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TECHNICAL REPORT

NCUM Regional Model Version 4 (NCUM-R: V4)

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March 2021

National Centre for Medium Range Weather Forecasting
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Abstract

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11	Security classification	Non-Secure
12	Distribution	Unrestricted Distribution
13	Key Words	Convective scale model , Rose/Cylc, HPC, NCUM-R

Contents:

1. Introduction to NCUM-R

NCMRWF Unified Modelling (NCUM) system is a seamless prediction system employed for all the applications from global to cloud-resolving resolutions, with traceable difference in its formulations relevant to various scientific configurations. The deterministic global model (NCUM-G) predicts the major synoptic scale features for the next 10 days daily and a set of nesting suites have been developed for various applications of mesoscale and convective scale predictions driven by the boundary conditions from the parent models. The high-resolution convective-scale models have the ability to simulate the details of mesoscale convective processes in an explicit manner in response to the more realistic and resolvable localised features over tropics in contrast to the poor representation of parameterised convective processes in coarser resolution models (e.g., Holloway et al., 2012). Furthermore, the short-range predictability skill of these convective-scalemodels is beneficial to a large extent for the more realistic simulation of meso scale convective systems (MCS) (Francis et al., 2020) and for a better diurnal variability in the model (Mamgain et al., 2018).

Earlier UK Met Office Unified Model (UM) versions uses "Unified Model User Interface" (UMUI), a Tcl/Tk based Graphical User Interface (GUI) which produces a set of scripts to set up and run the UM suitesfor model compilation, model run and reconfiguration. However, this software infrastructure for running scientific suites and applications has many issues including complexity, duplication, dependency on GUI, etc. To resolve these issues, UK Met Office introduced a new Python based framework, called 'Rose' as a replacement for the UMUI. Rose uses an open-source meta-scheduler called 'Cylc'as a replacement for the old Suite Control System User Interface (SCSUI) for scheduling various tasks in an operational suite (Oliver et al., 2017). In accordance with these changes, the global NCMRWF Unified Model (NCUM-G) under Rose/Cylc framework was implemented on Bhaskara High Performance Computer System (HPC) at NCMRWF, the details of which are presented in the report by Rakhi et al., (2016).Subsequently we have ported regional version of the model in Bhaskara under Rose/Cylc framework.

In this report we briefly discuss the details of this convection permitting model configuration of the Unified Model under Rose/Cylc environment implemented on Mihir HPC at NCMRWF. NCMRWF has been experimentally running mesoscale versions of NCUM model for many years which is basically UMUI based system (South Asian Models). These versions can be considered as V0 version. However, the first operationalized and documented version of convective scale model at 4km resolution directly nested to global NCUM model started running in 2016 (Mamgain et al., 2018) which is hereafter referred as version 1 of the NCUM regional model system (NCUM-R:V1). This version was adaptation of the nesting suite Singapore configuration (Anuragh et al., 2020) with a tropical science settings (SINGV2), which was later upgraded on Rose/Cylc system to NCUM-R:V2 (SINGV3) in 2017 (Jayakumar et al., 2017). An important decision was made to switch off the sub-grid scale convection parameterisation as at the grey zone resolution of 4km, the convective systems are partially resolved by the grid-scale microphysics. Though arguably 4km grid-size cannot be considered as fully cloud-resolving, the sub-grid scale part is expected to be negligible and hence it was decided to continue with the explicit representation of the convection till the implementation of the scale-aware convection scheme. This can lead to some bias in the model of missing some of the isolated light rainfall, but well organised and extreme rainfall peaks are well simulated and even found mostly over predicted. Table 1 lists all the NCUM-R upgradations starting from version V1, and further down the line with the subsequent upgradation in 2018 to the first version of Regional Atmosphere configuration for tropics (RA1-T) of UK Met Office convective scale model (NCUM-R:V3). Current upgradation of NCMRWF regional version (NCUM-R:V4) over India used a stable version (Unified Model version 11.1)of the tropical science regional atmosphere configuration version 2(RA2-T) under the UM science partnership (Bush et al., 2019), which is a little different from the model setup for the mid-latitudes (RA2-M). Different sections of this report describes major components of the forecasting system suite including the regional data assimilation,science configuration details, NCUM-R installation, regional ensemble prediction system details and finally applications and validation for this forecasting system.

1.1 Science configuration

The NCUM-R model domain covers the Indian mainland, Himalayan and the BIMSTEC (Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation) countries (62^{o}E-106^{o}E, 6^{o}S-41^{o}N), and with a grid resolution of 4km, uses 1,200 points in longitude and latitude (Figure 1 shows model orography). There are 80 vertical levels with the top of the model set at 38.5km. In the 80 vertical levels (labelled as L80) 59 levels are below the tropospause and 21 levels are above 18km to compensate for the higher height of the tropopause in the Tropics compared to mid-latitudes discussed below.

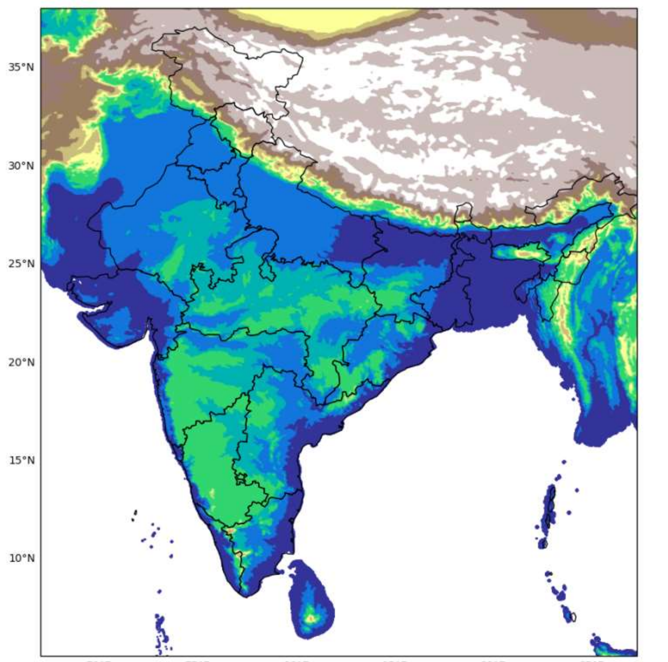

Figure 1: Orography (m) of NCUM-R.

The level thickness is stretched smoothly in the vertical, and so it has a maximum resolution of 5 m near the surface and a minimum resolution of 1.45 km near the model top. The model uses a time step of 120 seconds for the integration upto a forecast length of 75 hours. Major scientific configuration of the model is listed below.

1.1.1 Data assimilation:

The purpose of data assimilation is to determine a "best possible" atmospheric state, known as "analysis", using observations and short range forecasts. The "analysis" generated by the data assimilation system is used as initial condition for the model forecast. Data assimilation forms an important component of all numerical weather prediction (NWP) systems. It has been well known that the forecast performance of a NWP model critically depends on the quality of initial conditions. Hence much effort has been put into the improvements of assimilation techniques and use of all available good quality observations in the data assimilation system. NCUM-R assimilation-forecast system started using incremental 4D-Var data assimilation method, since its earlier up-gradation (NCUM-R: V3). In this system, the full nonlinear 4D-Var cost function is approximated by a series of minimizations of quadratic cost functions with linear constraints, proposed by Courtier et al. (1994) in order to make the 4D-Var operationally affordable (Rabier et al. 2000; Rawlins 2005 and Lawless et al. 2008). The linear constraints are derived by assuming that the evolution of small perturbations to a given base trajectory can be approximated using a simplified perturbation forecast model, which consumes less computational time.

The NCUM-R 4D-Var data assimilation system prepares 6 hourly (00, 06, 12 and 18 UTC) high resolution analysis, which is used as a model initial condition to make the forecasts. One of the major advantage of the 4D-Var system is its implicit use of flow-dependent background error co-variances.

1.1.2 Dynamical core

Non-hydrostatic version of the model uses a semi-implicit (SI) time stepping, and semi-Lagrangian (SL) dynamical advection scheme with Even Newer Dynamics for General atmospheric modelling of environment (ENDGame) dynamic core (Wood et al., 2014). Horizontal grids use Arakawa C staggering and the vertical discretisation is hybrid height-based vertical coordinate with Charney-Philips (Charney and Philips, 1953) vertical staggering. Temperature and horizontal velocities (u; v) are prescribed at the same level, whereas vertical velocity (w) and geo-potential are located at the interfaces (Figure 2). The main advantages of Charney-Philips grid in vertical are that it has no computational modes, and it is more consistent with thermal wind balance. The staggered Arakawa C-grid has the advantages of no averaging of pressure gradient, no grid decoupling, and better geostrophic adjustment for short waves (Fig. 2).

