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TECHNICAL REPORT

A Regional Land Data Assimilation System for NCUM-R

Abhishek Lodh, Ashish Routray, Devajyoti Dutta, John P. George and E.N. Rajagopal

July 2020

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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10	Abstract	A high resolution (4 km) regional Land Data Assimilation System (LDAS) has been developed for the regional NCMRWF Unified Model (NCUM-R) setup over Indian region. This regional LDAS is based on the global LDAS of Unified Model (UM) system of “UM Partnership”. Simplified Extended Kalman Filter (EKF) method is used in this land data assimilation system. Currently this regional LDAS is capable of generating soil moisture analysis at four soil levels covering the first 3 m depth. Screen level temperature and humidity analysis increments produced by the 3D-Var screen analysis as well as Advanced SCATterometer (ASCAT) soil moisture estimates from MetOp satellites are used in this regional LDAS system. The impact of the assimilation of the ASCAT soil moisture data in the NCUM-R system is studied for a case of monsoon low-pressure system during 25-28 September 2019, which produced significant amount of rainfall over eastern parts of India. Two numerical experiments i.e., CTL (without assimilation of ASCAT in regional LDAS) and ASCAT (with assimilation of ASCAT soil moisture data in regional LDAS) are conducted using the NCUM-R assimilation-forecast system. The NCUM-R with regional soil moisture analysis is integrated up to 72 hours in both the experiments from 06 UTC 25th September 2019 to 06 UTC of 28th September 2019. The results of the study indicate that the assimilation of ASCAT soil moisture data has a positive impact on the prediction of near surface meteorological variables.
11	Security classification	Unrestricted
12	Distribution	General
13	Key Words	Regional Land Data Assimilation, Extended Kalman Filter, ASCAT, Soil moisture

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Abstract

A high resolution (4 km) regional Land Data Assimilation System (LDAS) has been developed for the regional NCMRWF Unified Model (NCUM-R)setup over Indian region. This regional LDAS is based on the global LDAS of Unified Model (UM) system of "UM Partnership". Simplified Extended Kalman Filter (EKF) method is used in this land data assimilation system. Currently this regional LDAS is capable of generating soil moisture analysis at four soil levels covering the first 3 m depth. Screen level temperature and humidity analysis increments produced by the 3D-Var screen analysis as well as Advanced SCATterometer (ASCAT) soil moisture estimates from MetOp satellites are used in this regional LDAS system.

The impact of the assimilation of the ASCAT soil moisture data in the NCUM-R system is studied for a case of monsoon low-pressure system during 25-28 September 2019, which produced significant amount of rainfall over eastern parts of India.Two numerical experiments i.e., CTL (without assimilation of ASCAT in regional LDAS) and ASCAT (with assimilation of ASCAT soil moisture data in regional LDAS) are conducted using the NCUM-R assimilation-forecast system. The NCUM-R with regional soil moisture analysis is integrated up to 72 hours in both the experiments from 06 UTC 25th September 2019 to 06 UTC of 28th September 2019. The results of the study indicate that the assimilation of ASCAT soil moisture data has a positive impact on the prediction of near surface meteorological variables.

1. Introduction

A realistic description of land surface variables is likely to extend current prediction accuracies of Numerical Weather Prediction (NWP) models (Viterbo and Courtier, 1995; Koster et al., 2004; Ferranti and Viterbo, 2006). Constraining the land surface state accurately in the land surface model of the NWP system through the assimilation of observations is essential for accurate simulation of land surface variables in the short and medium range time scales (Meng et al., 2012, Xia et al., 2019).

The National Centre for Medium Range Weather Forecasting (NCMRWF) is operationally using global (~12 km) and high resolution regional (~4 km) NWP systems. The NCMRWF Unified Model (NCUM) NWP system is adapted from UM system of "UM Partnership". A high resolution regional NCMRWF Unified Model (NCUM-R) has been configured for the Indian domain (50^{o}E-110^{o}E, 5^{o}N-45^{o}N), which is being used for generating 3-days numerical weather predictions (Routray et al., 2019, Dutta et al., 2019). Four Dimensional Variational (4D-VAR) data assimilation method is used to produce the initial conditions (or analysis) for NCUM-R. The dynamical core of the NCUM-R solves the non-hydrostatic equations of motion with semi-Lagrangian advection and semi-implicit time stepping. It also has semi-implicit, semi-Lagrangian, predictor–corrector numerical scheme (Cullen et al., 1997; Davies et al.,2005) to solve the deep-atmosphere dynamics.

