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Implementation of New High Resolution NCUM Analysis-Forecast System in Mihir HPCS

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ABSTRACT

NCMRWF Unified Model (NCUM) is adapted from the Unified Model (UM) available under UM Partnership on Met Office Shared Repository Service. This seamless prediction system is used for medium range numerical weather prediction at NCMRWF. The NCUM global system is upgraded recently with a latest UM (version 10.8), with an improved model horizontal resolution of 12 km. Observation Processing System, Hybrid 4D-Var data assimilation system, Surface data assimilation/preparation system, Unified Model and in-house developed Observation Pre-Processing System are the major components of the NCUM system. Descriptions of all major components of the new NCUM system and comparison with the previous operational system are given in this report. Report also includes some description of observation usage in the assimilation system and computational requirements in the Mihir HPCS of NCMRWF. This end-to-end global numerical weather prediction system routinely produces 10-day forecasts based on 00 and 12 UTC initial conditions. The NCUM forecast products are available at www.ncmrwf.gov.in

1. Introduction

NCMRWF Unified model (NCUM) is used for generating 10-day numerical weather forecastsat NCMRWF routinely since 2012 (*Rajagopal et al., 2012, George et al., 2016*).NCUM is adapted from the Unified Model (UM) system available under "UM Partnership". The NCUM assimilation-forecast system has been upgraded periodically to adapt new developments in science and technology for improving the numerical forecasts. There have been four major upgrades of NCUM global assimilation-forecast system in the past and the current upgrade described in this report is the fifth one (Table-1).

Uniqueness of the UM is its seamless modeling approach. The same dynamical core and, where possible, the same parameterization schemes are used across a broad range of spatial and temporal scales. The UM's dynamical core solves compressible non-hydrostatic equations of motion with semi-Lagrangian advection and semi-implicit time stepping. Sub-grid scale processes such as convection, boundary layer turbulence, radiation, cloud, microphysics and orographic drag are represented by parameterization schemes (in global model), which are being improved in latest versions of the model. The model uses a grid point discretization on a latitude-longitude grid system. In June, 2015 NCMRWF adapted the UM with "ENDGame (EG)" dynamics, which is based on a semi-implicit semi-Lagrangian discretization of the governing equation, prior to that the dynamics was New Dynamics (ND) scheme. This dynamical core permits more accurate coupling with physics parameterizations. The latest version of the model which is implemented at NCMRWF has "ENDGame" dynamical core with improved atmosphere and land configuration of physical processes.

Prediction of future state of the atmosphere by an NWP model largely depends upon the initial condition (analysis). The process of preparation of the "analysis" is known as Data Assimilation (DA). Quality controlled (and thinned, if required) observations are used in the DA system for preparation of the analysis. Data assimilation techniques provide the best estimate of the state of the atmosphere by combining the information regarding the state from model and observations. Advanced data assimilation methods have the ability to extract more useful information on the state of the atmosphere from the observations assimilated. Four-dimensional variational data assimilation (4D-Var) is one of the advanced data assimilation method used by several NWP centres.

Table 1: Various components of NCUM data assimilation systems and version numbers (and equivalent UK Met Office versions) since 2012

Implementation Month/Year	**DA System Version (NCUM)**	**OPS (UKMO Version)**	**VAR (UKMO Version, Resolution and DA Method**	**SURF (UKMO Version)**	**UM (UKMO Version, Dynamical Core and Resolution)**
April-2012	NCUM-DA1	OPS 27.1	VAR27.1 (N216L70) (4D-Var)	UKMO Surface files	UM7.7 (ND) (N512 L70)
Dec-2012	NCUM-DA2	OPS 27.2	VAR27.2 (N216L70) (4D-Var)	SURF30.0	UM7.9 (ND) (N512 L70)
Nov-2015	NCUM-DA3	OPS 30.1	VAR30.0 (N320L70) (4D-Var)	SURF30.0.1 (Soil Moisture-EKF)	UM8.5(EG) (N768 L70)
Oct-2016	NCUM-DA4	OPS 32.1	VAR32.0 (N320L70) (Hybrid 4D-Var)	SURF32.0 (Soil Moisture-EKF)	UM10.2(EG) (N768 L70)
May-2018	NCUM-DA5	OPS 2017-07	VAR 2017-07 (N320L70) (Hybrid 4D-Var	SURF 2017-07 (Soil Moisture-EKF)	UM10.8(EG) (N1024L70)

NCMRWF adapted the 4D-Var data assimilation system of UK Met Office in April 2012 and upgraded with its advance version periodically. A detailed description of the 4D-Var method used at NCMRWF with NCUM can be seen in *Rawlins et al.* (2007) and *Rajagopal et al.* (2012). In October, 2016 the 4D-Var system wasupgraded to Hybrid 4D-Var system. One of the main weaknesses of traditional 4D-Var approach is the difficulty of representing 'Errors of the Day' in the assimilation –flow dependent errors, which varies day to day. To address the flow dependent errors, hybrid-4DVar method was developed (*Clayton et al.,* 2013) where the term "hybrid" refers to the combination of climatological covariance and covariances calculated from an ensemble of forecasts, designed to sample the day to day varying uncertainty (*Andrew et al.*, 2015). The Hybrid 4D-Var system combines the advantages of traditional 4D-Var and the ensemble data assimilation. NCUM hybrid 4D-Var system uses the ensemble forecasts from the NCMRWF ensemble prediction system (NEPS) which uses ETKF (Ensemble Transform Kalman

Filter) method for perturbation generation. The use of Hybrid 4D-Var method for data assimilation in NCMRWF is a major step towards the application of emerging paradigm of ensemble data assimilation in operational NWP in India.