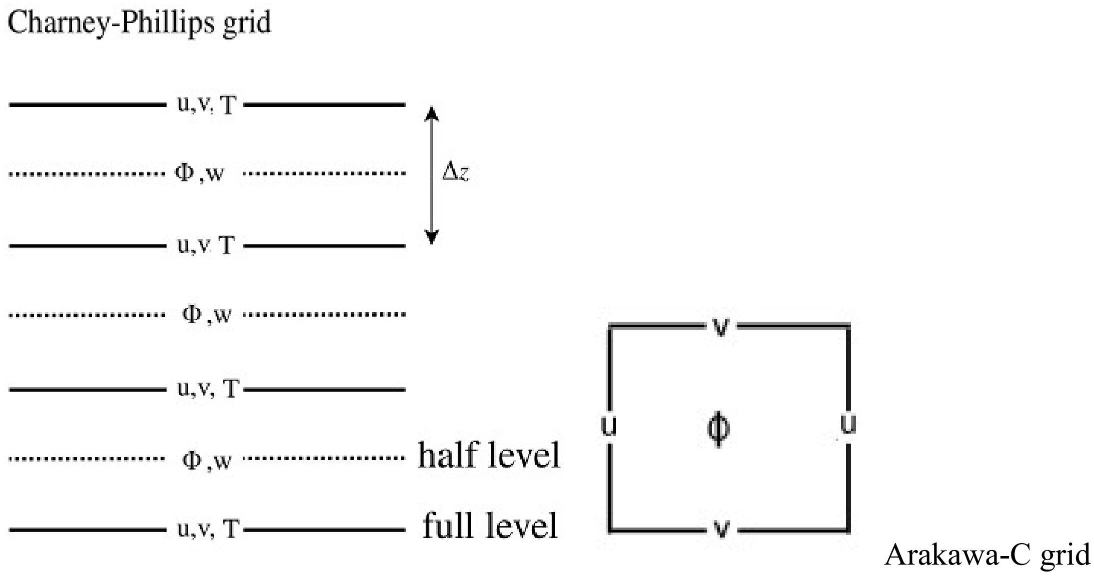

Figure 2: Charney-Phillips grid configuration of the model variables in vertical and Arakawa-C staggered grids.

Major differences of the later versions from the earlier settings of NCUM-R:V2 are the moisture conservation and stochastic perturbations. The excessive peak rain rates in the earlier version are due to the non-conservation of moisture in the semi-Lagrangian scheme. In cases where there are poorly resolved (grid-scale) updrafts, it can be shown that the semi-Lagrangian scheme doesn't cope with the stagnation point at the bottom of the column. Zero Lateral Flux (ZLF) scheme by Zerroukat and Shipway (2017) is acting as a mass restoration scheme in the lateral boundariesof limited area models (Fig. 3).The scheme works simply by zeroing the outer rims of the variable in the lateral boundary conditions (LBC) zone (where it will be over-written by LBC forcing anyway) in the advection stage. Stochastic boundary layer perturbations can be applied for moisture and temperature and arepart of the mid-latitude versions, hence not relevant to tropical settings.

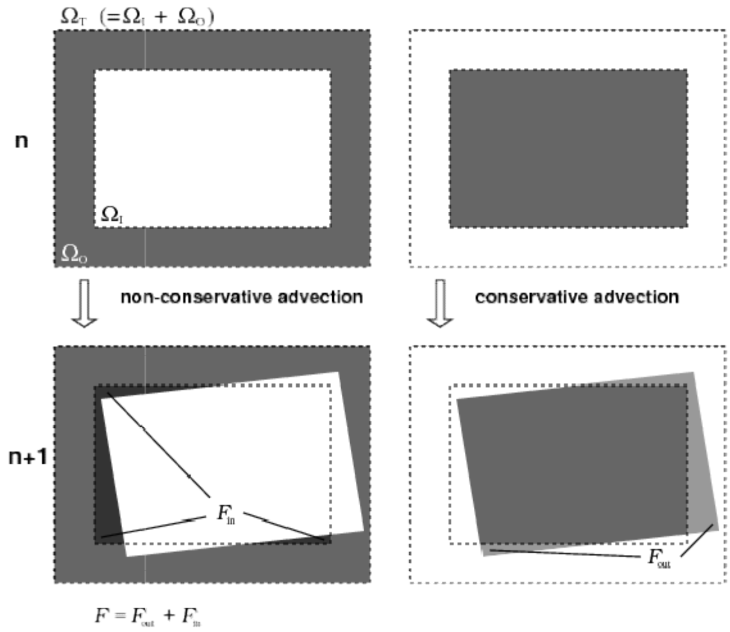

Figure 3. A schematic figure of pseudo-lateral boundary flux (PLF) computation (Aranami et al. 2015. The areas where ρ = 0 are in white and the areas where ρ ≠0 are in grey(non-white).Boundaries of ΩI and ΩO are indicated by dashed and solid line respectively.

1.1.3 Physical parameterizations

NCUM-R does not include a convection parameterization and relies on the model dynamics to explicitly represent convective clouds. Though 4km resolution is limited by the model filter scale in handling subgrid convective motion and cloud dynamics, in the absence of scale-aware scheme, additionally running with explicit mode approach gives relatively more realistic behaviour than the convection parameterization scheme (eg.,Francis et al., 2020).

Major physical parameterization schemes used under the new configuration are:

a. ***Large scale cloud scheme***: Earlier versions of the nesting suite (for eg. SINGV3.0) used in Smith (1990) diagnostic cloud scheme (Diag) along with fixed Relative Humidity (RH) crit profile, which is now part of the mid-latitude settings. Recent versions of tropical settings are working with the prognostic cloud and prognostic condensate (PC2) along with the prognostic RHcrit profiles. Further details of the PC2 are discussed in the Wilson et al., (2008). Time stepping diagram for the Diagand PC2 scheme is sketched in the Figure 1 and 2 respectively of Wilson et al., (2008). Performance of PC2 and Diag schemes and comparison against Interaction of convective organization with monsoon precipitation, atmosphere, surface and sea (INCOMPASS) flight observations are discussed in Jayakumar et al., (2020). The change in the cloud scheme increased the areal coverage of light to moderate rainfall (in the tropical settings version of the models).

b. ***Large scale precipitation:*** The microphysics scheme is originally based on Wilson and Ballard (1999). This scheme updates the grid box mean of *q*cl, the liquid water content (in terms of a specific humidity), *q*cf, the ice water specific humidity, the sum of the vapour plus liquid specific humidity, *q*T, the total specific humidity, and temperature T, separately for each microphysical processes. In convective scale models, microphysical processes are assumed to resolve all the sub-grid scale convection processes within the grid scale. The cloud microphysics scheme which is a single moment scheme based on Wilson and Ballard (1999) has undergone extensive modifications. The aerosol climatologies are prescribed over the domain except for the dust species which is prognostic. The activation of cloud droplet is coupled to aerosol concentration, which is specific to model's warm-rain scheme (Boutle *et al.* 2014). The cloud droplet number is derived from the climatological aerosols and is scaled by a factor of 1.4 before being used in the precipitation scheme. Ice microphysics parameterisation (Furtado *et al*. 2015) is based on the dual fall speed of both smaller ice crystals and larger ice aggregates along with the particle size distribution of ice is as described in Field *et al.*(2007).

c. ***Radiation***: The radiation scheme is based on Edwards and Slingo(1996).The short-wave (solar) and long-wave (thermal infrared) radiative transfers are modeled here. Radiation time step for prognostic (diagnostic) is taken 5 min (15 min) respectively. It considers two types of cloud, such as large scale cloud (random maximally overlap) and convective cloud (maximally overlapped). Latest updated spectral files improves the representation of H_2O, CO_2, O_3, and O_2 absorption and includes absorption from N_2O and CH_4. An updated solar spectrum is used. Bands 2 and 3 have new wavelength limits of 320 - 505nm and 505 - 690nm respectively. Changes result in increased atmospheric absorption and reduced surface (clear-sky) fluxes.

d. ***Orography:*** The effect of mountains on the flow is parameterized using gravity wave drag and the orographic flow-blocking schemes, following Webster *et al.* (2003). Currently, in the nested model, mean orography effect is only framed there; parameterized terms are effectively switched off.

e. ***Boundary layer:*** The boundary-layer scheme is the "blended" boundary layer parameterization (Boutle et al., 2014) . This scheme dynamically combines the1 D turbulent mixing scheme of Lock *et al.* (2000) with the 3D turbulent mixing by Smagorinsky (1963). Fragmentation of large scales in the turbulent motion is very sensitive to the subgrid mixing scheme. Smagorinsky mixing scheme in the model was used with a mixing length (Cs) of (0.5x the grid-length). In the model Cs=0.5 has been found to produce better looking convection by higher diffusivity, whereas the mid-latitude version of the model is using Cs=0.2.

f. ***Land surface and hydrology***: Exchanges of mass, momentum and energy between the atmosphere and the underlying land and sea surfaces are represented using the community land surface model Joint UK Land and Environmental Simulator (JULES) (Best et al., 2011).There is a proof-of-concept of the importance of mesoscale soil moisture gradients over northern India in initiating convection, based on INCOMPASS flight observations (Barton et al., 2019).

