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TECHNICAL REPORT

NCUM Data Assimilation System

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National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201309, INDIA

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Abstract

A latest version of Unified Model data assimilation system, which uses the advanced software environment rose/cylc, is implemented in the new High Performance Computer (HPC), Bhaskara at NCMRWF. Observation processing system (OPS 30.1), four dimensional variational data assimilation (VAR 30.1) and Unified Model (UM 8.5) are the main components of this atmospheric data assimilation system. This analysis system makes use of various conventional and satellite observations. The analysis produced by this data assimilation system is being used as initial condition for the daily operational high resolution (N768L70) global NCMRWF Unified Model (NCUM) 10-day forecast since January, 2016. A latest version of surface analysis system (SURF30.0.1), which prepares the surface analysis for the NCUM forecast, is also implemented in the new HPC. Various technical details of the data assimilation system are described in the report. The analysis and forecasts from this system are operationally available at NCMRWF web site.

1. Introduction

Global Numerical Weather Prediction (NWP) configuration Unified Model (UM) of UK Met Office with 4D-Var data assimilation system has been producing real-time medium range weather forecasts at NCMRWF since 2012. The UM system at NCMRWF (NCUM) was upgraded subsequently few times to adapt the developments at the Met Office. Recently, one of the latest versions of UM at a higher resolution has been implemented at NCMRWF in its new 350TF IBM iDataPlex High Performance Computing (HPC) system named "Bhaskara". The new global NCUM DA system uses advanced software environment of "Rose/cylc" as user friendly graphical interface and scheduler. The major components of the NCUM data assimilation system includes (i) Observation Processing System (OPS) which prepares the observations for the assimilation (ii) four dimensional variational data assimilation system (4D-Var or VAR) which produce the atmospheric analysis (analysis increments) and (iii) the Unified Model used for Numerical Weather Prediction. Surface data preparation system of Met Office (SURF) has also been implemented at NCMRWF for preparation of Snow, SST, Sea Ice and Soil Moisture analysis, which is used as surface boundary conditions for the forecasting with NCUM. Soil moisture analysis is produced by the land data assimilation system, which is a part of SURF, based on Extended Kalman Filter (EKF) algorithm. The new implementation of UM system at NCMRWF uses the UM components of Met Office Parallel Suite No. 34 (Parallel Suite is the version of operational NWP "system" at UK Met Office which includes specific version of UM, OPS, VAR and SURF). Parallel Suite 34 (PS34) includes UM8.5, OPS30.1, VAR30.1 and SURF30.0.1.

A data pre-processing system was developed at NCMRWF which prepares "obstore" or "bufr" format observation data input to the OPS system using the observations received at NCMRWF through GTS and various satellite data providers including NOAA-NESDIS and MOSDAC (ISRO) (Prasad, 2012; Prasad and Indira Rani, 2014). Post-processing and visualization packages were also developed at NCMRWF for various applications.

Horizontal resolution of new NCUM system is 17 km and has 70 levels in the vertical extends from surface to 80 km height. The 4D-Var data assimilation is capable of assimilating more observations compared to earlier versions. The new 4D-Var data assimilation system can be run as "hybrid 4D-Var" making use of forecasts from the ensemble prediction system for generating flow dependent background error ("errors of the day") in addition to "climatological" background errors used in the "traditional" (described in this report) 4D-Var system.

2. Components of the NCUM assimilation-forecast system

The OPS (OPS component of extract and process) prepares quality controlled observations for 4D-Var in the desired format. The OPS system processes and packs six hourly data in the desired format, centered at 00, 06, 12 and 18 UTC for the four data assimilation cycles (00, 06, 12 & 18 UTC cycles). The 4D-Var uses these quality controlled observations as well as NCUM short forecasts (known as "first guess" or "background") to produce the atmospheric analysis valid for these cycles. The NCUM short forecast run (12 hr) are carried out as a part of the data assimilation system based on the analysis (analysis increment) produced in each data assimilation cycle. These short forecasts from the model at N768 resolution provides the background fields for OPS and Var. SURF system, which produces the surface analysis (snow, SST, sea-ice and soil moisture) for initializing the surface conditions for the model forecast, also uses the background information from the 12 hr model short forecast in addition to required observations (or analysis).

Python based new "Rose/Cylc" framework for managing and running the UM components has also been installed at NCMRWF. Rose is a set of utilities which provide a common way to develop, manage and run the "suites" - such as "data assimilation suite" which contains data assimilation jobs of OPS, VAR, SURF etc. Cylc is the work flow engine and the "meta" scheduler which controls the "Rose" jobs. All the executable and jobs of NCUM components and the new "Rose/Cylc" environment is available in the "Bhaskara" HPC. A complete work flow of the new NCUM DA system is given in Figure1