Latest operational high resolution analysis-forecast system of UM is adopted as the new NCUM. Major improvement of this system, in comparison with the earlier version of NCUM system, is the higher resolution (~12km) of the global model. The major improvements in the new data assimilation system include the use of a latest version of fast radiative transfer model (RTTOV 11) in place of an older version and the capability to process and assimilate more satellite observations. A detailed description of the new NCUM global data assimilation and forecast system and technical aspects of its implementation in Mihir High Performance Computer System (HPCS) at NCMRWF are presented in the following sections. Mihir HPCS was commissioned at NCMRWF in January, 2018. Mihir HPCS is Cray-XC40 system with 2320 nodes running Intel Xeon Broadwell E5-2695 processors have a peak performance of 2,806 TFLOPS and has a total system memory of 290TB.

2. New NCUM Data Assimilation system (NCUM-DA5)

Hybrid 4D-Var data assimilation system has been used for creation of NCUM global analysis since October, 2016. This system uses the ensemble forecasts from the NEPS. The new DA system (NCUM-DA5) for the high resolution global NCUM is also a Hybrid 4D-Var system. The resolution of the new DA system is same, as the previous one, except the model resolution which is now enhanced from N768L70 (~17km) to N1024L70 (~12 km). The vertical resolution of the model and DA system also remains same, 70 levels (reaching up to 80 km height). The major difference between the NCUM-DA4 and NCUM-DA5 are the improvements in radiative transfer model, capability to assimilate more satellite observations and uses the ensemble forecasts from the22 members of 12-kmNEPS. Salient features of the new NCUM assimilation forecast system (Model, Data Assimilation, Surface Data preparation) are given in Table 2.

Improvements of DA5 in comparison with DA4 are given in Table3. Observations used in the DA-5 system currently are listed in Table4. NCMRWF pre-processing system is also improved to pre-process additional observation data sets. Various components of the NCUM-DA5 are given in the following sub-sections. A flow chart, comprising various NCUM-DA5 jobs, including data monitoring tasks, is presented in Figure1. However, due to increase in the model resolution, computational requirements increased manifolds, which lead to a reduction inensemble members of the NEPS system. In the new version of Hybrid 4D-Var, 22 (22+1) ensemble short forecasts are used compared to the 44 (44+1) ensemble short forecasts used in the NCUM-DA4.

Table 2: Salient features of the new NCUM Global Data Assimilation-Forecast System

Model	Atmospheric Data Assimilation	Surface Analysis
Model: UM Version 10.8 Domain: Global **Resolution**: 12 km, Levels 70 **No. of Grids**: 2048x1536 **Time Step**: 5 minutes **Physical Parameterizations**: GA6.1 (*Walters et al.*, 2017) **Dynamical Core**: ENDGame **Forecast length**: 10 days (based on 00 UTC and 12 UTC initial conditions)	**Resolution**: N320L70 (~40 km) with N144L70 Hessian based pre-conditioning **Method**: Hybrid incremental 4D-Var. Information on "errors of the day" is provided by NEPS forecast at every data assimilation cycle **Data Assimilation** Cycles: 4 analyses per day at 00, 06, 12 and 18 UTC. Observations within +/- 3 hours from the cycle time is assimilated in the respective DA cycle **Observations**: Observation Processing System does the quality control of observations. Variational bias correction is applied to satellite radiance observations. List of observations assimilated in NCUM-DA5 is given in Table 4	**Soil Moisture Analysis:** *Method:* Extended Kalman Filter *Analysis time:* 00, 06, 12 and 18 UTC *Observations assimilated:* ASCAT soil wetness observations(MetOp satellites), Screen Temperature and Humidity (pseudo observations from 3D-Var screen analysis) **SST and Sea Ice:** Updated at 12 UTC DA cycle with OSTIA based SST and sea-ice analysis **Snow Analysis:** Satellite-derived snow analysis (using IMS Snow from NOAA). Updated at 12 UTC DA cycle

Table 3: Major improvements in DA5 system at a glance in comparison with DA4

NCUM Component	**Improvements (NCUM-DA5 system over NCUM-DA4)**
OPPS	Use of more satellite observations Use of ECMWF ecCodes for the processing of AMSR, FY3C and AHI observations Improvements in the pre-processor to handle more observation data volume
VAR/OPS	Use of fast radiative transfer model RTTOV11 (RTTOV 9 in DA4) Use ATOVS, and AIRS and CrIS surface channels over land Provision to use geostationary WV channels over low cloud New ground GPS observation operator Assimilation capability for GMI observations Change in observation thinning of IASI and ATOVS
UM	Upgraded to UM10.8 Increase of horizontal resolution to N1024 (~12km) from N768 (~17km)
SURF	Improved snow analysis reconfiguration Higher version of JULES scheme in Land DA