1.2 Major Components under the work flow of the suite

The running of Limited Area Models (LAMs) in the forecast mode requires initial and boundary conditions either generated from another LAM or a global model analysis and forecast system. Four Dimensional Variational (4D-VAR) data assimilation method is used to produce the initial conditions (or analysis) for NCUM-R. Workflow management suites for data assimilation and forecast are separate. Forecast suite is exclusive of the data assimilation component, whilst it used the initial conditions prepared by the high resolution regional data assimilation suite. Lateral boundary conditions and the frames for the entire run period is generated by '***createbc***', and '***frame***' applications. Also it requires fixed surface boundary conditions, land surface characteristics and aerosol and dust climatologies which are generated by Central Ancillary Programs (CAP) and '***pptoanc***' tools. Creation of vegetation fraction ancillaries of Climate Change Initiative (CCI) land use/land cover (Lu/Lc) data for the domains is through activating the ANcillary Tools and Suites (ANTS) in anaconda/python environment. All these are bundled together in the Rose/Cylc software framework as separate '***apps***' which also includes the '**fcm_make**' app for compilation of the model and other components of the system. Also a full-fledgedland surface modelling system, namely, JULES and Suite Of Community RAdiative Transfer codes based on Edwards and Slingo (SOCRATES) are also coupled to the UM system. The entire modelling system is version controlled by Flexible Configuration Management (FCM) system.

Up-gradation in the NCUM-R is carried out in co-ordination with the Regional Model Evaluation and Development (RMED) working group of "UM Partnership". RMED is the coordinated effort of the Unified model (UM) partnership on km scale convection permitting models in order to optimise the activity and avoid duplication in addition to working for reducing known errors in the representation of deep convection in the model. UK Met Office provides model configurations which can be used by all members of group, currently state-of-the-art mid-latitude/tropical model configurations are available. The nesting suiteof UK Met Office (https://code.metoffice.gov.uk/trac/rmed/) incorporated all the local site modifications to make it portable to use by all "UM partners". Figure 4 is the site options available in the nesting suite, where the NCMRWF platform configuration is highlighted.

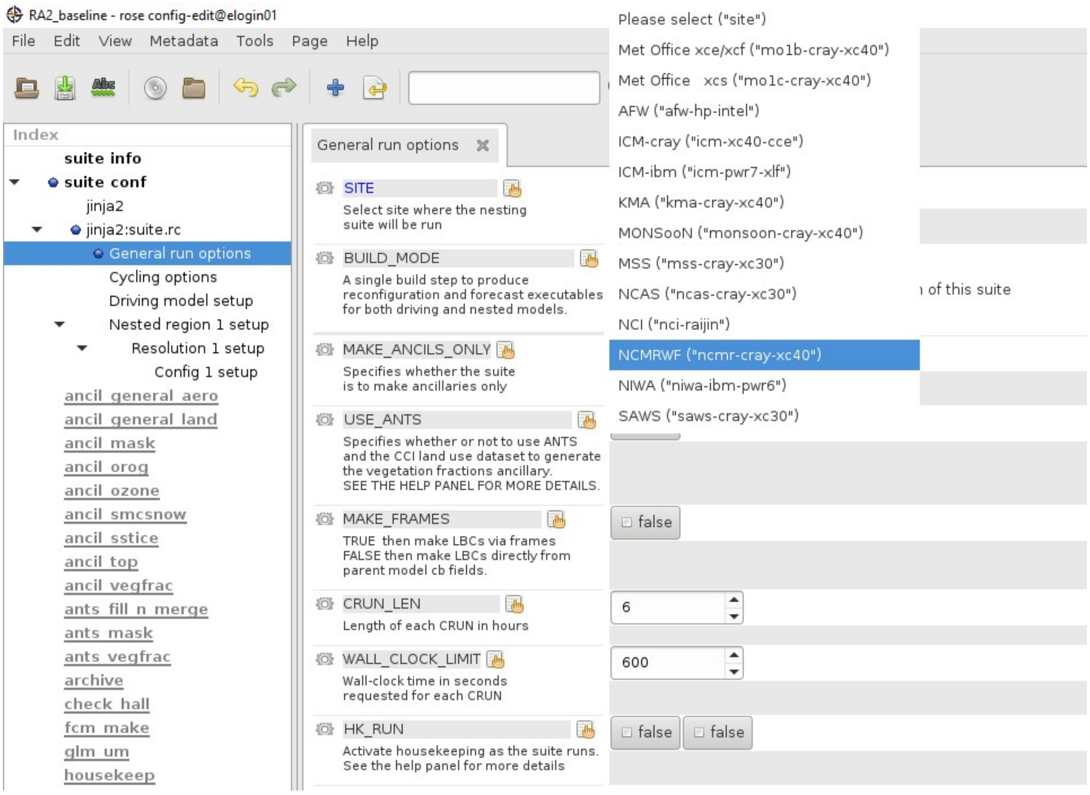

Figure 4.The site options available in the suite.

The model development processes in the UM system are documented by Trac wiki pages . Recent changes from the NCMRWF site will be made in the following branch,

https://code.metoffice.gov.uk/svn/roses-u/a/v/3/5/6/NCUMRV4_baseline@175133

This suite has similar rose job structure with the following major components (Fig.5) :

i. *rose-suite.conf* : This is used to define suite configurations outside of Cylc.

ii. *rose-suite.info*: This will give information such as when you created the suite and owner of this suite.

iii. *suite.rc*: This is used to define configurations in a Cylcsuite. Site specific task details are kept within the '*opt*' sub-folder, which will override the *rose-suite.conf* information (opt/rose-suite-ncmr.conf)

iv. *site*: Site specific configuration details such as host, node information and additional environment details are kept in '*suite.adds.rc*' file within ncmr-cray-xc40 sub-folder (site//ncmr-cray-xc40).

v. *app/* directory: This directory contains the configurations of the following applications run by the various tasks of the suite like; linking the initial and boundary conditions, ancillary file creation, compilation, LBC creation and the model itself. They are *install_cold, Ancil CAP, Ancil ANTS, Ancil locals, fcm_make, glm_um, um_createbc,um_pptoanc, and um***.**

vi.

a. *Install_cold*:Hard linking all the pre-requisites such as stashmaster, ancillaryfiles, spectral files etc. This directory contains an '*opt*' folder which contains two files for ncmrwf platform,*rose-app-ncmr-cray-xc40-idl.conf*and *rose-app-ncmr-cray-xc40.conf.*

b. *Ancil CAP*:CAP vn9.0 is used for the generation of ancillary for any domain. Land Sea mask, Orography, Aerosol climatologies, vegetation fraction, ozone, Soil moisture, Soil temperature and SST/Sea Ice are prepared for the LAM at NCMRWF. *um_pptoanc* is the tool used for converting pp files to ancillary format.

c. *ANCIL ANTS*: CCI land-sea mask and vegetation fraction is generated through the app

d. *ANCIL LOCAL: SRTM and CartoSat orography is generated through using IDL routines.*

e. *fcm_make:*This app is used to build the model executable, where site specific platform details are include in the file within the '*opt*' sub-folder (eg. *rose-app-ncmr-cray.conf*)

f. *glm-um*: This app includes the driver model, mainly global configurations: recon, glm_forecast etc. In the operational suite, this app only link to the archived files from the umfcst.

g. *createbc:* Lateral boundary generation for the nested model *is* accomplishedby *um_createbc* apps. Lateral boundary condition frequency is 3-hour.

h. *um*: LAM forecast includes mainly input data records generation (recon) and forecast task. *Opt*folder includes the specific science configurations, which override the namelists in the default configuration file,'rose-app.conf'.

