the highest quality.

GFS_PREP script also calls the various programs to perform different pre-processing and quality control tasks, which are briefly described below and additional documentation on the structure of PREPBUFR files in particular can be found at [http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB/toc/prepbufr/](http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB/toc/prepbufr/).

(i) **PREPOBS_PREPDATA**

Purpose of this program is to read in and consolidate observations dumped from individual BUFR DATA databases, perform rudimentary checks on the data, and organize upper-air data by decreasing pressure. It adds forecast background (first guess) interpolated to each observation location, adds observational error (read in from a look-up table) to each observation, performs some rough quality control checks on surface pressure (vs. the background), and converts dry bulb temperature to virtual and dew point temperature to specific humidity for surface data.

This program is multi-tasked amongst 8 processors on the Param Padma machine to speed up processing time. In order to load-balance the run streams, each of the input data dump files are divided into 8 equal parts by the program PREPOBS_MPCOPYBUFR. Next, PREPOBS_PREPDATA runs in 8 parallel run streams, with each run
using the mini-dump files as input. Each run stream uses all of the dump types, but for each type only 1/8th of the original dump is processed. A program called PREPOBS_LISTHEADERS runs immediately after PREPOBS_PREPDATA in run each stream, reordering all message types in each "mini" PREPBUFR file according to that specified in the BUFR mnemonic table.

(ii) **PREPOBS_CQCBUFR**

This program performs complex quality control on rawinsonde height and temperature data to identify or correct erroneous observations that arise from location, transcription or communications errors. Attempts are made, when appropriate, to correct commonly occurring types of errors. Erroneous data that cannot be corrected are flagged and those are not considered by the analyses. The checks used are: hydrostatic, increment, horizontal statistical, vertical statistical, baseline and lapse rate. These multiple checks are based upon differences of various observations from the six-hour model forecast valid for the observation time (first guess). This program also applies inter sonde (radiation) corrections to the quality controlled rawinsonde height and temperature data. The degree of correction is a function of the rawinsonde instrument type, the sun angle and the vertical pressure level. Finally, this program converts rawinsonde and dropwinsonde dry bulb temperature to virtual and rawinsonde and dropwinsonde dew point temperature to specific humidity.

(iii) **PREPOBS_PROFCQC**

This program performs complex quality control on wind profiler data in order to identify erroneous data and remove it from consideration by the analyses.

(iv) **PREPOBS_PREPACQC**

This program performs quality control on conventional AIREP, and AMDAR (Aircraft Report, Aircraft Meteorological Data Relay) wind and temperature data. The flight tracks are checked, with reports failing the check flagged and duplicate reports removed. In addition, AIREP are quality controlled in two ways: isolated reports are compared to the first guess with outliers flagged, and groups of reports in close geographical proximity are inter-compared using both a vertical wind shear check and a temperature lapse check.
(v) **PREPOBS_ACARSQC**

This program performs rudimentary and gross quality control checks on ACARS aircraft wind and temperature data. Reports failing the quality control checks are flagged.

(vi) **PREPOBS_OIQCBUFR**

It performs an optimum interpolation based quality control on the complete set of observations in the PREPBUFR file. As with the complex quality control procedures, this program operates in a parallel rather than a serial mode. That is, a number of independent checks (horizontal, vertical, geostrophic) are performed using all admitted observations. Each observation is subjected to the optimum interpolation formalism using all observations except itself in each check. A final quality decision (keep, toss, or reduced confidence weight) is made based on the results from all prior platform-specific quality checks and from any manual quality marks attached to the data.

FORTRAN programs of the data preparation modules are located on Param Padma Computer at /gpfss1/datapro/esmf/sorc in the directories listed below:

- prepobs_monoprepbufr.fd
- prepobs_mpcopybufr.fd
- prepobs_oiqcbufr.fd
- prepobs_prepacqc.fd
- prepobs_prepanow.fd
- prepobs_acarsqc.fd
- prepobs_prepdata.fd
- prepobs_cqcbufr.fd
- prepobs_cqvad.fd
- prepobs_prevents.fd
- prepobs_prepssmi.fd
- prepobs_listheaders.fd
- prepobs_profcqc.fd

3. **Global Analysis Scheme**

The global analysis scheme in GFS framework is based on Spectral Statistical Interpolation (SSI) (Parrish et al., 1997, Parrish and Derber, 1992 and Derber et al. 1991). The analysis problem is to minimize the equation

\[ J = J_b + J_o + J_c \]  \hspace{1cm} (I)
where, $J_b$ is the weighted fit of the analysis to the six hour forecast (background or first guess), $J_o$ is the weighted fit of the analysis to the observations and $J_c$ is the weighted fit of the divergence tendency to the guess divergence tendency. $J_c$ also includes a constraint to limit the number of negative and supersaturated moisture points.