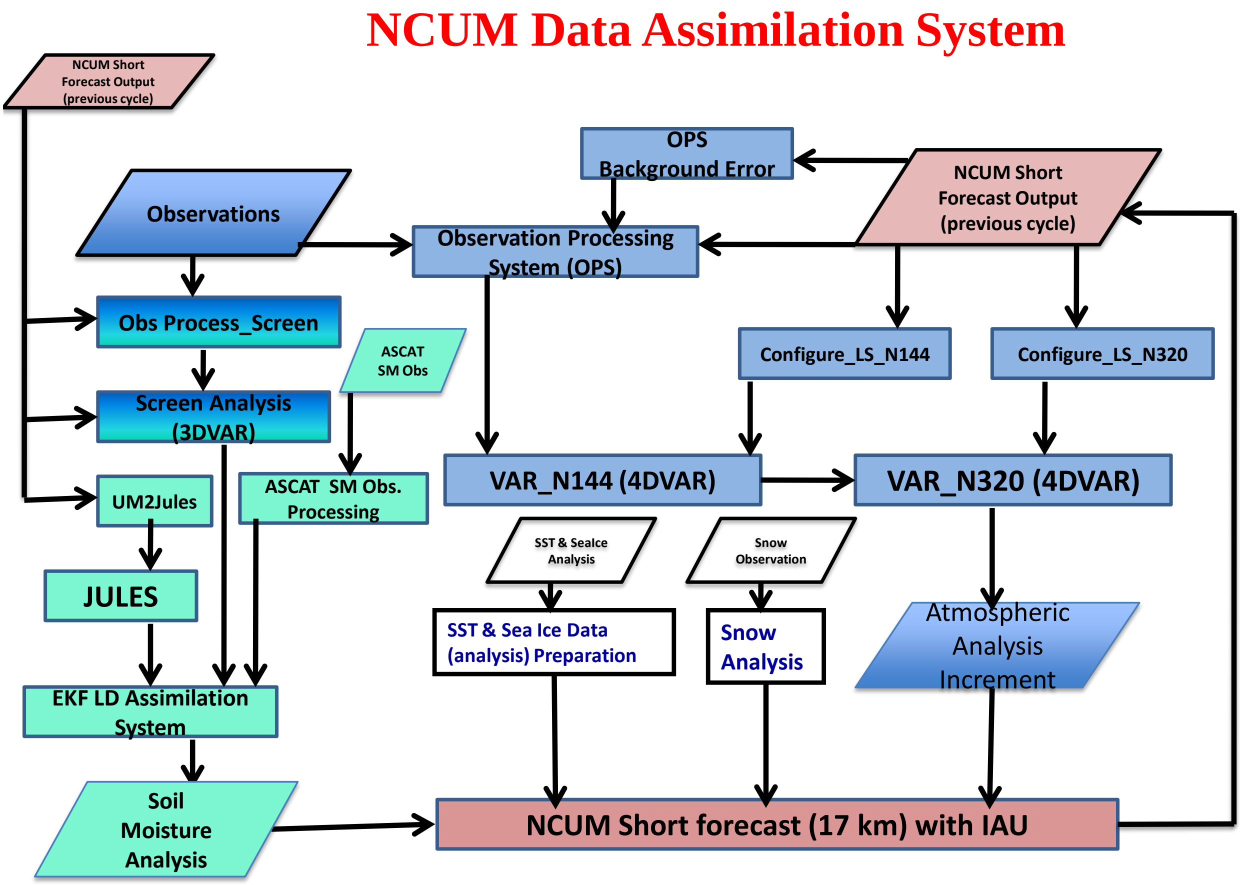

Figure 1: Flow diagram of NCUM DA system with showing PS-34 components

2.1 Observation Processing System

Observation Processing System (OPS) generally refers to the executable "OpsProg_ExtractAndProcess", which prepares and pack the quality controlled observations for 4D-Var system. During this step OPS read the observations from obstore/BUFR and model background fields from a previous short forecast run of the model. OPS assign "data use flags" containing the information regarding the particular observations such as whether a particular observation/station should be used (based on the information available in stations list file), its probability of error (PGE- Probability Gross Error) etc. The quality control procedures like check for extreme values, performs buddy checking, etc. are part of the OPS ExtractAndProcess. The main OPS outputs are files containing quality controlled and processed observations (VarObs), the model forecast interpolated in time and position to match observation in the VarObs file (VarCx), and the optional archival output of the input observations in "obstore" format.

Observations processed in the OPS30.1.0 include those from conventional platforms as well as from various satellites (Table 1). The OPS system processes multispectral and hyper-spectral radiances (Brightness Temperature) from various satellites. Most of the observation inputs for the OPS system are prepared by "NCMRWF observation preprocessing system" using observations available at NCMRWF from various sources including GTS observations available through IMD. Some of the radiance observations from Met Office (in "obstore" format) are also used currently. However efforts are going on to replace the observations received from Met Office in the NCUM system with observations received and pre-processed at NCMRWF.

The full "OPS software package" of PS34 (OPS30.1) contains not only the OPS "Extract and Process" program but host of other programs which can be used for various related applications such as monitoring of observations before and after "OPS Extract and Process" step, programs used for preparation of model background errors etc. Most of the OPS executables are run through "wrapper script", which is also created by the OPS build process. Table 2 gives the list of executables (.exe) and wrapper scripts produced by the OPS build at NCMRWF.

Table 1: List of observations processed for 4D-Var in OPS30.1 at NCMRWF

Observation Type	Sub-types (observation)
Surface (Surface Observations)	SYNOP, AWS, SHIP, BUOY, METAR
Sonde (Atmospheric profiles)	RS/RW, PILOT Balloon, Wind Profiler
Aircraft (Aircraft observations)	AIREP, AMDAR, ACARS
Satwind (Atmospheric Motion Vectors)	Meteosat-7& 10, GOES-E& W, INSAT-3D, MTSAT, AQUA,TERRA, NOAA & METOP
Sactwind (Ocean surface wind)	MetOp-A & B
GPSRO	COSMIC
GOESCLR Radiances	GOES-E & W
MVIRICLR Radiances	Meteosat-7
SEVIRICLR Radiance	Meteosat-10
MTSATCLR Radiance	MTSAT
ATOVS Radiance	NOAA and MetOp-A & B
ATMS Radiance	Suomi-NPP
CrIS Radiance	Suomi-NPP
AIRS Radiance	AQUA
IASI Radiance	MetOp-A & B