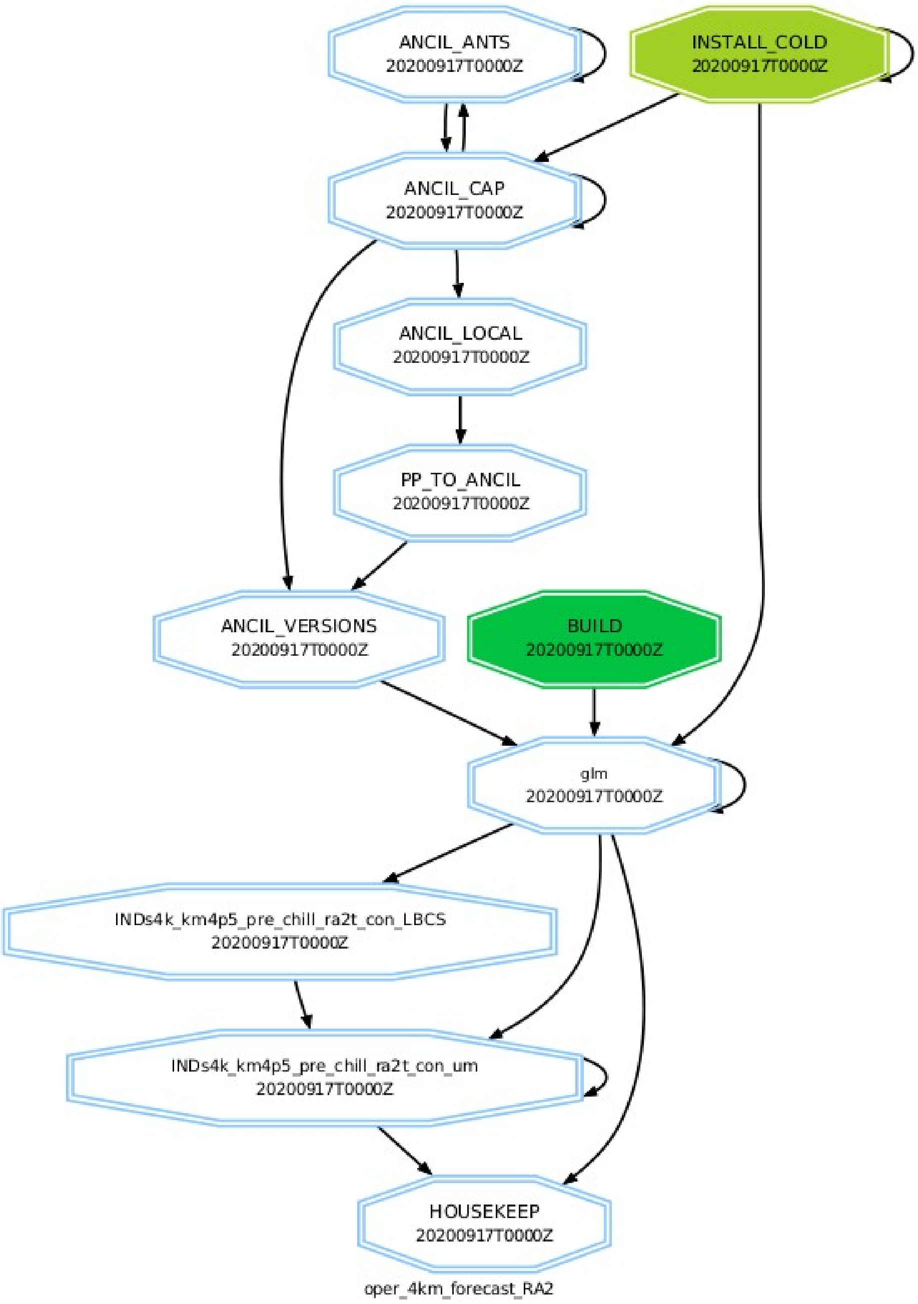

Figure 5. Different *apps* used in the input work flow management of the NCUM-R suite

2. NCUM-R installation in Mihir

The options for adding additional branches and adjusting the versions of the UM, JULES and SOCRETES can be found against the "um_sources" environment variable of the fcm_make app. Branches are added as a space separated listas shown in the Figure 6.

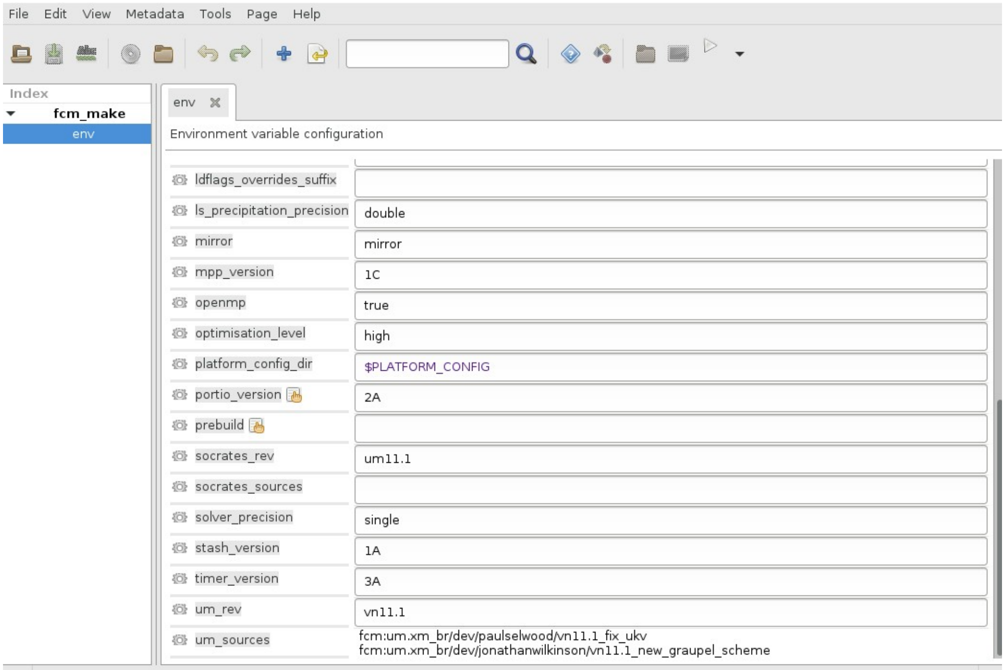

Figure 6.Source code listed in the *fcm_make* app of the the suite (Fig.5)

2.1. Optimisation of NCUM-R

The Configuration file or “config file” (app/fcm_make/rose-app.conf) contains options to change the type of executable being built and to select which revision of the config files are to be used. The optimisation level of the build, whether or not to compile with OpenMPor use the pre-build location can all be found in the "Basic compilation" section.Cray Developer Toolkit (CDT)module consists of “cdt/17.03”with cce/8.5.8, cray-libsci/16.11.1., and cray-mpich/7.5.3 modules used for the Cray CC, Fortran XC40 compilers. GCOM-6.0 is compiled using ‘cce.8.5.7’. Following environment was made available to suite by incorporating changesin site folder for NCMRWF, namely, ‘*ncm-xc40-cce*’.

Job submission to machine is done using *PBS* with the following launching option: 1536 processors of atmospheric decomposition (NX=32, NY=48) and OMP threads of 3 is taking around Wall clock time (WCT) of ~1hourfor the forecast job for a forecast lead time of 75 hours. *Createbc* app used in the suite is running in *serial* using the Mamu node, and it is optimised for the WCT of ~6minutes.

2.2. In-house ancillary developments

2.2.1 CartoSat orography

Shuttle Radar Topography Mission (SRTM) sampled at 3 arc-seconds (approximately 90 meters), based orography is generated based on SIDL program routines. In addition to that, the CartoSat Digital Elevation Model (DEM) high resolution data has been digitally generated from Cartosat satellite observations by Indian Space Research Organisation (ISRO) and the data sets are available as tiles of 1º×1º spatial resolution, which were downloaded from the Bhuvangeoportal of ISRO. From these raster tiles, the orography for NCUM-R domain was generated by performing the following procedures; (further details are in Sethunadh et al., 2019). The Cartosat data is in the World Geodetic System 1984 (WGS 84) (Yadav and Indu, 2016) and the geoid undulations are computed using Spherical Harmonic Coefficients for Earth's Gravitational Potential (Earth Gravitational Model EGM2008) data from the U.S. National Geospatial-Intelligence Agency (NGA) web portal. The corrected data are then bi-linearly interpolated to the model grid. In the NCUM-R, the mean orography is improved by removing sinks and spikes in the DEM to avoid numerical instability due to grid-scale spurious forcing (Webster et al. 2013), and the same method has been applied for both SRTM and CartoSat DEMs. In addition to this, the default land-sea mask is also applied for both DEMs.

2.2.2 ISRO Lu/Lc

Indian Space Research Organisation (ISRO) provides Advanced Wide Field Sensor data, from that derive the meso-scale models compatible Land use Land cover (Lu/Lc) data over the Indian region. NCUM uses by default the International Geosphere and Biosphere Programme (IGBP) Lu/Lc dataset which is based on NationalOceanic and Atmospheric Administration’s (NOAA) Advanced Very High Resolution Radiometer (AVHRR). Unnikrishnan et al. (2016) have shown the advantage of ISRO land use/land cover (Lu/Lc) instead of the International Geosphere and Biosphere Programme (IGBP) Lu/Lc for the short-range forecast of precipitation and surface temperature from the NCUM Global model. The ISRO Lu/Lc has are solution of 1km and is derived for a more recent period compared to that of IGBP. Figure 7 is the broad leaves and C3 grass distribution from three sources of Lu/Lc in the southern peninsula, where ISRO Lu/Lc is clearly indicating the deforestation happened in the Western Ghats during recent periods. The urban surface are represented by a single urban tile and impacted in the un-realistic surface balance in the model, and it may be overcome by the two tile scheme and availability of the morphology data in the future. Hence we are operationally still using IGBP Lu/Lc which has less urban fraction tile value and the coverage.