(i) **Analysis variables**

The analysis variables are normalized vorticity, unbalanced divergence, unbalanced temperature, ozone, surface skin temperature, specific humidity and coefficients for the bias correction of the satellite radiance data. Each of these variables are deviations from the background decomposed in the vertical based on the vertical error covariance and are normalized with the standard deviation of the error. The balanced part of the divergence and the temperature are implied using a linear balance equation from the vorticity.

(ii) **Horizontal Representation**

The analysis variables are defined spectrally. For comparison to the observations, the variables are transformed to Gaussian grid and then linearly interpolated to observation locations.

(iii) **Horizontal Resolution**

Horizontal resolution is in spectral triangular truncation of 254 (T254). The quadratic T254 Gaussian grid has 768 gridpoints in the zonal direction and 384 gridpoints in the meridional direction. The resolution of the quadratic T254 Gaussian grid is approximately 0.5x0.5 degree.

(iv) **Vertical Representation and domain**

The analysis is performed directly in the model's vertical coordinate system. This sigma $(\sigma = p/p_s)$ coordinate system extends over 64 levels from the surface (~997.3 hPa) to top of the atmosphere at about 0.27hPa. This domain is divided into 64 layers with enhanced resolution near the bottom and the top, with 15 levels is below 800 hPa, and 24 levels are above 100 hPa. The vertical sigma levels and the approximate pressures are given in Table 2.
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<th>L</th>
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<th>σ</th>
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<td>997.34</td>
</tr>
</tbody>
</table>
(v) **Observation types**

Presently, global analysis scheme of GDAS uses the following data shown in Table 3.

**Table 3: Observations currently used in GDAS at NCMRWF**

<table>
<thead>
<tr>
<th>Observation type</th>
<th>Global (GFS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiosonde</td>
<td>u,v,T,q,Ps</td>
</tr>
<tr>
<td>Pibal winds</td>
<td>u,v</td>
</tr>
<tr>
<td>wind profilers</td>
<td>u,v</td>
</tr>
<tr>
<td>Surface land observations</td>
<td>Ps</td>
</tr>
<tr>
<td>Surface ship and buoy observations</td>
<td>u,v,T,Ps,q</td>
</tr>
<tr>
<td>Conventional aircraft reports (AIREP)</td>
<td>u,v,T</td>
</tr>
<tr>
<td>AMDAR aircraft reports</td>
<td>u,v,T</td>
</tr>
<tr>
<td>ACARS aircraft reports</td>
<td>u,v,T</td>
</tr>
<tr>
<td>GMS, METEOSAT, INSAT, GOES cloud drift IR and visible winds</td>
<td>u,v</td>
</tr>
</tbody>
</table>

(vi) **Fit of Analysis with Observations**

Analyses thus generated are compared with observations to evaluate its fit with observations. Fig. 2 depicts the root mean square error (RMSE) of analysed variables computed against RS/RW observations for different analysed meteorological parameters (u, v, t, q), at various pressure levels, over two region viz. global and tropics (30ºS to 30ºN), averaged over 0000UTC of February 2007. RMSE of wind components are less than 5m/s and temperature is less than 2ºC, which are well within the expected limits. As seen from the plot, the global RMSE is less than that of tropics, which highlights the need for assimilation of more satellite products for improving analysis over tropical regions.
Fig. 2: RMSE of analysed variable against RS/RW observations over (i) global & (ii) tropical region averaged over 0000UTC Feb’ 2007 (a) u-comp wind, (b) v-comp. wind , (c) temperature & (d) sp. humidity
4. Forecast Model

Forecast model is a primitive equation spectral global model with state of art dynamics and physics (Kaplan et al., 19997, Kanamitsu 1989, Kanamitsu et al. 1991, Kalnay et al. 1990). More details about the global forecast model are also available at [http://wwwt.emc.ncep.noaa.gov/gmb/moorthi/gam.html](http://wwwt.emc.ncep.noaa.gov/gmb/moorthi/gam.html) and [http://www.emc.ncep.noaa.gov/gc_wmb/Documentation/TPB_oct05/T382.TPB.FINAL.htm](http://www.emc.ncep.noaa.gov/gc_wmb/Documentation/TPB_oct05/T382.TPB.FINAL.htm). The salient features of the model are briefly described below.