Table 2: Scripts and Executables produced by OPS30.1 build

```
/gpfs2/home/umprod/NCUM/PS34/OPS30.1.0/BuildDir/build/build/bin

BUFRdecode.exe                 OpsScr_BackErrCreate         OpsScr_Setup
mkmdblseq.exe                  OpsScr_BuildMeto             OpsScr_SetupCycleTime
mkmdblseq.sh                   OpsScr_BuildSpecificSetup    OpsScr_SetupMetDB
OpsFn_MakeDir                  OpsScr_BuildUtils            perturb-varobs
OpsFn_ODBCompile               OpsScr_CxCreate              print-acobs
OpsFn_rttov9_id                OpsScr_ExtractAndProcess     print-assoc
OpsProg_BackErrCreate.exe      OpsScr_InitODB               print-cx
OpsProg_CxCreate.exe           OpsScr_MOPS                  print-obstore
OpsProg_ExtractAndProcess.exe  OpsScr_rttov9_ascii2bin      print-varobs
OpsProg_KillRPC.exe            OpsScr_rttov9_build_exes     rttov9_ascii2bin_coef.exe
OpsProg_MOPS.exe               OpsScr_SatRad_BuildBiasCheck
OpsProg_SatRad_BiasCheck.exe   OpsScr_SatRad_CheckBias
```

2.2. Variational Data Assimilation System

Atmospheric Data assimilation system produces the best possible estimate of state of the atmosphere using observations and short range forecast (background) from an NWP model. Observation and background error information is also required for the data assimilation system. Data assimilation system implemented at NCMRWF is based on incremental 4D-Var method. A detailed description of the 4D-Var system can be seen in Rawlins et al. (2007) and Rajagopal et al. (2012). 4D-Var tries to find the best estimate of the state of the atmospheric (or "analysis") using "background" or “first guess” (a short forecast from a previous analysis), observations in a time window as well as error statistics of background and observations. The 4D-Var system produce the analysis by minimizing a cost function (penalty function) which describes the departure of the analysis from background and observations which distributed in the time window. The minimization (of cost function) problem has to be solved using of iterative techniques. To make the analysis problem manageable, the 4D-Var system uses a "perturbation forecast" (PF) model which is approximately the tangent-linear to the full model.

This 4D-Var system uses single outer loop of non-linear model which provides linearization states and background fields for the assimilation system. In the new 4D-Var implementation for global data assimilation at NCMRWF, the resolution of the 4D-Var system was increased from the earlier resolution of N216 (~60km in mid-latitudes) to N320 (~40km in mid-latitudes). A low-resolution 4D-Var at N144 is run ahead of the main 4D-Var run at N320 resolution. The low-resolution 4D-Var provides a Hessian preconditioning that reduces the run-time (computational cost) of high-resolution 4D-Var run. This Hessian preconditioning leads to quicker convergence of the 4D-Var algorithm hence a significant reduction in run-time 4D-Var at N320 resolution. A schematic representation of this system can be seen in Figure 2. The issue of convergence in minimization is important because each iteration is very expensive in 4D-Var. The current 4D-Var implementation uses maximum of 30 iterations in the inner loop for N144 and a maximum of 40 iterations in the inner loop for N320 resolution 4D-Var. The 4D-Var at N320 resolution produces the analysis increments which will be used in the forecast model. These analysis increments, with respect to the background state, are added to the background (produced by the previous cycle NCUM model short forecast valid for same analysis increment time) in the NCUM model step of IAU (Incremental Analysis Update) in the beginning of the model integration. This 4D-Var data assimilation system can also run as 3D-Var system (by making few changes in some control/namelist files.

Like "OPS software package" (OPS 30.1), "VAR software package" (VAR30.1) of PS34 contains not only the program for the "conventional" variational analysis scheme ""VarProg_AnalysePF**"** but also the program for "hybrid" analysis scheme (VarProg_AnalyseEn)**,** Background error creation programmers (CVT), programs for FSO (Forecast Sensitivity to Observation) etc. Most of the VAR executables are run through a "wrapper script", which are also generated by the VAR build process. Table 3 gives the list of executables (.exe) and wrapper scripts produced by VAR 30.1 build.