Table 4: Observations assimilated in NCUM Global Data Assimilation System (NCUM-DA5)

Observation Type	**Observation Description**	**Assimilated Variables**
AHIClear	Advanced Himawari Imager radiances from Himawari-8	*Brightness Temperature (*T_b)
Aircraft	Upper-air wind and temperature from aircraft	u, v, T
AIRS	Atmospheric Infrared Sounder onboard AQUA Satellite	T_b
AMSR	Radiances from AMSR-2 onboard GCOM satellite	T_b
ATOVS	AMSU-A, AMSU-B/MHS, HIRS from NOAA-18 &19, MetOp-A&B	T_b
ATMS	Advanced Technology Microwave Sounder in NPP satellite	T_b
CrIS	Cross-track Infrared Sensor observations in NPP satellite	T_b

FY3C	Radiances from Micro Wave Humidity Sounder (MWHS) onboardFY3C Satellite	T_b
GMIhigh&GMIlow	Observations from Global Precipitation Measurement (GPM) Microwave Imager (GMI) instrument	T_b
GOESClear	Cloud clear Imager radiances from GOES	T_b
GPSRO	Global Positioning System Radio Occultation observations from various satellites (including MT-ROSA)	Bending Angle
Ground GPS	Ground based GPS observations from various locations	Zenith Total Delay
IASI	Infrared Atmopheric Sounding Interferometer from MetOp-A&B	T_b
IN3DSndr	INSAT-3D Sounder Radiances	T_b
MTSAPHIR	SAPHIR microwave radiances from Megha-Tropiques	T_b
Satwind	Atmospheric Motion Vectors from various geostationary and polar orbiting satellites (including INSAT-3D)	u, v
Scatwind	Advanced Scattrometer in MetOp-A & B, ScatSat-1, WindSat	u, v
SEVIRIClear	Cloud clear observations from SEVIRI of METEOSAT 8 & METEOSAT 11	T_b
Sonde	Radiosonde observations, upper-air wind profile from pilot balloons, wind profiles, VAD wind observation from Indian DWR	u, v, T, q
Surface	Surface observations from Land and Ocean	u, v, T, q, P_s
SSMIS	SSMIS Radiances from DMSP satellites	T_b

2.1 Observation Pre-Processing System (OPPS)

NCMRWF receives global meteorological observations through Global Telecommunication System (GTS) via Regional Telecommunication Hub (RTH), IMD, New Delhi and majority of satellite observations through internet data services, directly from various satellite data producers such as NOAA/NESDIS, EUMETCAST, ISRO etc. Continuous efforts are going on to acquire and utilize maximum number of observations from global observing system (satellites, aircrafts, ground stations, balloons, ships, buoy etc.), as quickly as possible for its real time/near real-time inclusion in the data assimilation system.