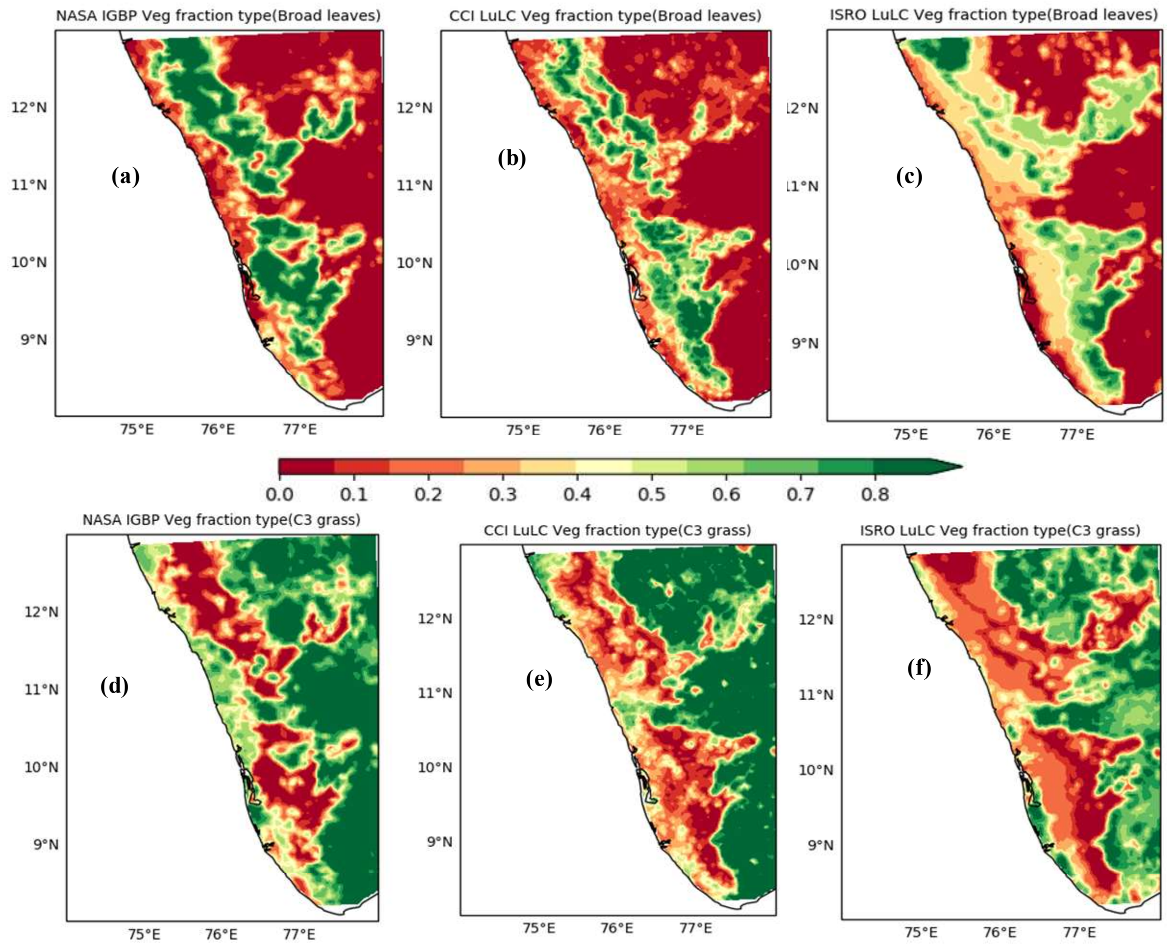

Figure 7. Broad leaves fraction (Kerala) derived from IGBP (left panel) and ISRO Lu/Lc (right panel).

3. Upgradation of model : NCUM-R:V4

Previous versions of the regional model implemented in the NCMRWF is tabulated in Table 1. The current upgraded version is based on the RA2 version of the nesting suite from RMED. Major difference in RA2 with respect to the RA1 is listed in the below mentioned link of wikipage (https://code.metoffice.gov.uk/trac/rmed/wiki/ra2). Table 2 lists the changes between the RA1 and RA2 as different ticket numbers assigned for those particular changes. The vertical levels of RA2 versions for tropical and mid-latitudes have been unified to 90 levels (#36), whereas in RA1, it was 80 and 70 respectively. However, for NCMRWF implementation, the levels have been retained as 80, which is the same as for the previous version (NCUM-R:V3). This was essential to match with the upgraded Regional Data Assimilation (RDA) suite, which is tailored for 80 levels. Also some changes are applicable for mid-latitude configurations only, like, 'Improved ice cloud fraction in mixed phase clouds' (#38) which is used for the Diag scheme in RA1-M. Many other changes are part of unification of global and limited area suites, even if it may not be universally applicable for all regions. Changes in the JULES land surface processes include, melting of the snowpack from the base over warm ground (#20), form drag over sea ice (#37), reduce the convective gust contribution to the surface exchange (#42) and limit the drag over ocean at high wind speeds (#43). The changes to boundary layer include Leonard flux terms (#27), some bug fixes in Smagorinsky scheme (#30), and use of real fluxes from JULES scheme (#39) for boundary layer type diagnosis (rather than diagnosing the same with surface flux computation before the call to JULES).

Apart from these science changes mentioned above, additional local changes implemented in the NCUM-R:V4 with respect to the NCUM-R:V3 are listed below. These changes are implemented for all the frameworks of the model (RDA, ensemble, etc.).

Lightning scheme: A new blended electric scheme following McCaul et al. (2009) is employed to predict thelightning flash rate. Afurther study by Wilkinson (2017) suggested that lightning in the United Kingdom Variable-resolution (UKV) model was displaced by the order of 50-75 km and was overforecast by a factor of six. Sandeep et al., (2020) further experimented this scheme for the Indian region by changing graupel water path (GWP) threshold, and the option to generate graupel by allowing collision between ice and rain. To avoid over estimation of the lightning count in the model, following Wilkinson (2017), we have set storm detection thresholds of GWP to 200 gm^{-2}.

Table 1: The chronology of operational NCUM-R model versions at NCMRWF. .

NCUM Versions	Nesting suite configuration (RMED)	Implementation year	Domain	GUI
NCUM-R:V1	SINGV2	2016	AI	UMUI
NCUM-R:V2	SINGV3	2017	AI	Rose/Cylc
NCUM-R:V3	RA1	2018	AI + BIMSTEC	Rose/Cylc
NCUM-R:V4	RA2	2020	AI + BIMSTEC	Rose/Cylc

Table 2. Summary of changes (tickets) between RA1 and RA2 (adopted from Bush et al, 2019, UK Met Office Report on 'RA2 Assessment').

Ticket	Summary	Milestone
#20	Improvements to the Treatment of Lying Snow	RA2
#27	Leonard Terms	RA2
#30	Minor corrections to the Smagorinsky scheme, including horizontal diffusion of liquid cloud	RA2
#36	Unify vertical level sets in Mid-Latitude and tropical configurations	RA2
#37	Implement Form Drag over Sea Ice	RA2
#38	Improved ice cloud fraction in mixed phase clouds	RA2
#39	Use real surface fluxes in convection diagnosis	RA2
#42	Reduce convective gustiness contribution to surface exchange to be consistent with GA	RA2
#43	Limit drag over the ocean at high wind speeds	RA2

Visibility parametrization: Aerosol mass mixing ratio (m) is assumed to be fixed for the earlier version of the nesting suite. Here we use aerosol climatology fields in the visibility calculation. Climatology gives mass of 5 different aerosol species, which are combined to create a single aerosol number. Then Invert the murk number-mass relationship to retrieve a single aerosol mass.

In the following branch,

https://code.metoffice.gov.uk/trac/um/log/main/branches/dev/ianboutle/vn11.4_aero_vis

calculation of m value is using the aerosol climatology. We need to switch on murk (l_murk=.true.) and use it in the visibility calc (l_murk_vis=.true.), while all other murk switches (l_murk_advect, l_murk_lbc, l_murk_source and l_autoconv_murk) are to be kept false. It will only work when the aerosol climatologies are being used (l_mcr_arcl=.true.). Additionally, we need to initialise the aerosol field (stash=90) in the items name list of the reconfiguration. A tuning factor of 2 has been applied to the aerosol number concentration, which has a feedback on the visibility parameterisation. Verification of the revised visibility scheme in the 1.5km model with United Kingdom Chemistry and Aerosols (UKCA) (red curve) and climatological aerosol (blue curve) against IGI airport METAR observation (black curve) is plotted in figure 8. Green curve represents the visibility of the model with the fixed aerosol mass of 200µg/m3. It can be observed from the figure that significant improvement on the diurnal cycle of visibility values are better matching with the observed curve Model biases of fast fog lifting and sharp rise in the screen temperature in the morning hours have been slowed down with the new visibility scheme, though the highly peaking visibility bias in the mid-day is still persistent.