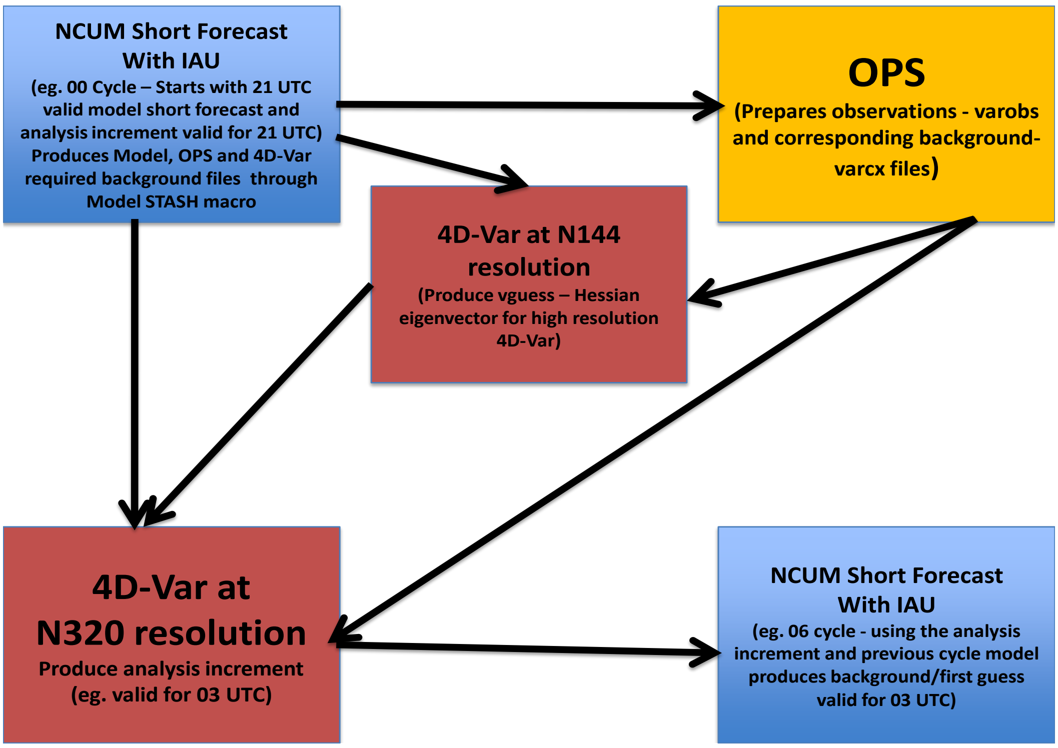

Figure 2: Schematic of NCUM atmospheric data assimilation system with dual N144/ N320 4D-Var approach

Table 3: Scripts and Executables produced by VAR 30.1 build

```
/gpfs2/home/umprod/NCUM/PS34/VAR30.1.0/BuildDir/build/bin

OpsFn_rttov9_id               VarProg_FSOCombineWindows.exe  VarScr_FSOCombineTotals
OpsScr_rttov9_ascii2bin       VarProg_FSOProcessMaps.exe     VarScr_FSOCombineTotalsTS
rttov9_ascii2bin_coef.exe     VarProg_FSOProcessTotals.exe   VarScr_FSOPlot
var_fso_box_plot.pro          VarProg_FSOProcessWindows.exe  VarScr_HelpCompileAll
var_fso_fltscl.pro            VarProg_ObsSens.exe            VarScr_HelpCompileParallel
var_fso_is_defined.pro        VarProg_SV.exe                 VarScr_HelpCompileSerial
var_fso_ll_vec2poly.pro       VarProg_TestCov.exe            VarScr_ObsSens
var_fso_map_plot_std.pro      VarProg_TestPFModel.exe        VarScr_Reconfigure
var_fso_run_box_plot.pro      VarProg_UMFileUtils.exe        VarScr_ReconParallel
var_fso_run_map_plot.pro      VarScr_AnalysePF               VarScr_ReconParallel_old
VarProg_AnalyseEn.exe         VarScr_BuildSpecificSetup      VarScr_Setup
VarProg_AnalysePF.exe         VarScr_CheckLSDir              VarScr_SV
VarProg_CovAccStats.exe       VarScr_ConfigureLS             VarScr_TestPFModel
VarProg_CovPFstats.exe        VarScr_CovAccStats             VarScr_UMFileUtils
VarProg_CovSampleEn.exe       VarScr_CovPFstats
VarProg_FSOCombineMaps.exe    VarScr_CreateEM
VarProg_FSOCombineTotals.exe  VarScr_FSOCombine
```

The main inputs to the 4D-Var ("VarProg_AnalysePF") are:

(i) LS states (produced by model short forecast when VAR STASH MACRO is switched on): The appropriate linearization state (LS) fields at every hour during the assimilation interval are written during the Model integration (Short forecast based on previous analysis, eg. 00 cycle short forecast produce 7 LS states, "ca" files at every hour from 03 UTC to 09 UTC. These files which are at model resolution (N768) are reconfigured onto the PF model grid (N320).

(ii) CxFields (Var_cx files produced by OPS): This file contains model variables at the observation points. These are obtained by OPS by interpolating the forecast fields in space and time fields written out during the model integration (short forecast). OPS use "*pp_006" files generated by the short forecast (pp_006 file is produced by model short forecast when OPS STASH MACRO is switched on)

(iii) Observations (Var_obs files produced by OPS): Quality controlled observations, with associated error variances, etc. produced by OPS

(iv) Background error covariance statistics (Climatological file): Used within the T and U transforms within the 4D-Var algorithm, which transforms the analysis fields between PF space and control variable space.

(v) Guess: If a guess different from the background is to be used, either PFguess (Guess state minus background state on the PF model grid) or VGuess (Guess state minus background state as a control variable) is used.

2.3. Surface Analysis for NCUM

The surface analysis package (“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. SST and Sea Ice are obtained from the OSTIA analysis, but SURF program “SurfProg_OSTIA2NWP” interpolates it at NCUM model resolution. The Snow analysis (snow depth and amount) is produced by the SURF program “SurfProg_Snow” using snow cover data “IMS Snow” (from NESDIS) received at NCMRWF. Soil moisture analysis is prepared by the Extended Kalman Filter (EKF) based Land Data Assimilation System, which is also a part of the SURF package (Figure 3). Technical details of this EKF based land surface data assimilation scheme is described in Candy, 2012. The EKF based system makes use of a stand-alone version of the JULES land surface model (jules.exe). Skin temperature and soil temperature can also be assimilated (in future) using this EKF based land data assimilation system. Screen level atmospheric analysis of temperature and humidity (produced by 3D-Var atmospheric analysis system) as well as ASCAT (Advanced SCATterometer) soil wetness observations from MetOp satellites are used in the EKF System. Quality control and processing of soil moisture (including conversion to volumetric unit) is done by “SurfProg_ASCAT”. “SurfProg_EKF” prepares the EKF based analysis for four soil layers of 10 cm, 25 cm, 65 cm and 2 metre at N768 resolution. Soil moisture analysis has to be prepared at every six hourly intervals whereas Snow, SST and Sea Ice are required only once in a day, at 12 UTC cycle.