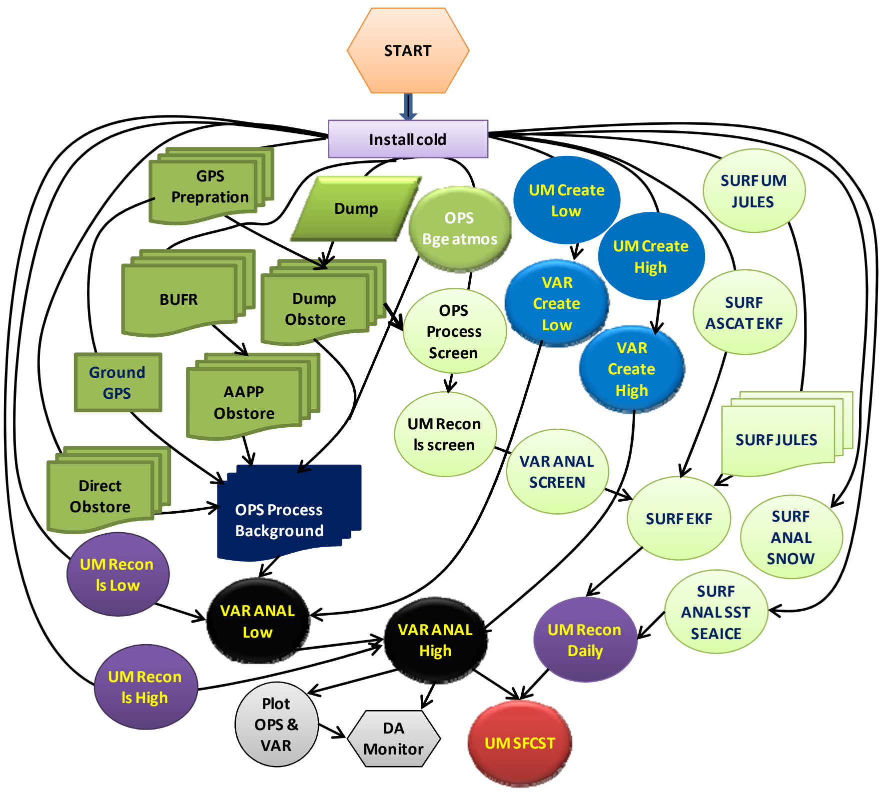

Figure 1: Flow chart of the NCUM-DA5

NCMRWF has developed an observation pre-processing system (OPPS) (Figure 1: green boxes in flow chart) for NCUM to prepare the various types of observations in the desired format for its assimilation. Observations for the desired data assimilation window (±3hour) centered at the analysis time are selected and packed in the format required for OPS by the pre-processor system. The preprocessing system of NCUM make use of NCEP observation pre-processing system, AAPP (7.10), ECMWF bufr decoder, ECMWF ecCodes, etc. The OPPS packs all observations in the "obstore" format, separate files for each observation type, which can be read by OPS. The current version of the OPPS has the capability to process and pack more observation types in the "obstore" format compared to its previous versions.

2.2 Observation Processing System (OPS)

The OPS prepares quality controlled observations for Hybrid 4D-Var in the desired format. OPS reads observations packed by the OPPS in the "obstore" format and perform quality control on the observations and reformat the observations for its use in the Hybrid 4D-Var. OPS is comprised of two components, namely, extract and process. The "extract component" retrieves the observations and computes corresponding background values from the short (short lead time) forecast from the previous analysis at the observation locations. The "process component" does the quality control and reformats the observations for its use in the Hybrid 4D-Var.

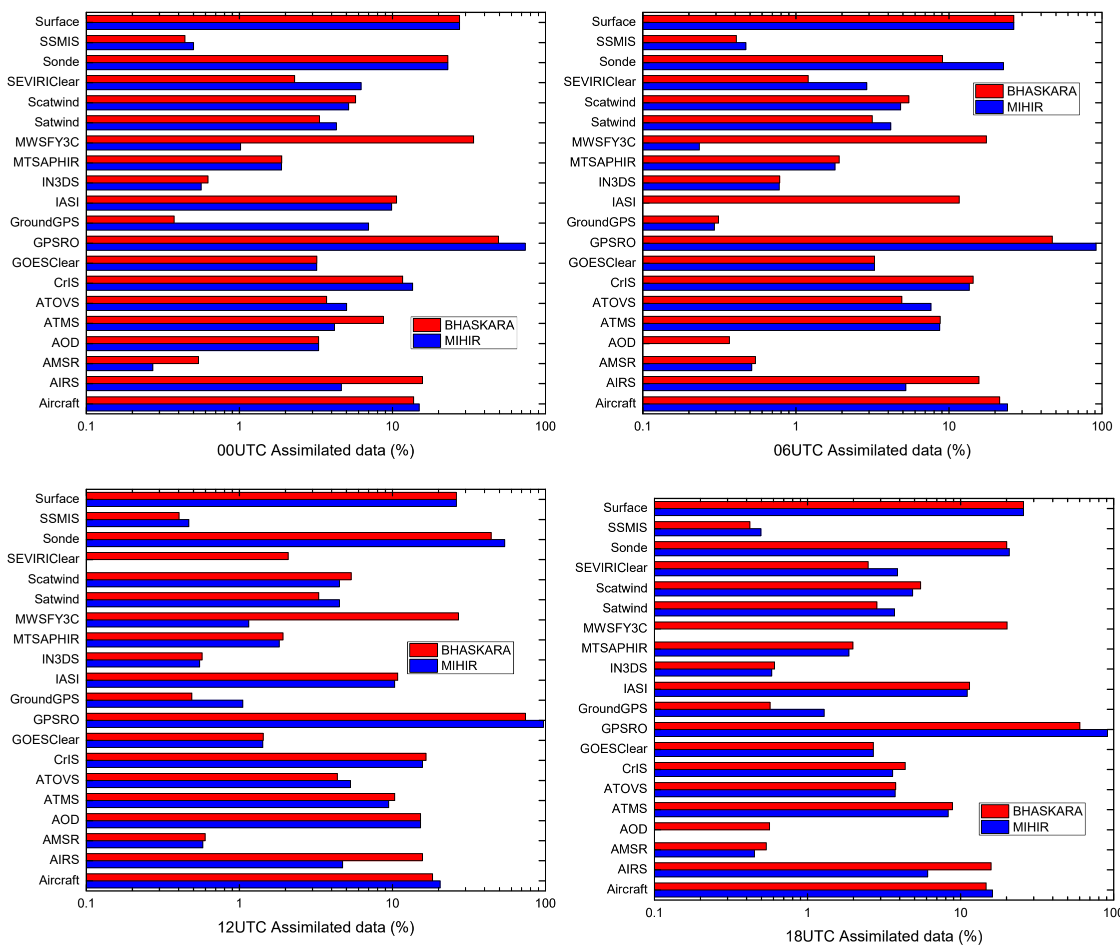

Figure 2: Comparison (%) of observation assimilated in NCUM-DA4 (runs inBhaskara) and NCUM-DA5 (runs inMihir) for a typical day (four DA cycles)