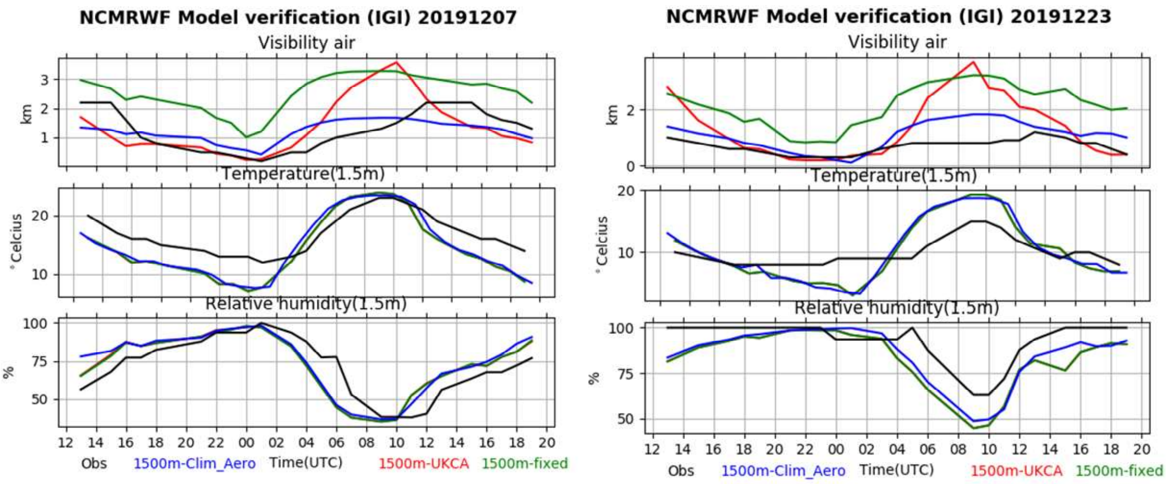

Figure 8.Comparison of Visibility (km), surface temperature (ºC), RH (%) from 1.5km model simulation with the options: UKCA (red curve), aerosol climatology (blue curve) and fixed aerosol mass (green curve).

Cloud droplet number tapering parameterisation: This scheme allows cloud droplet numbers to be tapered from their maximum value down to a lower value towards the surface introduced in the London Fog Model to compensate for the too low visibility values (Wilkinson et al 2013). Normally Indian conditions are very different from UK, as we have more fog and very low visibility values in general. Visibility parameterisation is based on the climatological aerosol discussed above, where the aerosol mass is calculated for the entire column. Hence the cloud droplet calculation limited by the cloud droplet tapering height and the fixed surface concentration is omitted in this configuration. The comparison of the precipitation patterns with the tapering OFF (b) and ON (c) for the 48 hour forecast valid for the 003Z, 15 Oct 2020 against the IMD-NCMRWF merged (using Satellite and Rain Gauge) rainfall analysis is illustrated in the figure 9. Sensitivity of the tapering option to the convection in the Orissa and Andra Pradesh coastal and Mumbai grids is very much clearly evident here with Maharashtra pattern of rainfall is somewhat delinked from the west coast with tapering ON (c).

Multilayer snow scheme: Multi-layer snow scheme is introduced in the place of simple (zero-layer) scheme of JULES (Walter et al., 2019). The inclusion of multi-layer snow is a major improvement in the land surface model in the recent upgradation of NCUM global model (to PS43) and is expected to affect the high terrain Himalayan regions. This may impact surface energy balance due to the modifications in the surface albedo and the snow melting in PS43 version of the model.

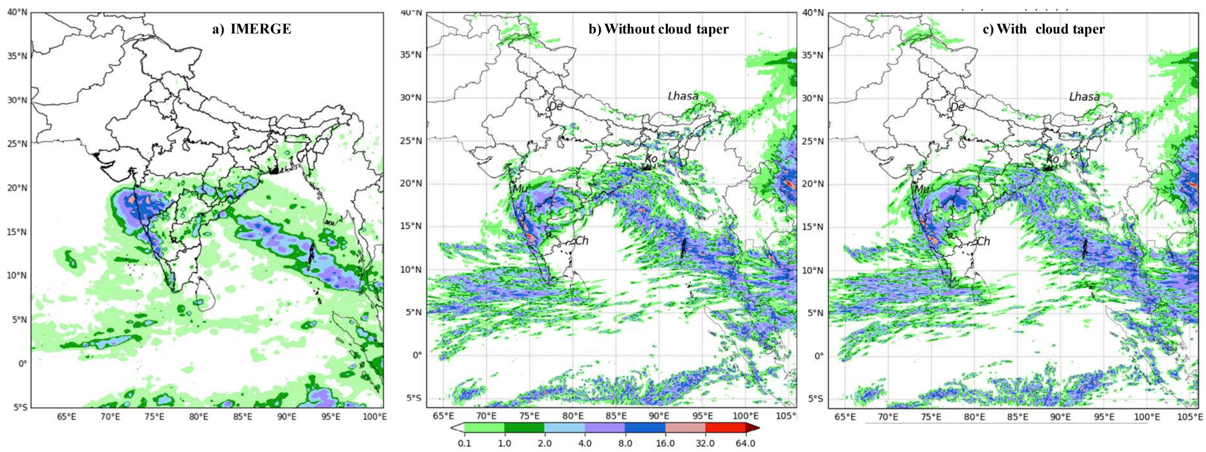

Figure 9. 24-hr accumulated precipitation valid for the 14 Oct 2020, 3UTC from the Day-2 forecast of (c) with and (b) without cloud tapering experiments along with the IMD-NCMRWF (IMERGE) observation data sets.

4. Upgradation of Regional Data assimilation

The 4D-Var data assimilation implemented with the current upgradation of NCUM-R system have additional capabilities to assimilate more radiances from different satellites such as all sky radiances fromsome of the AMSU-A channels of Advanced TIROS Operational Vertical Sounder (ATOVS); radiances from Global Precipitation Mission (GPM) Microwave Imager (GMI) high/low frequency channels; Special Sensor Microwave Imager and Sounder (SSMI/S) and INSAT-3D Imager Radiances.. The GMI can measure a range of precipitation types and severity. The 13 channels of GMI measure vertically and horizontally polarized radiances between 10.6 and 183 GHz. The measured radiances are the product of the interaction of surface-emitted radiation with water vapor, liquid, and solid hydrometeors in the atmosphere (Hou et al. 2014; Skofronick-Jackson et al. 2016).The low-frequency channels measure moderate-to-heavy precipitation, while the higher frequencies measure moderate-to-light precipitation.The SSMI/S instrument has twenty four channels to measure the Earth's radiation at frequencies between 19 and 183 GHz (Kunkee et al. 2008). The SSMI/S instruments measure temperature and humidity profile using a conical scanning mode so that the viewing area and slant path remain nearly constant as it scans the earth. The SSMI/S observations also allow simultaneous retrievals of surface and atmospheric parameters with a uniform spatial resolution across the scan swath. The F17 and F18 satellite'sSSMI/S radiances are also assimilated in the regional 4D-Var assimilation system.List of observations assimilated in the new regional data assimilation system is listed in Table 3.

A comparison is made between mean departure of observations from background fields (O – B) and from analysis fields (O – A) to evaluate the effectiveness of the 4D-Vardata assimilation system. The root mean square error (RMSE) of O – B and O – A from different satellite observations are provided in Figure 10. It is clear that the mean RMSE of analysis departure is less compared to the background departure in case of all satellite instruments, as expected from any robust data assimilation system.

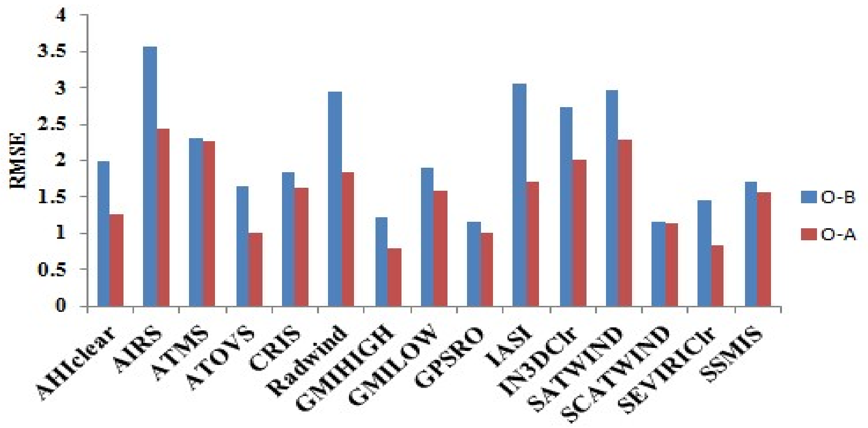

Figure 10.Mean RMSE of O – B and O – A from various satellite

Table 3: Observations assimilated in the regional 4D-Var system.