(i) **Horizontal Representation**

The horizontal representation is spectral (spherical harmonic basis functions) with transformation to a Gaussian grid for calculation of nonlinear quantities and physics.

(ii) **Horizontal & vertical Resolution/domain**

Same as described in global analysis system.

(iii) **Vertical Representation**

Same sigma coordinate as discussed in global analysis scheme. Vertical discretisation and staggering is achieved by Lorenz Grid. Quadratic-conserving finite difference scheme (Arakawa and Mintz, 1974) is used.

(iv) **Time Integration Scheme(s)**

The main time integration is leapfrog for nonlinear advection terms. Semi-implicit method is used for gravity waves and for zonal advection of vorticity and moisture. An Asselin (1972) time filter is used to reduce computational modes. The physics are written in the form of an adjustment and executed in sequence. For physical processes, implicit integration with a special time filter (Kalnay and Kanamitsu, 1988) is used for vertical diffusion. In order to incorporate physical tendencies into the semi-implicit integration scheme, a special adjustment scheme is performed (Kanamitsu et al., 1991).

The model time step for T254 is 7.5 minutes for computation of dynamics and physics. The full calculation of longwave radiation is done once every 3 hours and shortwave radiation every hour (but with corrections made at every time step for diurnal variations in the shortwave fluxes and in the surface upward longwave flux).
(v) **Smoothing/Filling**

Mean orographic heights on the Gaussian grid are used. Negative atmospheric moisture values are not filled for moisture conservation, except for a temporary moisture filling that is applied in the radiation calculation.

(vi) **Atmospheric Dynamics**

The model uses primitive equations with vorticity, divergence, logarithm of surface pressure, specific humidity, virtual temperature.

(vii) **Horizontal Diffusion**

Scale-selective, second-order horizontal diffusion after Leith (1971) is applied to vorticity, divergence, virtual temperature, and specific humidity and cloud condensate. The diffusion of temperature, specific humidity, and cloud condensate are performed on quasi-constant pressure surfaces (Kanamitsu et al. 1991).

(viii) **Gravity-wave Drag**

Gravity-wave drag is simulated as described by Alpert et al. (1988). The parameterization includes determination of the momentum flux due to gravity waves at the surface, as well as at higher levels. The surface stress is a nonlinear function of the surface wind speed and the local Froude number, following Pierrehumbert (1987). Vertical variations in the momentum flux occur when the local Richardson number is less than 0.25 (the stress vanishes), or when wave breaking occurs (local Froude number becomes critical); in the latter case, the momentum flux is reduced according to the Lindzen (1981) wave saturation hypothesis. The treatment of the gravity-wave drag parameterization in the lower troposphere is done by the use of the Kim and Arakawa (1995) enhancement.

(ix) **Radiation**

The longwave (LW) radiation in GFS employs a Rapid Radiative Transfer Model (RRTM) developed at AER (Mlawer et al. 1997). The parameterization scheme uses a correlated-k distribution method and a linear-in-tau transmittance table look-up to achieve high accuracy and efficiency. In addition to the major atmospheric absorbing gases (viz. ozone, water vapor, and carbon dioxide), the algorithm also includes various minor absorbing species such as methane, nitrous
oxide, oxygen, and up to four types of halocarbons (CFCs). In water vapor continuum absorption calculations, RRTM-LW employs an advanced CKD_2.4 scheme (Clough et al. 1992). A maximum-random cloud overlapping method is used in the GFS application. Cloud liquid/ice water path and effective radius for liquid water and ice are used for calculation of cloud-radiative properties. Atmospheric aerosol effect is not included in this version of the model.