The OPS system processes and packs observations within the data assimilation window (±3 hour in each 6 hourly DA cycle) of the global NCUM DA for 00, 06, 12 and 18 UTC data assimilation cycle. The new OPS system implemented as part of the NCUM DA-5 system is a latest UK Met Office OPS system (version OPS-2017.07), which is part of their Parallel Suite-40 (PS40), operationally being used at UK Met Office. Major improvements of the new OPS, compared to the previous version, are given in Table 2. Figure 2 depicts the percentage of observations available for assimilation after processed by the OPS (observation selected after quality control and thinning by the OPS (which is used by Hybrid 4D-Var) during different assimilation cycles for a typical day) of NCUM-DA4 (run in Bhaskara) and NCUM-DA5 (run in Mihir). The number of observations processed and assimilated for a typical cycle, are shown in Figure 3(a). The systematic errors in the satellite radiances are corrected before assimilation using Variational Bias Correction technique (VarBC) (*Auligne and McNally*, 2007).

2.3 Hybrid 4D-Var Data Assimilation (VAR)

Major improvements of the new Hybrid 4D-Var system implemented at NCMRWF are listed in Tables 2 & 3. The Hybrid 4D-Var system blends the "climatological" background error with day-to-day varying flow dependent background errors from the new high resolution 12-km NEPS. The hybrid approach is scientifically attractive because it elegantly combines the benefits of ensemble data assimilation (flow-dependent co-variances) with the known benefits of 4D-Var (simultaneous treatment of all observations etc.) within a single data assimilation system (*Barker*, 2011). A detailed description of the 4D-Var system developed for UM can be seen in Rawlins et al. (2007). The Hybrid 4D-Var system uses ensemble perturbations at the start of the time window in combination with the PF model (Figure 1). A brief description on the NCUM Hybrid 4D-Var system is given in *Kumar et al*., (2018). In this Hybrid 4D-Var system also, like the in the previous DA4 version, dual resolution (N144/N320) 4D-Var approach is used (Figure 1: black color). The initial low-resolution DA run is made at N144 resolution (~90 km) and provide Hessian eigenvectors/initial guess for the higher-resolution run at N320 resolution (~40 km). This Hessian preconditioning leads to quicker convergence of the 4D-Var algorithm which renders a significant reduction in the run time of high resolution 4D-Var. The evolution of the cost function (J) and contribution from background term (J_b) and observation term (J_o) in a typical data assimilation cycle is depicted in Figure 3(b, c, and d)

The data assimilation is performed with a set of variables different from the model variables, known as control variables. The purpose of these transforms is to provide an approximate preconditioning for the VAR assimilation scheme by transforming the model variables to a set of nearly uncorrelated variables. An important assumption made in the building of variational data assimilation system is that the forecast errors in the control variables are statistically independent, so that no cross-covariance information needs to be defined in the space of control variables. The control variables used in the NCUM DA system are stream function, velocity potential, unbalanced pressure and a humidity variable. Control variable for dust is its mixing ratio. Transformation from model variable to control variable is known as T-transform and from control variable to model variable is known as U-Transform.