Types of OBS	Assimilated Variables	OBS Description
AHIClear	Brightness Temperature (Tb)	Advanced Himawari Imager radiances from Himawari-8
AIRS	Tb	Atmospheric Infrared Sounder of MODIS
ATMS	Tb	Advanced Technology Microwave Sounder in NPP& NOAA20 satellites
ATOVS	Tb	AMSU-A (All sky), AMSU-B/MHS from NOAA-18 &19, MetOp-A&B
Aircraft	U,V,T	Upper-air wind and temperature from aircraft
CrIS	Tb	Cross-track Infrared Sensor observations in NPP&NOAA20 satellite
GPSRO	Bending angle	Global Positioning System Radio Occultation observations from various satellites
Radar	Vr	Radial velocity
SEVIRIClear	Tb	Cloud clear observations from SEVIRI of METEOSAT 8 &11
Satwind	U,V	Atmospheric Motion Vectors from various geostationary and polar orbiting satellites (including INSAT-3D& INSAT-3DR)

Sonde	U,V,T &q	Radiosonde (TAC & BUFR),Pilot balloons, Wind profiles &Radar VAD winds
Surface	U,V,T, q & Ps	Surface observations over Land and Ocean (TAC & BUFR), TC bogus (Surface Pressure)
GMIhigh	Tb	Global Precipitation Measurement (GPM) Microwave Imager (GMI) instrument
GMIlow	Tb	
IN3DImgs	Tb	INSAT-3D Imager Radiances
SSMI/S	Tb	SSMIS Radiances

5. Upgradation of Regional Ensemble Prediction system

The regional ensemble prediction system of NCMRWF (NEPS-R) has 12 ensemble members (1 control + 11 perturbed). The model domain of the upgraded version of NEPS-R is consistent with the NCUM-R: V4 (Figure 1). The horizontal resolution and vertical resolution of this regional ensemble prediction system is 4 km and there are 80 vertical levels up to a height of 38.5 km respectively similar to deterministic versions. The model uncertainties in NEPS-R are taken care by Random Parameters (RP) scheme.Earlier version of NEPS-R is presented in the technical report by Kiran Prasad et al. (2019), which describes the details of this forecasting system and the implementation method.

NEPS-R has recently been subjected to major changes in its initial condition and science configurations. The initial and boundary conditions of previous version of NEPS-R were directly downscaled from NEPS-G output. In the new version of NEPS-R the perturbations generated by Ensemble Transform Kalman Filter (ETKF) of NEPS-G are added by Incremental Analysis Update (IAU) method to the analysis prepared by the regional 4DVar data assimilation system to provide the perturbed initial conditions. The deterministic operational regional model running from the regional 4DVar analysis is used as the control member. Initial conditions for dust and soil moisture are now being taken from the global analysis instead of climatological values. Further, dust parameterization scheme is switched on with dust being used as a prognostic variable. Three new parameters from the land-surface scheme were added for use with the RP2b scheme in this version as listed below.

· *Leaf area index, lai*: Ancillary data containing leaf area index for each plant functional type.

· *Rate of change of vegetation roughness length for momentum with height, dz0v_dh*: Array, parametercontrolling the rate of change of vegetation roughness length for momentum with height for each plantfunctional type.

· *Ratio of roughness length of heat to momentum, z0hm_pft*: Array, parameter defining the ratio of theroughness length of heat to the roughness length of momentum.

Tropical Cyclone strike probability and the probabilistic forecast of lightning and fog are also now being generated in addition to the existing forecast products of probabilistic precipitation, mean and spread of mean sea level pressure (MSLP) and wind at 850hPa from the upgraded NEPS-R.Figure 11 shows the strike probability forecast of NEPS-R for the Cyclone Nivar based on the initial condition of 00 UTC, 25th November 2020. Probability of having cyclone centre within 120km distance from a location in next three days is expressed as the strike probability of the cyclone at that location.

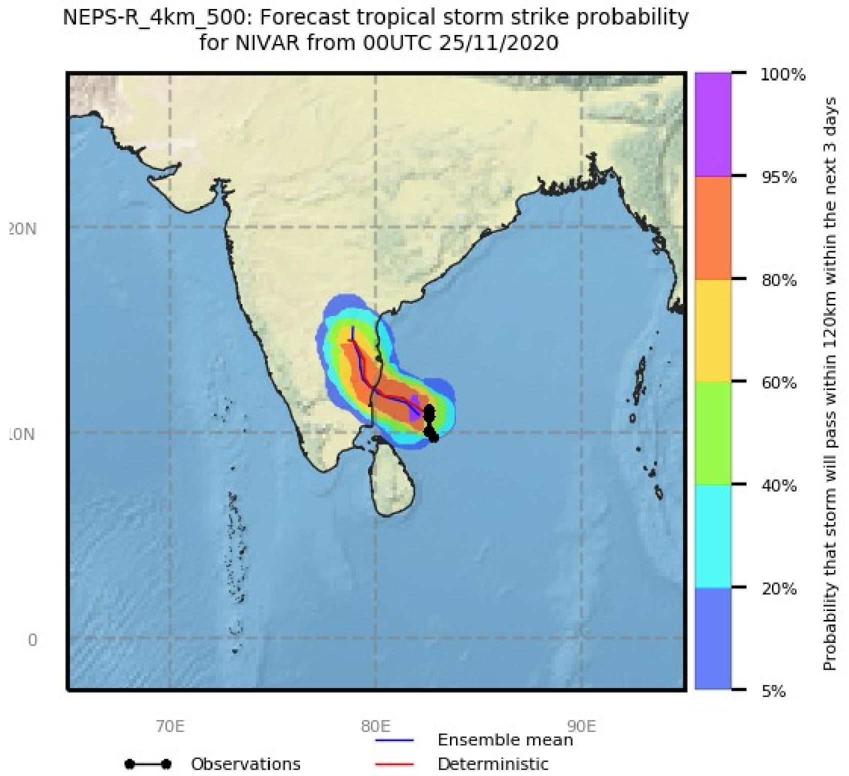

Figure 11. The strike probability forecast of NEPS-R for tropical cyclone 'Nivar' based on initial condition of 00 UTC, 25th November 2020.

6. Applications and validation

NCMRWF is running a deterministic version of 4 km limited area model in real-time for a forecast lead time of 75 hours and the forecast products are routinely displayed in NCMRWF homepage (http://www.ncmrwf.gov.in/product_main_ind.php). The model run produces improved forecasts of localised features of important weather events such as floods, thunderstorms, fog, visibility, dust, gust, lightning, etc. Figure 12 (i-l) shows comparison measures of the 24-hourly accumulated total lightning flash counts predicted by NCUM-R:V3 and NCUM-R:V4 models against the IAF/IITM Earth Network Lightning Sensor (ENLS) observations. It can be observed that with the upgraded version the areal extend of the lightning flashes are better comparable with the observations in NCUM-R:V4, with lesser RMSE and bias compared to NCUM-R:V3. In general NCUM-R:V3 over predicted the flash rates over parts of land as well as oceanic area, while NCUM-R:V4 has better match with the observations. Apart from the all India domain, localised and city domains at 1.5km and 330m resolutions are also developed for various applications (eg. Delhi Fog Model (Jayakumar et al., 2018), AmarnathYatra forecasts etc.). In addition, specialised forecast products are delivered to the solar and wind energy applications, Snow and Avalanche Study Establishment (SASE), India Meteorology Department (IMD), and defence organisations.

Major application of this model products are in

- Severe Weather Warning products (3-hourly precipitation, wind gust, lightning, dust concentration) are generated specifically for the IMD operational activities. Lightning products are available in System for Thunderstorm Observation, Prediction and Monitoring (STORM) website https://srf.tropmet.res.in/srf/ts_prediction_system/index.php. Forecast from the 4km model also started appearing in the cyclone bulletins. Visibility forecast is included in the winter FDP bulletins.

- Lightning products are available for Regional Integrated Multi-Hazard Early Warning System for Africa and Asia.

- Forecast is being provided for running integrated flood warning system - IFLOWS-Mumbai and Chennai Flood Warning System- CFLOWS.

- Rainfall forecast is used by Geological Survey of India as a input to the Early Warning Landslide system (currently setup for the pilot regionssuch as Darjeeling and Nilgiri).

- Land surface forecast products are used in the Convective-scale regional coupled environmental prediction model evaluation and development project under The Weather and Climate Science for Service Partnership-India.

- Forecast productsare made available for the operational application of Army.

- Solar and wind power companies are using the forecast products.

- Forecast products are provided to Bhabha Atomic Research Centre, Mumbai, for their dispersion models.