“SURF package” (SURF 30.0.1) contains various programs used for various steps in surface analysis. Like OPS and VAR executables, most of the SURF executables are also run through “wrapper scripts”, which are also generated during the SURF build process. Table 4 gives the list of executables and wrapper scripts produced by SURF 30.0.1 build.

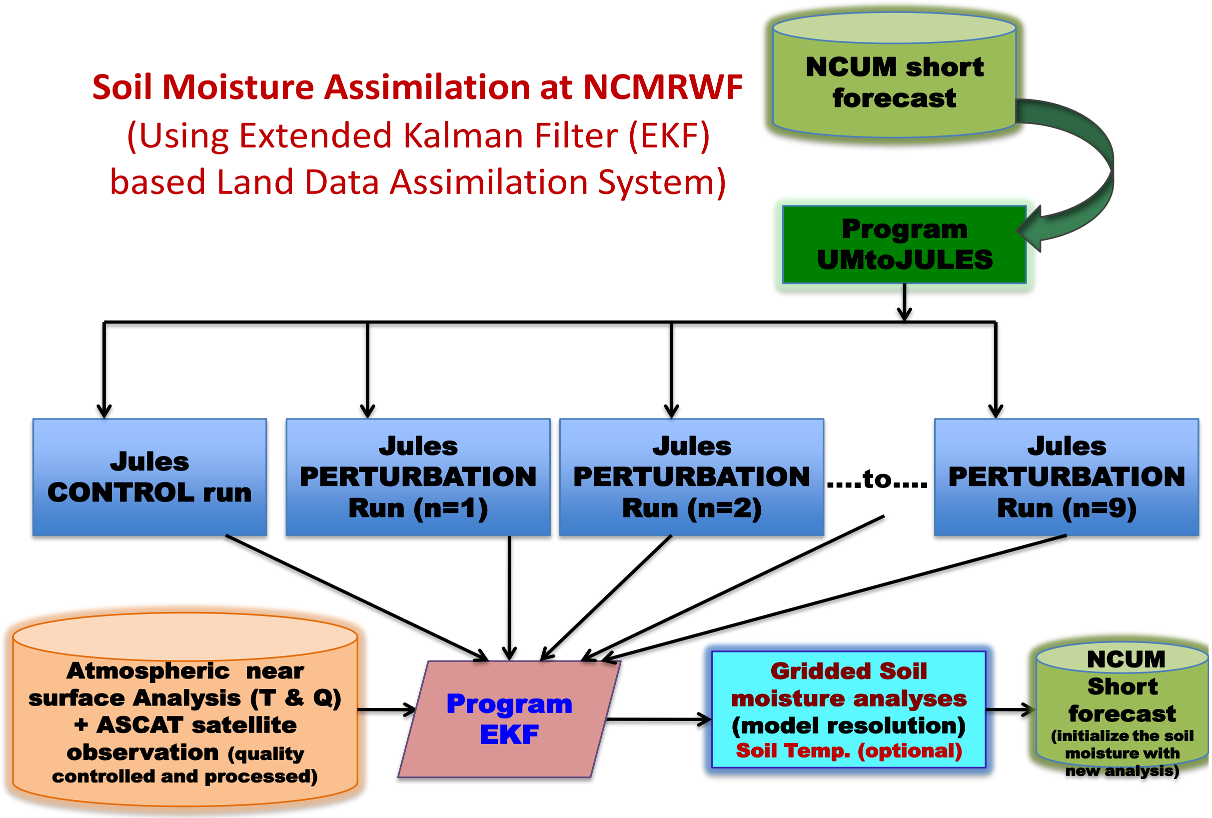

Figure 3: Schematic of EKF based Land data assimilation system used for soil moisture assimilation implemented at NCMRWF

Table 4: Scripts and Executables produced by SURF 30.0.1 build

```
/gpfs2/home/umprod/NCUM/PS34/SURF30.0.1_SNOW/BuildDir/surf30.0.1/build/bin

jules.exe                      SurfProg_ASCAT.exe               SurfScr_OSTIA2NWP_ORIG
OpsScr_SetupMetDB              SurfProg_EKF.exe                 SurfScr_PreOPSPostSurfTasks
SurfComp_PreOPSPostSurfTasks   SurfProg_OSTIA2NWP.exe           SurfScr_PreOPSPreSurfTasks
SurfComp_PreOPSPreSurfTasks    SurfProg_SMC.exe                 SurfScr_RunJules
SurfComp_RunJules              SurfProg_SMNudge.exe             SurfScr_RunJules_ORIG
SurfComp_Run_Surf              SurfProg_Snow.exe                SurfScr_SetupCycleTime
SurfIF_PreOPSPostSurfTasks     SurfProg_UMtoJules.exe           SurfScr_SnowAnalysis
SurfIF_PreOPSPreSurfTasks      SurfScr_ASCATsoilWetness         SurfScr_SnowAnalysis_ORIG
SurfIF_RunJules                SurfScr_ASCATsoilWetness_ORIG    SurfScr_SoilMoistureAnalysis
SurfIF_Run_Surf                SurfScr_EKF                      SurfScr_SoilMoistureNudge
SurfList_PreOPSPostSurfTasks   SurfScr_EKF_ORIG                 SurfScr_SSTtoFEP
SurfList_PreOPSPreSurfTasks    SurfScr_HelpCompile              SurfScr_Surf
SurfList_RunJules              SurfScr_OperatorSwitches         SurfScr_UMtoJules
SurfList_Run_Surf              SurfScr_OSTIA2NWP                SurfScr_UMtoJules_ORIG
```