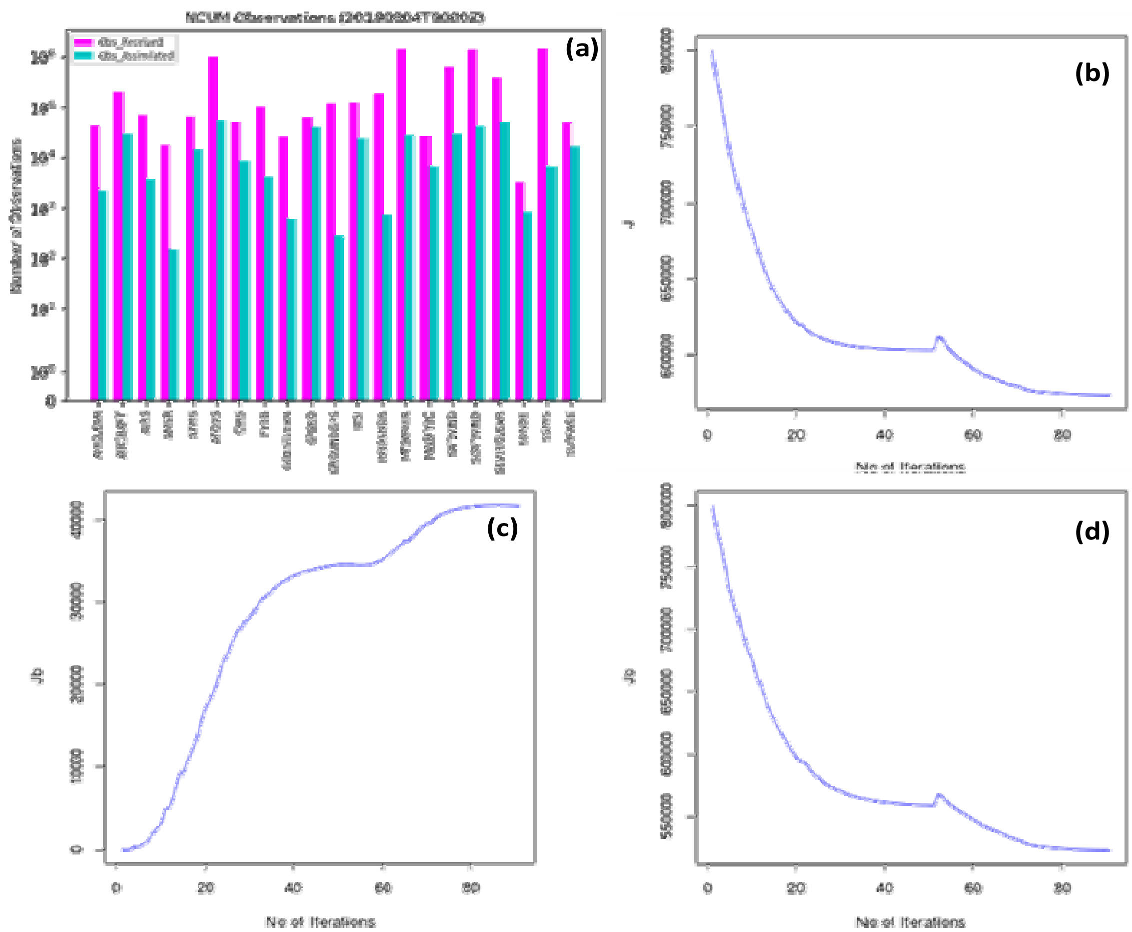

Figure 3: (a) Number of observation received and assimilated, (b-d) evolution of 4D-Var cost functions for a typical cycle

The ETKF prepares ensemble perturbations forthe NEPS at 00, 06, 12 and 18 UTC and the short forecast is prepared based on the Hybrid 4D-Var analysis with ensemble perturbations. Hybrid 4D-Var uses these ensemble forecasts for the flow dependent background errors. The linearization states for the perturbation forecast model in VAR is taken from the short forecast of the high resolution UM (Figure 1: purple color). The high resolution NCUM forecastsare interpolated to (reconfiguration) to the VAR resolution. Global atmospheric analysis valid for 00, 06, 12 and 18 UTC is produced every day. The new VAR system is adapted from UK Met Office, VAR version VAR-2017.07, which is part of their PS40.

2.4 NCMRWF Unified Model (NCUM)

Unified Model implemented at NCMRWF has been used for NWP since 2012 (*Rajagopal et al., 2012*). The NCUM system is being upgraded periodically to adapt the new scientific and technological developments for improving the predictions.

Unified Model version 10.8 (UM10.8), which is the part of latest "Operational Suite (PS40)" of UK Met Office, is adapted in the new NCUM. There is not much difference in the model dynamics or representation of physical processes in comparison with the previous version of NCUM (based on UM 10.2). However, the horizontal resolution of the model is increased to ~12 km in this upgradation while the vertical levels are the same (L70).

Dynamical core is the so-called heart of the atmospheric models, the component of the model that deals with the numerical solution of the primitive equations. The "ENDGame" dynamics introduced in UM version 8.5 was a major development in improving the dynamical core of the model (*Wood et al.*, 2014). This was adopted duringthe up-gradation to NCUM-DA3. ENDGame improved the accuracy of the solution and reduced damping. This helps to produce more details in the simulations of synoptic features such as cyclones, fronts, troughs and jet stream winds. The current operational Global NWP (Atmosphere), is built from the components of global atmosphere (GA6) and global land (GL6) configurations of UM (*Walters et al.*, 2016). It is mentioned in *Walters et al.*, 2016 that "Alongside developments of the model's physical parameterizations, ENDGame also increases variability in the tropics, which leads to an improved representation of tropical cyclones and other tropical phenomena. Further developments of the atmospheric and land surface parameterizations improve other aspects of model performance, including the forecasting of surface weather phenomena". Details of the

UM systems can be seen at https://code.metoffice.gov.uk/trac/nwpscience/wiki/ModelInfo/global/history

2.5 Surface Analysis Preparation System (SURF)

SURF system, adapted from UK Met office, prepares surface analysis for the atmospheric model (Table 2). SURF system includes Extended Kalman Filter (EKF) based Land Data Assimilation System as well. The surface analysis system (SURF) implemented at NCMRWF prepares the surface initial fields of Snow (amount and depth), Sea Surface Temperature (SST), Sea Ice extent & depth and Soil Moisture for NCUM model forecast (Figure 1: light green colour). SST and Sea Ice analysis data are obtained from the Operational Sea surface Temperature and sea-Ice Analysis (OSTIA) system (*Donlon et al., 2011*). The SURF system interpolates this analysis in the required model resolution for its use in the model as surface boundary conditions. The Snow analysis (snow depth and amount) is produced by the SURF system is using daily snow data from the NOAA National Environmental Satellite Data and Information Service (NESDIS) Interactive Multi-sensor Snow and Ice Mapping System (IMS) to update the snow condition in the model (*Drusch et al. 2004; Pullen et al. 2011*). In the new SURF implementation also (as from DA3 onwards), EKF (Extended Kalman Filter) based system prepares the soil moisture analysis (*Lodh et al., 2016*). EKF based land data assimilation system implemented at NCMRWF uses JULES (Joint UK Land Environment Simulator) land surface model. Soil moisture observations from ASCAT as well as the surface (atmospheric) level analysis increments of moisture and temperatures (pseudo observation) are used in the EKF system for generating the soil moisture analysis at every 6 hour (00, 06, 12 and 18 UTC).