A comparison of 24-hourly accumulated rainfall and lightning flash counts predicted for day-1 forecasts of NCUM-R between the previous (NCUM-R:V3, namely RA1DA) and current (NCUM-R:V4, namely RA2DA) operational runs with the initial conditions from the respective regional analysis system was carried out for the 5 days initial conditions for the active monsoon period coinciding with the Kerala Floods (2019) extreme event (00Z 8-12 August 2019). Figure 12 shows the spatial distribution of the 5-day mean rainfall (a & c) along with the IMD-NCMRWF rainfall analysis (b & d) both gridded at the same observational grid of 25km resolution for RA1DA and RA2DA respectively. Both RA1DA and RA2DA features major patterns with some minor differences. RA1DA's systematic bias of over prediction of the peak rainfall is slightly reduced in RA2DA, especially off the Kerala coast and the east coast rain-shadow region is better simulated in RA2DA when compared to the observation. RMSE (e & g) and bias (f & h) are also shown for RA1DA and RA2DA respectively, which shows mixed signals at different locations. Similarly, the lower panels (i-p) gives the lightning distribution and verification statistics. Both RA1DA and RA2DA shows over prediction of lightning flash counts in compared to the observed patterns, whereas RA2DA marginally better match with a reduced distribution of peak flash counts.

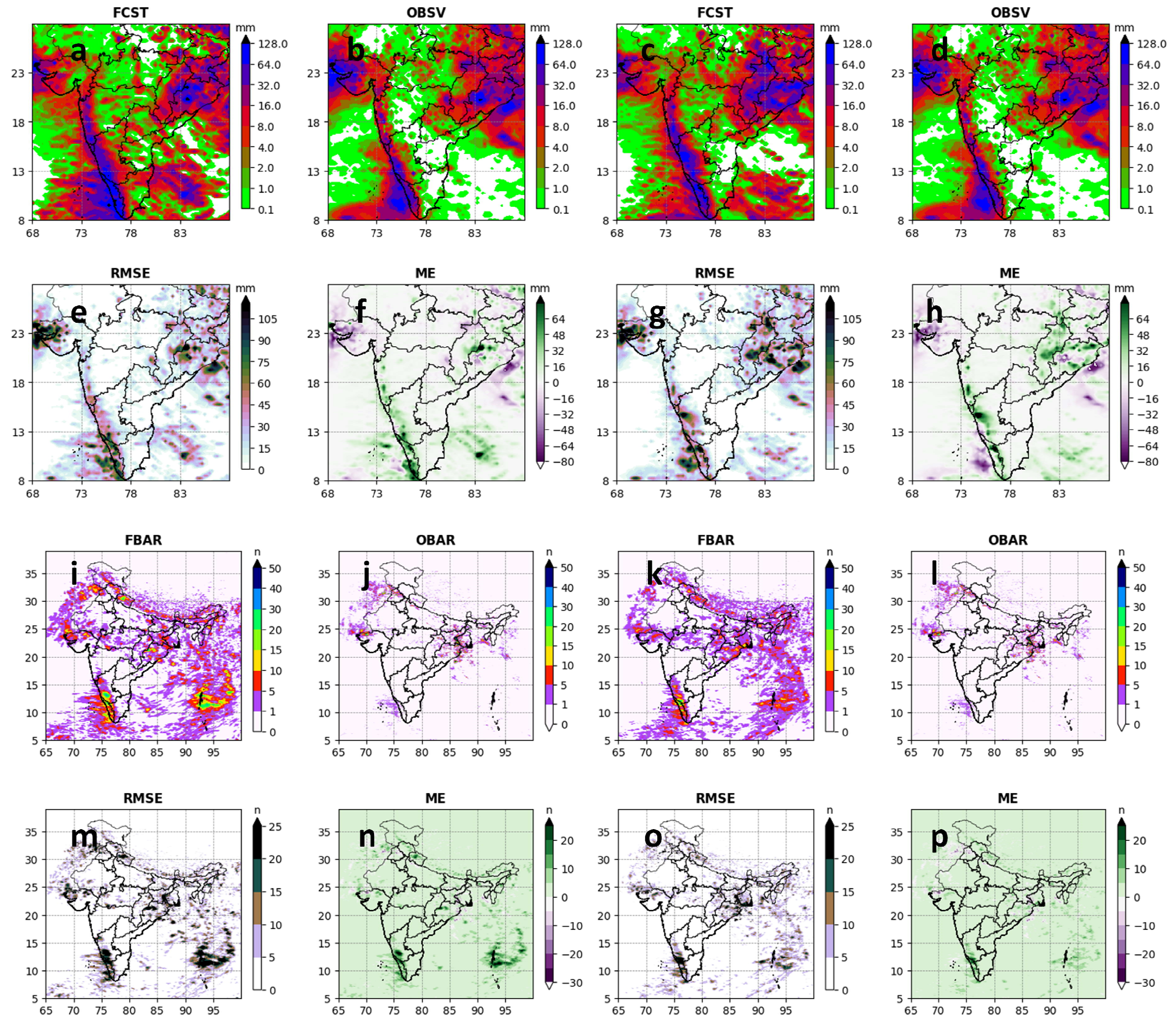

Figure 12. The spatial distribution of mean daily rainfall (cm/day) (a-d) and lightning flash counts (i-l) along with the root mean squared errors (e,g,m,o) and bias (f,h,n,p) against IMD-NCMRWF satellite-gauge merged rainfall analysis and IAF/IITM Earth Network Lightning Sensor datasets respectively.

Another validation matrix is shown in Figure 13 featuring the difference in fractional skill scores (FSS) (RA2DA-RA1DA) computed for the domain (68-98ºE, 8-28ºN), avoiding the data-sparse regions of Himalayas and the distant oceanic regions, for accumulated precipitation (a) and flash counts (b) respectively, with respect to the observed estimates. The x-axis has different thresholds and y-axis has various grid-widths (1-15) for the computation of FSS. The improvement in FSS is denoted by green upward pointing triangles and the deterioration is shown by red-colored downward pointing triangles and the sizes are relative to the maximum and minimum values of the differences which are also noted in the title. It can be seen that there is an overall improvement in the scores particularly with the precipitation scores at extreme thresholds and flash counts at lower thresholds.

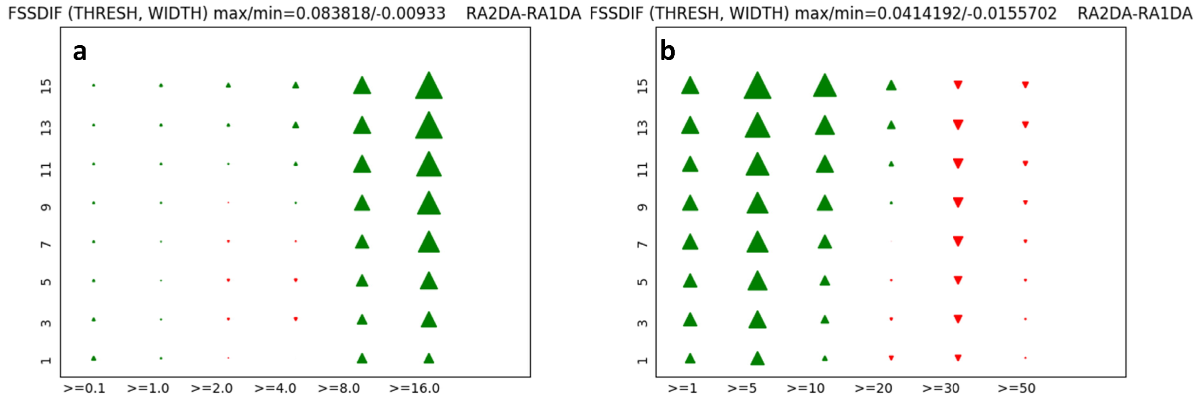

Figure 13. The difference in fractional skill scores (RA2DA-RA1DA) for total precipitation (a; cm/day) and total lightning flash counts (b) for 24hr forecasts for the initial conditions of 00Z 8-12 August, 2019 over the domain (68-98E, 8-28N) with different thresholds (x-axis) against grid-widths of 1,3,5,7,9,11,13, and 15. The green upward triangles shows the positive values and red downward triangles denotes the negatives with sizes relative to the maximum and minimum as displayed in the title.

7. Summary

In this report we have briefly discussed the science configuration and work flow management method adapted for the new the convection permitting versions of NCMRWF Unified Model (NCUM-R) run on Rose/Cylc software framework. The in-house developments with respect to the regional model ancillary developments using ISRO Lu/Lc and SRTM/Cartosat orographies data sets have also been described. This data sets have contributed to the improvementof the quality of the forecasts and have been used with various mesoscale model versions (and applications).The change made in new NCUM-R system are not only specific to deterministic model configuration, but also in the regional data assimilation and regional ensemble prediction systems. The advantages of the upgraded NCUM-R system have been demonstrated with various verification statistics compared against the previous version. Current use of various model forecast products are also listed in the last section of the report. Major changes with respect to NCUM-R:V4 is reflected in the UM partners Regional Model Evaluation and Development (RMED) trac pages.

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