2.4. Unified Model

The Unified Model (Version 8.5) was implemented as part of the upgradation of NCUM assimilation-forecast system at NCMRWF on the new HPC. Compared to earlier versions there are major changes in the physics options and dynamics. The new model uses ENDGame dynamics which employs semi-implicit semi-Lagrangian discretization of the governing equations. Horizontal resolution of the new mode is N768 with 70 levels in the vertical. The resolution in the deterministic global model has been increased from 25 km to 17 km. A technical summary of the model is given in Table 5. A detailed description of this version of model is given in Appendix-I. This version of the UM still uses “Unified Model User Interface” (UMUI) for operating the model. UMUI produces a set of scripts which are used to set up and run the model compilation, model run and reconfiguration. However in operational implementation, scripts produced by UMUI are modified and used for the model run. Snow, SST and Sea Ice analysis are included in the model through “reconfiguration” step. Soil moisture is updated during the short forecast run of the NCUM data assimilation. The short forecast run uses the IAU option. The analysis increments used in the model is produced by 4D-Var whereas the previous cycle short forecast provides the “start dump” (first guess). A schematic of the NCUM short forecast system is given in Figure 4.

Table 5: Summary of Unified Model (Version8.5) implemented at NCMRWF

Model version	**UM8.5**
Dynamical core	ENDGame (Even Newer Dynamics for General Atmospheric Modelling of the Environment)
Resolution	~ 17km in mid latitude
Grid	1536 x 1152
Model levels	70, lid ~80km
Forecast length	240 hrs
Time step	7.5 mins
Radiation Time Step	1 hour

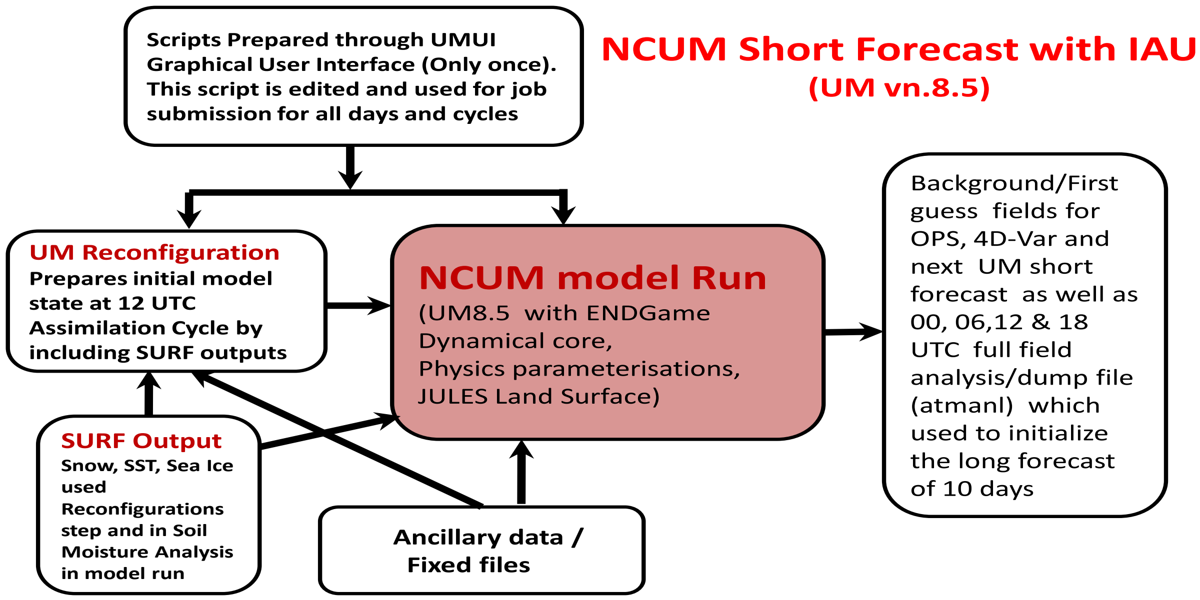

Figure 4: Schematic of "short forecast" system using Unified Model at NCMRWF

3. Rose/cylc Framework to Run NCMRWF Data Assimilation System

"Rose" is a framework for managing and running meteorological suites. It is a open source software comprising of a group of utilities and specifications which aim to provide a common way to manage the development and running of scientific application suites. "Cylc" is a workflow engine and meta-scheduler for "Rose" suites. It was developed collaboratively by National Institute of Water and Atmospheric Research (NIWA), New Zealand and UK Met Office (A Rose/cylc documentation can be found at http://metomi.github.io/rose/doc/rose-rug-introduction.html). It specializes in continuous workflows of repeating (cycling) tasks such as those used in weather and climate forecasting and research. It can be used for cyclic and non-cycling applications. Rose framework/environment has following advantages.