The shortwave (SW) radiative transfer parameterization is based on Hou et al., 2002. The parameterization uses a correlated-k distribution method for water vapor and transmission function look-up tables for carbon dioxide and oxygen absorptions. The model contains eight broad spectral bands covering ultraviolet (UV) and visible region (< 0.7 Å), and choices of one or three spectral bands in the near infrared (NIR) region (> 0.7 Å). Ten correlated-k values are used in each NIR spectral band. The model includes atmospheric absorbing gases of ozone, water vapor, carbon dioxide, and oxygen. For liquid water clouds, cloud-optical property coefficients are derived based on Slingo (1989), and coefficients for ice clouds are based on Fu (1996). Atmospheric aerosol effect is included in the SW radiation calculation. A global distributed seasonal climatology data from Koepke et al. (1997) is used to form a mixture of various tropospheric aerosol components. Aerosol optical properties and vertical profile structures are established based on Hess et al. (1998). Horizontal distribution of surface albedo is a function of Matthews (1985) surface vegetation types in a manner similar to Briegleb et al. (1986). Monthly variation of surface albedo is derived in reference to Staylor and Wilbur (1990).

For both LW and SW, the cloud optical thickness is calculated from the predicted cloud condensate path. The cloud single-scattering albedo and asymmetry factor are functions of effective radius of the cloud condensate. The effective radius for ice is taken as a linear function of temperature decreasing from a value of 80 microns at 263.16 K to 20 microns at temperatures at or below 223.16K. For water droplets with temperatures above 273.16 K an effective radius of 5 microns is used and for supercooled water droplets between the melting point and 253.16 K, a value between 5 and 10 microns is used. Effects from raindrops and snow are not included in this version of GFS.

(x) Convection

Penetrative convection is simulated following Pan and Wu (1994), which is based on Arakawa and Schubert (1974) as simplified
by Grell (1993) and with a saturated downdraft. Convection occurs when the cloud work function exceeds a certain threshold. Mass flux of the cloud is determined using a quasi-equilibrium assumption based on this threshold cloud work function. The cloud work function is a function of temperature and moisture in each air column of the model grid point. The temperature and moisture profiles are adjusted towards the equilibrium cloud function within a specified time scale using the deduced mass flux. A major simplification of the original Arakawa-Shubert scheme is to consider only the deepest cloud and not the spectrum of clouds. The cloud model incorporates a downdraft mechanism as well as the evaporation of precipitation. Entrainment of the updraft and detrainment of the downdraft in the sub-cloud layers are also included. Downdraft strength is based on the vertical wind shear through the cloud. The critical cloud work function is a function of the cloud base vertical motion. Mass fluxes induced in the updraft and the downdraft are allowed to transport momentum. The momentum exchange is calculated through the mass flux formulation in a manner similar to that for heat and moisture. In order to take into account the pressure gradient effect on momentum, a simple parameterization using entrainment is included for the updraft momentum inside the cloud.

(xii) Shallow convection

Following Tiedtke (1983), the simulation of shallow (non-precipitating) convection is parameterized as an extension of the vertical diffusion scheme. The shallow convection occurs where convective instability exists but no convection occurs. The cloud base is determined from the lifting condensation level and the vertical diffusion is invoked between the cloud top and the bottom. A fixed profile of vertical diffusion coefficients is assigned for the mixing process.

(xii) Cloud Fraction

The fractional area of the grid point covered by the cloud is computed diagnostically following the approach of Xu and Randall (1996) using the formula

$$C = \max \left\{ R^{0.25} \left(1 - \exp\left(-\frac{2000 \times (q_e - q_{r,\text{min}})}{\min[\max((1-R)q^{0.75}, 0.0001), 1.01]}\right)\right), 0.0\right\}$$
where $R$ is the relative humidity, $q^*$ is the saturation specific humidity and $q_{cmin}$ is a minimum threshold value of $q_{min}$. The saturation specific humidity is calculated with respect to water phase or ice phase depending on the temperature. The fractional cloud cover $C$ is available at all model levels. There is no cloud cover if there is no cloud condensate. Clouds in all layers are assumed to be randomly overlapped.

(xiii) **Grid-scale Condensation and Precipitation**

The prognostic cloud condensate has two sources, namely convective detrainment and grid-scale condensation. The grid-scale condensation is based on Zhao and Carr (1997). The sinks of cloud condensate are grid-scale precipitation, which is parameterized following Zhao and Carr (1997) for ice, and Sundqvist et al. (1989) for liquid water, and evaporation of the cloud condensate which also follows Zhao and Carr (1997). Evaporation of rain in the unsaturated layers below the level of condensation is also taken into account. All precipitation that penetrates the bottom atmospheric layer is allowed to fall to the surface.