3. Rose/Cylc Software Environment for Development & Managing Suites

"Rose" is a framework for managing and running "suites" (suite is a collection of scientific application software for a common purpose). "Rose" contains all the features required for configuration management of "suites" and their components. "Cylc" is the "suite" engine or work flow engine (tools formanaging the workflows required by the Rose) that drives task submission and monitoring. Cylc has all the key features required for both operational and research job scheduling - including run, rerun, kill, poll, hold individual task or a family of tasks. NCMRWF uses "Rosie" database for suite management. Both Rose and Cylc are Open Source projects, managed under GitHub. The DA suite has many inter-dependent jobs and these jobs have further numerous tasks which too have interdependencies (Figure 4). The new NCUM global assimilation-forecast system is implemented in the new Mihir HPCS. The resources used for the operational data assimilation suite of NCUM-DA5 are given in Table5.

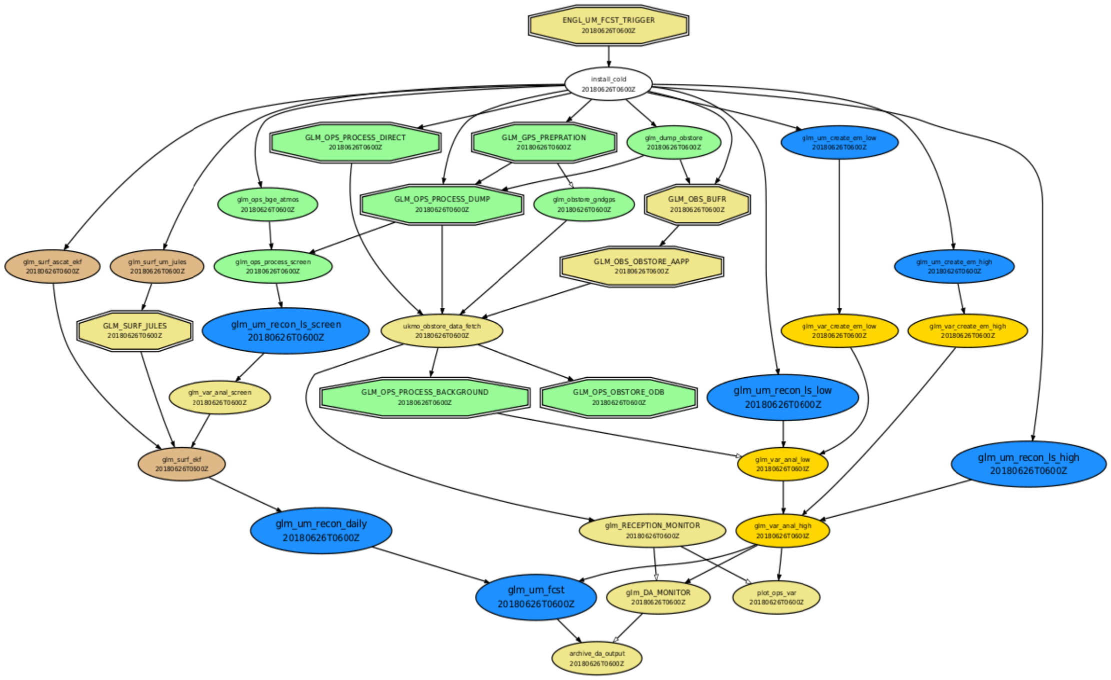

Figure 4: Schematic of the flow of NCUM-DA5 jobs in ROSE/Cylc environment

Table 5: Computational resources used by the various components of the operational NCUM-DA5 in Mihir HPCS

App	No of nodes	Runtime (Wall-clock)	Compiler used
OBS_prep	1 (MAMU**)	~900 sec	Intel
glm_ops_process_{DATA*}	22	~320 sec	Intel
glm_um_recon_ls_low	7	~140 sec	Cray
glm_um_recon_ls_high	7	~180 sec	
glm_um_create_em_low	11	~145 sec	
glm_um_create_em_high	11	~250 sec	
glm_var_anal_low	48	~240 sec	Intel
glm_var_anal_high	136	~1020 sec	
glu_um_recon_daily	2	~230 sec	Cray
glu_um_fcst	274	~390 sec	

***AHIClear, Aircraft, AIRS, AMSR, AOD, ATMS, ATOVS, CRIS, GOESClear, GMIhigh, GMIlow, GPSRO, GroundGPS, IASI, IN3DS, MTSAPHIR, MWSFY3C, Satwind, Scatwind, SEVIRIClear, Sonde, SSMIS, Surface**
****MAMU: Multiple Application Multiple User**

4. Operational Runs of NCUM Assimilation-Forecast System

The new NCUM system become operational in the last week of May, 2018 after extended trail runs in the new Mihir HPCS at NCMRWF. This high resolution global NWP system routinely produces 10 day forecasts based on 00 UTC and 12 UTC initial conditions. The forecast products are routinely provided to various users. A sample forecast plot of precipitation and its verification is depicted in Figure5. Various numerical forecast products are developed for general and user specific applications which include forecast plot of major meteorological variables at standard pressure levels, meteogram for location specific forecast etc. The NCUM analysis and forecast products are available at www.ncmrwf.gov.in .