- Easy to understand and modify the configuration files that are used
- Runs the suite and applications
- User friendly - GUI with various functionalities, a different user in the same site can run the suite without any modification
- Portability between various computing platforms and environments are relatively easy
- Version controlled and hence easily identifiable in the archive environment.

The suite "NCUM_OPS_VAR_SURF" used for NCUM data assimilation (except short forecast) is a collection of various Rose application (OPS, VAR and SURF) configurations. The Rose suite contains the following main/essential files and directories (Table 6). The "suite.rc" is the "cylc" configuration file. "rose-suite.conf" is the rose suite configuration file. The "app" directory contains configuration files for various applications run by the tasks of the suite. In the operational data assimilation suite, configuration files for all OPS tasks, VAR tasks and SURF tasks are present. The meta directory contains metadata configuration for the various applications. "rose-meta.conf" is the metadata configuration file. "bin" directory contains other scripts and executables used in the suite. There are 5 different types of Rose configuration files: (i) rose-suite.info contains discovery information, (ii) rose-suite.conf contains suite settings, (iii) rose-app.conf is the configuration file for application settings, (iv) rose-meta.conf describes the metadata for suite and application and (v) rose.conf is the site and user configuration file.

Figure 5 shows a screenshot of a PS34 cylc window (GUI) of the NCUM data assimilation job. Different colors show the status of each application like, succeeded, running, submitted, waiting, etc.