(xiv) **Planetary Boundary Layer**

Planetary Boundary Layer (PBL) scheme is based on Troen and Mahrt (1986) [Hong and Pan, 1996, Basu et al., 2002]. The scheme is still a first-order vertical diffusion scheme. There is a diagnostically determined PBL height that uses the bulk-Richardson approach to iteratively estimate a PBL height starting from the ground upward. Once the PBL height is determined, the profile of the coefficient of diffusivity is specified as a cubic function of the PBL height. The actual values of the coefficients are determined by matching with the surface-layer fluxes. There is also a counter-gradient flux parameterization that is based on the fluxes at the surface and the convective velocity scale.

(xv) **Orography**

Orography data sets used in GFS are based on a United States Geological Survey (USGS) global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 km). Orography statistics including average height, mountain variance, maximum orography, land-sea-lake masks are directly derived from a 30-arc second DEM for a given resolution (NCEP Office Note 424,
Hong, 1999). Fig. 3 depicts the topography of the model over India and adjoining region.

![Topography of T254L64 model](image)

**Fig. 3. Topography of T254L64 model**

(xvi) **Ocean**

At NCEP daily sea surface temperature analysis by optimum interpolation (OI) method that assimilates observations from past seven days is used (Reynolds and Smith, 1994). The sea surface temperature anomaly is damped with an e-folding time of 90 days during the course of the forecast. The SST analysis files are downloaded from NCEP and used at NCMRWF.

(xvii) **Sea Ice**

The sea-ice model is based on Winton’s (2000) three-layer (two equally thick sea-ice layers and one snow layer) thermodynamic process. It predicts sea-ice/snow thickness, surface temperature, and ice temperature structure. The analyzed fractional ice cover (downloaded from NCEP) is kept unchanged for the entire forecast. For
this model, heat & moisture fluxes and albedo are treated separately for ice and open water in each grid box (Wu et al. 1997).

(xviii) **Snow Cover**

Snow cover is obtained from an analysis done by NESDIS and US Air Force, updated daily (downloaded from NCEP at NCMRWF). When the snow cover analysis is not available, the predicted snow in the data assimilation is used. Precipitation falls as snow if the temperature at sigma=0.85 is below 0°C. Snow mass is determined prognostically from a budget equation that accounts for accumulation and melting. Snowmelt contributes to soil moisture, and sublimation of snow to surface evaporation. Snow cover affects the surface albedo and heat transfer/capacity of the soil, but not of sea ice.

(xviii) **Surface Characteristics**

Roughness lengths over oceans are determined from the surface wind stress after the method of Charnock (1955). Over sea ice the roughness is uniform (0.01 cm). Roughness lengths over land are prescribed from data of Dorman and Sellers (1989), which include 12 vegetation types. The surface roughness is not a function of orography. Over oceans the surface albedo depends on zenith angle. The albedo of sea ice is a function of surface skin temperature and nearby atmospheric temperature as well as snow cover (Grumbine, 1994). Albedoes for land surfaces are based on Matthews (1985) surface vegetation distribution Longwave emissivity is prescribed to be unity (black body emission) for all surfaces. Soil type and Vegetation type database from GCIP (GEWEX Continental-Scale International Project) is used. Vegetation fraction monthly climatology based on NDVI (Normalized Difference Vegetation Index) 5-year climatology is used.

(xix) **Surface Fluxes**

Surface solar absorption is determined from the surface albedos, and longwave emission from the Planck equation with emissivity of 1.0. The lowest model layer is assumed to be the surface layer (sigma=0.996) and the Monin-Obukhov similarity profile relationship is applied to obtain the surface stress and sensible and latent heat fluxes. The formulation is based on Miyakoda and Sirutis (1986). Thermal roughness over the ocean is based on a formulation derived from TOGA COARE (Zeng et al, 1998). Land surface evaporation is comprised of three components: direct evaporation from the soil and
from the canopy, and transpiration from the vegetation (Pan and Mahrt, 1987).