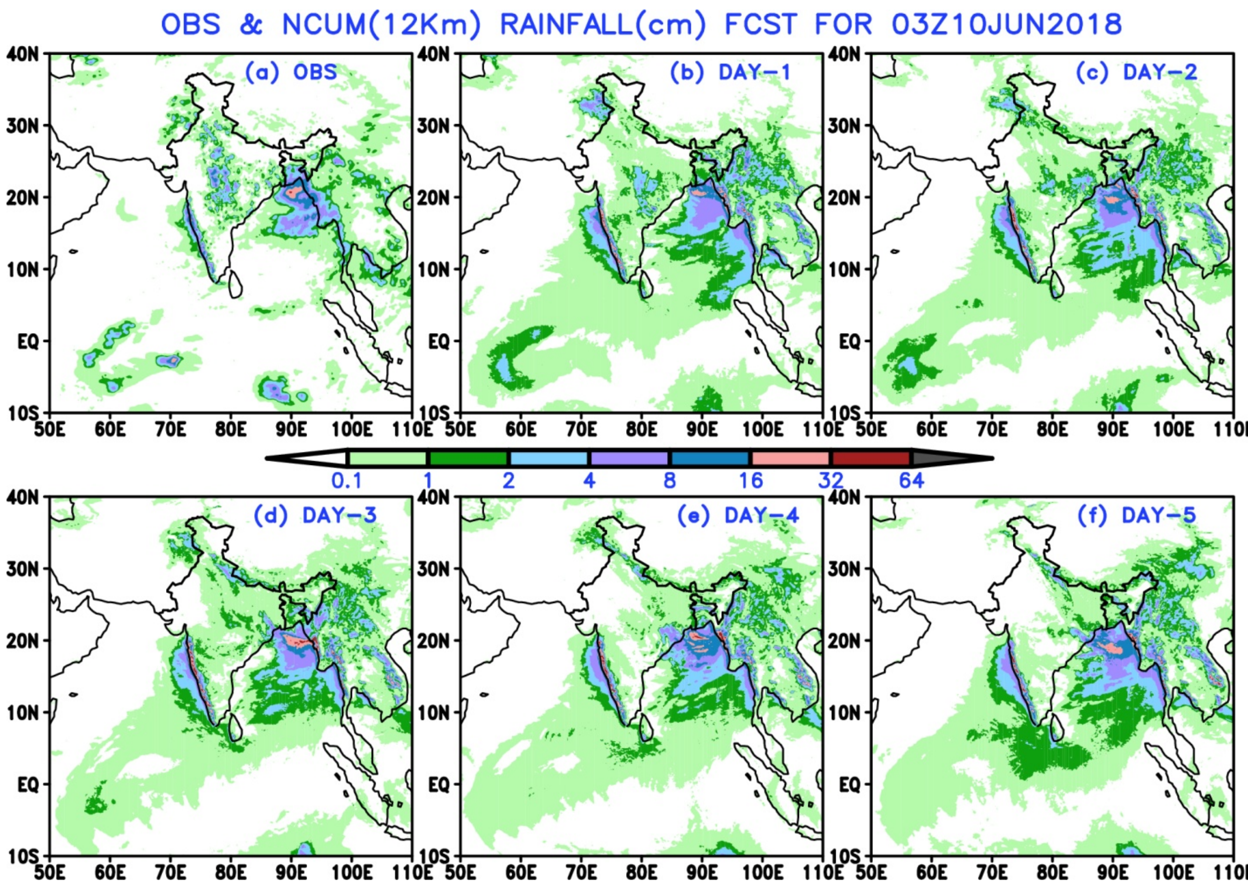

Figure 5: (a) Observed rainfall and (b-f) day-1 to day-5 rainfall forecast valid for 03 UTC of 10 June, 2018

5. Summary

High resolution NCUM analysis-forecast system is implemented and made operational in the new Mihir HPCS installed at NCMRWF. The new NCUM system is based on the components of UM Parallel Suite number 40 (PS40). The 12 km horizontal resolution global model uses ENDGame dynamical core with GA6 Physics. Data assimilation system is Hybrid 4D-Var, which uses 12-km NEPS ensemble forecasts for flow dependent background error calculation. Surface data preparation system, SURF, of PS40 is used for preparation of surface boundary conditions. Land data assimilation system prepares the soil moisture analysis. Various forecast products are being prepared routinely and made available on NCMRWF website.

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