Table 6: Rose suite for NCUM data assimilation – Applications and Configuration files

```
/gpfs2/home/umprod/NCUM/PS34/roses/NCM_OPS_VAR_SURF

app                                                 suite.rc_25aug2015       suite.rc_surf_snow
bin                                                 suite.rc_ops_var         suite.rc_ultra
etc              rose-suite.info                    suite.rc_OPS_VAR         suite.rc.VARonly
MakeConfFile.sh  suite.rc                           suite.rc_ORIG_04sep      suite.rc_wrkng_21aug2015
meta             suite.rc_03sep2015_shared          suite.rc_SURF_08sep2015
readme.txt       suite.rc.03sep.rani                suite.rc_SURF_11sep2015
rose-suite.conf  suite.rc_14092015                  suite.rc_SURF_EKF
                                 $ cd app

fcm_make_ops                   gl_ops_process_scatwind   glu_var_config_ls_n144
fcm_make_var                   gl_ops_process_sonde      glu_var_config_ls_n320
gl_ops_bge_create              gl_ops_process_surface    gl_var_anal_n144
gl_ops_process_aircraft        glu_ops_process_screen    gl_var_anal_n144_old
gl_ops_process_aircraftsonde   glu_surf_anal_snow        gl_var_anal_n320
gl_ops_process_airs            glu_surf_anal_sst_seaice  gl_var_anal_n320_old
gl_ops_process_atovs           glu_surf_ascat_ekf        ops_gl
gl_ops_process_goesclear       glu_surf_ekf              ops_ukv
gl_ops_process_gpsro           glu_surf_jules            var_gl
gl_ops_process_iasi            glu_surf_um_jules
gl_ops_process_satwind         glu_var_anal_screen
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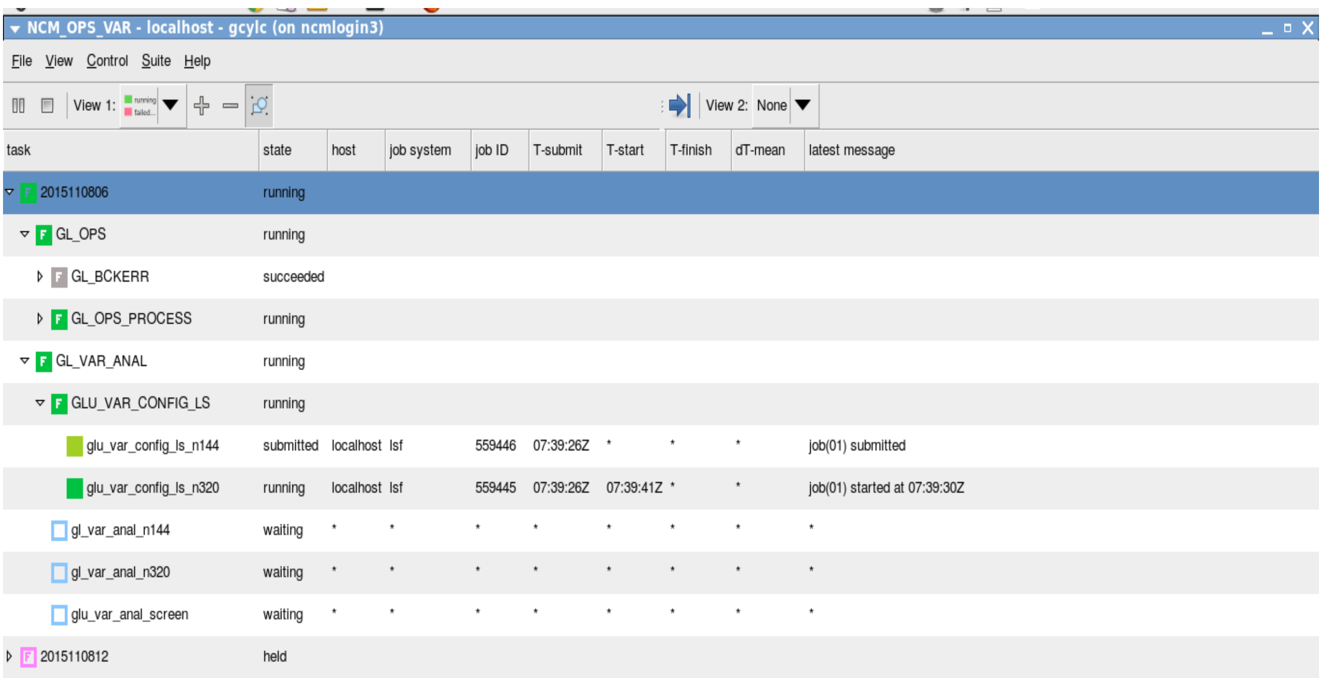

Figure 5: Run time cylc window (GUI) of the NCUM Data Assimilation job

4. Analysis and Forecast Products

The real-time 10 day forecasts based on the new NCUM data assimilation system started in October, 2015. The analysis and forecast products from this system are available daily in NCMRWF web site (www.ncmrwf.gov.in)..

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Appendix-I

Description of the Global Unified Model (Version 8.5)

a) Dynamical core - The ENDGame

In UM8.5, dynamical core of the model is upgraded from the so-called "New Dynamics" in the older version to "ENDGame". The new model (UM8.5) and the old model (UM7.9) share many aspects of their design; both employ semi-implicit semi-Lagrangian finite-difference discretisations of the same basic equation set and use the same relative staggering between variables. There are, however, a number of ways in which ENDGame differs from New Dynamics.

The most significant differences between ENDGame and New Dynamics are:

1) ENDGame uses a nested iterative time step structure (more implicit, approaching Crank-Nicolson), which improves its numerical stability;
2) Iterative time stepping allows a simpler approach to solving the Helmholtz equation , which reduces one of the bottle necks in scalability;
3) Increased stability allows the time-weights in the semi-implicit time stepping to be much closer to the time-centred value of 0.5 (alpha time-weights, all equal to 0.55), which improves accuracy and reduces the damping in the model;
4) Same Semi-Lagrangian (SL) advection for all variables (cf. Eulerian continuity equation + SL in New Dynamics) and removal of non-interpolating in the vertical for theta advection
5) Increased stability also allows the removal of almost all explicit numerical diffusion. The only damping applied is a sponge-layer that damps the vertical velocity near the top of the model and also extends to the surface very close to the poles. I.e., No polar filtering or horizontal diffusion, control near lid and poles achieved by implicit damping of w giving improved scalability and accuracy;
6) The horizontal grid is shifted half a grid length in both directions so that scalars are no longer held at the poles (V -at-poles (cf. u, w and all scalars) means not solving Helmholtz problem at singular point of grid.
7) There are subtle changes to many of the prognostic variables, e.g. virtual dry potential temperature is used as the thermodynamic prognostic, whilst all moist prognostics move from specific quantities to mixing ratios. Also, potential

temperature advection now utilises a fully three-dimensional semi-Lagrangian scheme;

8) One unique and scientifically useful capability of the ENDGame core is the ability to switch the underlying equation set solved, without changing the numerical scheme. ENDGame is capable of solving, within the same numerical framework, either the NHS or the NHD equations and further invoking constant or varying gravity (with height).

b) Model Physics - The GA6.1/GL6.1 science.

The significant developments in the 8.5 version of the Unified Model in addition to the ENDGame dynamical core are the changes in the model physics. The model physics are described below.

- **Radiation scheme:**
    - Solar constant reduced to the latest estimated value of 1361W/m^2;
    - Improved CO2 and O3 LW absorption using method of Zhong and Haigh [2000], which improves heating/cooling in the stratosphere;
    - Radiation timestep reduced to 1 hour from 3hour, which improves the accuracy of the radiation scheme
    - Removal of the “Delta” aerosol climatology;
    - An update to the albedo of sea ice.
- **Boundary layer scheme:**
    - Shorter “Mes” tails in stability functions and other changes to mixing in stable boundary layers over land, and “Sharpest” over sea (Lock et al, 2001) ;
    - Revised stability functions for unstable boundary layers, to use the ”conventional” functions from the Met Office large-eddy model;
    - Revised diagnosis of shear-dominated boundary layers to improve cloud fields in cold air outbreaks.
- **A prognostic cloud fraction and condensation (PC2) scheme:**
    - Improved cloud erosion method and numerical definition for mixed-phase cloud;
    - New cirrus term and use of the model winds in the shear term in the treatment of falling ice cloud fraction;

    - Smoother phase change for cloud condensate detrained from convective plumes;
    - Apply cloud optical depth filter and diagnostic convective cores to improve the consistency of the standard cloud diagnostics.
- **Large-scale precipitation scheme:**
  - Implement improved drizzle size distribution to better match observations and further reduce spurious light rain;
  - Loop microphysics sub-stepping over the column rather than in each level;
  - Use aerosol climatologies for CCN in second indirect effect, again to replace the use of an inappropriate land/sea split.
- **Convection scheme:**
  - Introduction of the 5A convection scheme, with the removal of an ill-formulated convective energy correction;
  - An increased entrainment rate in deep convection (and related modified detrainment rates). This follows the work of Klingaman and Woolnough (2014), which shows that increasing entrainment parameter significantly improves modes of tropical variability such as the Indian Monsoon, tropical cyclones and the Madden–Julian oscillation;
  - Smoothed adaptive detrainment of qcl, qcf and tracers;
- **Gravity wave drag:**
  - Introduction of the 5A orographic gravity wave drag scheme, which includes a ”cut-off mountain” approach to diagnosing mountain-wave drag and the distribution of the applied drag from the breaking of waves over a layer representing their vertical wavelength.