(xix) **Land Surface Processes**

The GFS land-surface model component is based on NOAH Land Surface Model (NOAH LSM). The NOAH LSM (Chen, et al. 1996) has 4 sub-surface layers and contains treatment of frozen soil, ground heat flux, and energy/water balance at the surface, along with reformulated infiltration, runoff functions and an upgraded vegetation fraction.

To obtain initial values of soil moisture and soil temperature, the NOAH LSM should cycle continuously in the GDAS. Values are then updated every model time step in response to forecasted land-surface forcing (precipitation, surface solar radiation, and near-surface parameters: temperature, humidity, and wind speed). Since the land component of the GDAS is forced by GFS model precipitation, rather than observations, it is constrained by nudging soil moisture, with a 60-day relaxation, towards an externally supplied global soil moisture monthly climatology.

(xx) **Chemistry**

Ozone is a prognostic variable that can be updated in the analysis and transported in the model. The sources and sinks of ozone are computed using zonally averaged seasonally varying production and destruction rates provided by NASA/GSFC.

5. **Porting on CRAY-X1E**

As the analysis scheme and model integration takes sufficiently large time in Param Padma machine (one analysis cycle ~ 4hr. and 168 hour prediction ~ 5hr.), so for real-time running purpose it has been decided to port and implement them on CRAY-X1E. Few essential steps required to port the analysis scheme and the forecast model of GFS on CRAY-X1E are listed below:

(i) In ‘makefiles’ and compile scripts compilers & compiler options were changed accordingly.

(ii) Cray X1E does not allow compiling an application with -d options along with a library built with -4 option. Hence some of the libraries like ‘sfcio’ are built with -d option as
well. In this process, care is also taken to keep the size of all variables unchanged.

(iii) For ESSL library calls equivalent Fortran subroutines are added – for example dbsrch.f, sbsrch.f

(iv) For Fast Fourier Transform (FFT) routines ESSL library is used on IBM. However, the source codes of these routines are also available with GFS. These source codes (fftpack, four2grid_thread, fftpack etc.) are compiled on CRAY-X1E and used in GFS instead of corresponding library routines.

(v) ‘poe’ command in the submission shell scripts is replaced by ‘aprun’

(vi) SSI code is compiled for SSP (Single Streaming Processor) while forecast model is compiled for MSP (Multi Streaming Processor). This has been decided based on performance of the respective applications.

One cycle of analysis takes about 70 minutes of computing time in 112 SSPs (Single-Streaming Processor) on Cray X1E. The model takes about 100 minutes of computation time in 28 MSPs (Multi-Steaming Processors) of Cray X1E for a 168-hr model forecast.

FORTRAN programs of the various components for the global analysis-forecast system are located in CRAY-X1E at /prod/prodT254L64/sorc in the directories listed below:

- global_angupdate.fd
- global_sig igen.fd
- global_chg igen.fd
- global_sigavg.fd
- global_chgres.fd
- global_sighdr.fd
- global_cycle.fd
- global_sigzvd.fd
- global_fcst.fd
- global_ssi.fd
- global_postevents.fd
- global_postgp.fd
- global_satcount.fd
- global_sfchdr.fd

FORTRAN libraries used by GFS analysis and forecast model are located at /prod/prod/T254L64/lib (on Cray X1E) and the same are listed below:

- liblandsfcutil_4.a
The source codes of the FORTRAN libraries used by the GFS are located at /gpfs1/datapro/esmf/lib/sorc on Param Padma and at /prod/prod/T254L64/lib/sorc on Cray X1E in the directories listed below:

bacio
bufr
crex
crtm
decod_ut
esmf
ip
irsse
landsfcutil
sfcio
sigio
sp
w3

6. Post Processing and Plotting

Post processing and plotting are done on Param Padma machine. Post processing can be done at various horizontal
resolutions (viz., 0.5, 1.0, 2.5 degree etc.). At present it is set at 1º x 1º resolution for daily run. Post processing of different 3-D (multi-level) atmospheric parameters viz. u, v, t, z, q, rh, \( \omega \) etc. are done at 26 pressure levels. Similarly the 2-D parameters (single-level), viz. rainfall, cloud, soil temperature, soil moisture, fluxes etc. are also post processed. The vertical pressure levels on which 3-D fields are post processed are 1000, 975, 950, 925, 900, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa levels. Post-processed outputs are in NCEP GRIB format. The respective files used for post-processing on Param Padma are:

Scripts : /gpfs1/datapro/esmf/gfs_jobs/gfs_post_254.sh
Source: /gpfs1/datapro/esmf/sorc/global_postgp.fd
Input :   /prod/prod/T254L64/data/ANAL/gdas.'yyyymmdd'
          /prod/prod/T254L64/data/FCST/gdas.'yyyymmdd'
Output: /gpfs1/datapro/T254L64_post/gdas.'yyyymmdd'

Plots of these post-processed outputs are generated using GrADS (http://grads.iges.org/grads/grads.html) package. Plotting of geopotential and wind for 0000UTC analysis and forecasts at 925, 850, 700, 500, 200 hPa levels and 24 hourly-accumulated rainfalls over Indian region (15°S to 55°N, 20°E to 140°E) are done regularly.

7. Weather Analysis and Prediction

GFS described above at T254L64 resolution has been implemented experimentally at NCMRWF from 1st January 2007. Since then, it is running in near real time mode, everyday. Analyses and predictions based on 0000 UTC (5.30 AM) of each day are available by 1000 UTC (3.30 PM) of that day. First 6 hours i.e. (0000-0600UTC) is the waiting time for receiving of global data while the later 4 hours is required for generation of analyses and forecast products. Fig. 4 depicts the wind and height analyses at 850 hPa for 0000UTC 1st January 2007.

As seen from the analysis of 0000UTC, 1st January 2007 the main Indian land at 850 hPa level was under the grip of anticyclonic flow with its centre over west cost near Mumbai. Two strong westerly troughs are seen north of 40°N along 30°E and 65°E. Another prominent cyclonic circulation is seen near equator just west of Brunei, centred near 110°E/4°N. To verify this analysis generated at NCMRWF with some standard analysis, NCEP generated analysis (FNL) valid for the same time, are shown in Fig. 5.
One can see that the analysed positions of all the major synoptic features discussed above for NCMRWF analysis (Fig. 4) are matching well with NCEP analysis (Fig. 5), though there are some differences between two analyses, specially over Southern Hemisphere.

Fig. 4: Analysed geopotential height and wind at 850 hPa
NCMRWF (T254L64) valid on 0000UTC 1st January 2007

Fig. 5: Analysed geopotential height and wind at 850 hPa
NCEP (FNL) valid on 0000UTC 1st January 2007
Predicted rainfall (5-day FCST valid for 0000UTC 6\textsuperscript{th} Jan.) based on 0000UTC 1\textsuperscript{st} Jan. 2007 by NCMRWF T254L64 GFS along with TRMM observation valid for same time are shown in Fig. 6. TRMM Rainfall observations have been acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA’s Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

Fig. 6: (a) Day 5 forecast rainfall from T254L64 GFS and (b) TRMM 24hr. accumulated rainfall valid for 0000 UTC 6\textsuperscript{th} January 2007
Observation (Fig. 6a) shows prominent rainfall band along the equator, mainly coinciding with inter tropical convergence zone (ITCZ). This feature is captured well in the model prediction (Fig. 6b), though the amount of predicted rainfall is less than the observed along ITCZ. Another zone of heavy rainfall is seen between 5°N to 10°N, with three maximas, along 105°E, 115°E and 140°E. These three maximas though have captured in the 5-day prediction, but their centres are not exactly matching with the observed centres.

TRMM observation has also shown some rainfall over Mediterranean Sea, Aral Sea and adjoining region associated with mid-latitude westerly trough. Rainfall over Mediterranean Sea region has been captured in day-5 prediction, but the model did not predict the rainfall zone near Aral Sea. Light rain has been observed over Jammu & Kashmir region and the model has also been able to predict this rainfall zone in 5-day in advance.

Widespread rainfall activity occurred over northwest India associated with well-marked western disturbance over this region on 11th February 2007. Fig. 7 depicts the wind and height analysis at 500-hPa level on 0000UTC 11th February 2007. The westerly trough along 70°E over Pakistan and adjoining region is well captured in the analysis.

Predicted height and wind fields 6 day in advance (based on 0000UTC 6th Feb), valid for the verifying date, are shown in Fig. 8. Though the predicted position of the trough is matching quite well with that of the analysed one but it is less intense than the analysed trough. However, there is an over prediction of the strength of the trough along 60°E between 45°N to 55°N.

Fig. 9 shows TRMM observed rainfall on 0000UTC 11th February 2007 along with Day-3, Day-5, Day-6 model predicted rainfall (based on initial analysis of different days), all valid for 0000UTC 11th February 2007.

TRMM observations shows widespread heavy rainfall (8-16 cm) associated with western disturbance (WD) over northwest India. It is seen from the plot that, model could predict this heavy rainfall epoch consistently up to 6 days in advance, though there is an under prediction of rainfall amounts.
Fig. 7: Analysed geopotential height and wind at 850 hPa NCMRWF (T254L64) valid for 0000UTC 11th February 2007

Fig. 8: Day 6 forecast height and wind at 850 hPa level based on 0000UTC 6th February 2007
Fig. 9: TRMM 24hr. accumulated rainfall observation and model rainfall predictions valid for 0000 UTC 11th February 2007
(a) Observation, (b) D3 FCST, (c) D5 FCST & (d) D6 FCST

A marked deficiency is also noticed in the model prediction, especially in the pre-monsoon season, associated with the formation of spurious strong cyclonic vortices near the low latitude tropical region. In general this type of vortices are noticed on some days from 72hr. prediction onwards. Fig. 10 depicts 168 hr. prediction of wind and
height fields valid for 29th April 2007 along with the analysis valid for same time.

(a)

(b)

Fig. 10: Predicted (168hr.) and analysed height and wind at 850hPa valid at 0000UTC 29th April 2007
An intense cyclonic circulation is predicted by the model over north east of Sri Lanka centred at 82ºE/12ºN in 168 predictions valid for 0000UTC 29th April 2007 (Fig 10a). The same is not seen in the verifying analysis (Fig. 10b) valid for the same time. In the reality also no such cyclonic system of that intensity formed over Bay of Bengal region during that period, though a very feeble cyclonic circulation can be seen at 87ºE/5ºN in the verifying analysis.

NCEP also had faced this type of problem previously in their global model and the same was resolved greatly after assimilating satellite radiance data (Pasch et al., 2002). At NCMRWF, few runs during this period have been tried using NCEP processed NOAA satellite radiances. Fig. 11 depicts the predicted wind and geopotential height fields at 850 hPa valid for 0000UTC 29th April 2007, from the run with NCEP processed NOAA radiances discussed above.

![Image](image_url)

Fig. 11: Predicted (168hr.) geopotential height and wind at 850hPa valid at 0000UTC 29th April 2007 with assimilation of NCEP processed NOAA radiance data
In the model prediction with assimilated NOAA radiances, the intensity of the cyclonic circulation discussed above reduces drastically. Predicted intensity of the cyclonic system centred around 87°E/7.5°N matches with the observed one (Fig 10b), though there is a slight northerly shift in predicted position (Fig. 11). This example again asserts the need of satellite radiance assimilation to improve tropical weather prediction. Work has already been initiated to process NOAA radiances (AMSU, HIRS) at NCMRWF for assimilating the same into GFS in experimental basis.

8. Concluding Remarks

GFS global data assimilation and model system at T254L64 resolution has been implemented at NCMRWF, on Param Padma and Cray-X1E computer systems. It is running in real-time mode since 1st January 2007. In this implementation, one analysis cycle and seven day forecast run takes about 3 hours. NCMRWF has plan to port the data pre-processing and post processing packages on LINUX environment (to avoid machine dependency).

At this stage of implementation, only conventional data sets and satellite AMVs are being assimilated in GFS. NCMRWF has plans to add other data sets such as satellite radiances, QSCAT winds etc. to the assimilation system in near future.

T254L64 system is running regularly without any interruption at NCMRWF for the last five months. Weather analysis and predictions generated by the system are reasonably good and match well with that produced by other leading NWP centres. NCMRWF is in the process of comparing T254L64 products with that of operational T80L18 model and as well as with NWP products of other leading centres in more objective manner for forthcoming monsoon season. This will enable us to evaluate the skill of T254L64 GFS system in more detailed and comprehensive manner.

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References

Alpert, J.C., S-Y Hong and Y-J Kim, 1996: Sensitivity of cyclogenesis to lower troposphere enhancement of gravity wave drag using the Environmental Modeling Center medium range model. Proc. 11th Conference. on NWP, Norfolk, 322-323


Hong, S.-Y., 1999: New global orography data sets. *NCEP Office Note #424*. 

39