Joint UK Land Environment Simulator (JULES) land surface model (Best et al., 2011; Clark et al., 2011, Unnikrishnan et al., 2016) is coupled with the NCUM-R to represent the soil and vegetation processes. Land surface and sub-surface soil levels are included in JULES model. The JULES land surface model is used to represent surface-atmospheric interaction processes in NCUM-R. The surface of each land grid box is subdivided maximum upto nine sub-types i.e., five sub-types of vegetation and four non-vegetated surfaces. The surface types used in JULES model are broadleaf trees, needle-leaved trees, temperate C_3 grass, tropical C_4 grass, shrubs, urban areas, inland water, bare soil and land ice.

Soil moisture is a key driver in the exchanges of water and heat fluxes between the ground and the atmosphere.Hence soil moisture plays a major role in regulating air temperature and humidity, especially over near surface levels. Land surface initial conditions of soil moisture for the high resolution NCUM-R are interpolated from the coarse resolution global analysis. The global soil moisture analysis of NCUM (Lodh et al., 2016) is produced by the Simplified Extended Kalman Filter (EKF) based global land data assimilation system (LDAS). Soil moisture is an important surface variablethat affects the surface weather and hydrological budget significantly, which is highly variable in space and time. Therefore, it is important to provide accurate soil moisture state at high resolution for improving the prediction skill of high resolution models. Thus to produce high resolution soil moisture analysis, regional LDAS is developed. The regional LDAS developed for NCUM-R is based on global LDAS adapted from “UM Partnership”. The new regional data assimilation system has the capability to assimilate soil moisture observations from different sources. The globalLDAS uses ASCAT soil wetness observations from MetOp-A & B satellites and pseudo observations of near surface atmospheric analysis increments of humidity and temperature from NCUM screen analysis. The following sections describes the details of the regional LDAS and the observations assimilated to produce the high resolution analysis. Furthermore, a study is carried out to understand the impact of the assimilation of ASCAT soil moisture in the regional LDAS within the NCUM-R frame work. The impact of the assimilation of the ASCAT soil moisture data in the NCUM-R system is studied for a case of monsoon low-pressure system during 25-28 September 2019, which produced significant amount of rainfall over eastern parts of India. The preliminary results obtained from this study are also discussed in the report.

2. Regional Land Data Assimilation System (LDAS)

Simplified Extended Kalman Filter (EKF) based regional LDAS is developed for assimilation of soil moisture in the high resolution NCUM-R system.

For each grid point, the analysed soil moisture state vector x^a is computed at time $t_i$as

$$x^a(t_i) = x^b(t_i) + K_i[y(t_i) - \mathbf{H}x^b(t_i)]$$

x^b is the background soil moisture state vector,

$\mathbf{H}$ is the Jacobian matrix of the observation operator,

y is the observation vector and

K is the Kalman gain matrix, which computed at the time $t_i$as:

$$K_i = [\mathbf{B}^{-1} + \mathbf{H}_i^T \mathbf{R}^{-1} \mathbf{H}_i]^{-1} \mathbf{H}_i^T \mathbf{R}^{-1}$$

where $\mathbf{H}_i$is the linearised observation operator computed through finite differences by considering individual perturbations of the model state vector (x),$\mathbf{B}$is the background error covariance matrix and $\mathbf{R}$ is the observation error covariance matrix. Both background error covariance matrix **B** and the observation error matrix**R,** are static, with diagonal terms composed of error variances.

The Jacobian elements $\mathbf{H}_{mn,i}$ of the observation operator at time t_i can be written as:

$$\mathbf{H}_{mn,i} = \frac{H_{m,i}(x^b + \delta x_n^b) - H_{m,i}(x^b)}{\delta x_n}$$

$\delta x_n$is the small amount of perturbation of thenthcomponent of the model state vector.Index m represents the m^{th} element of the observation vector.

The elements of the Jacobian of the non-linear observation operator (***H***) are computed using offline perturbed forecast runs of standalone JULESv5.1 land surface model (Source: http://jules-lsm.github.io/vn5.1/). The atmospheric forcings for the off-line JULESv5.1 model run are obtained from theNCUM-R short lead time forecasts (6-hour). The overall schematic flow of regional LDAS designed currently for the assimilation of soil moisture is shown in Figure 1.

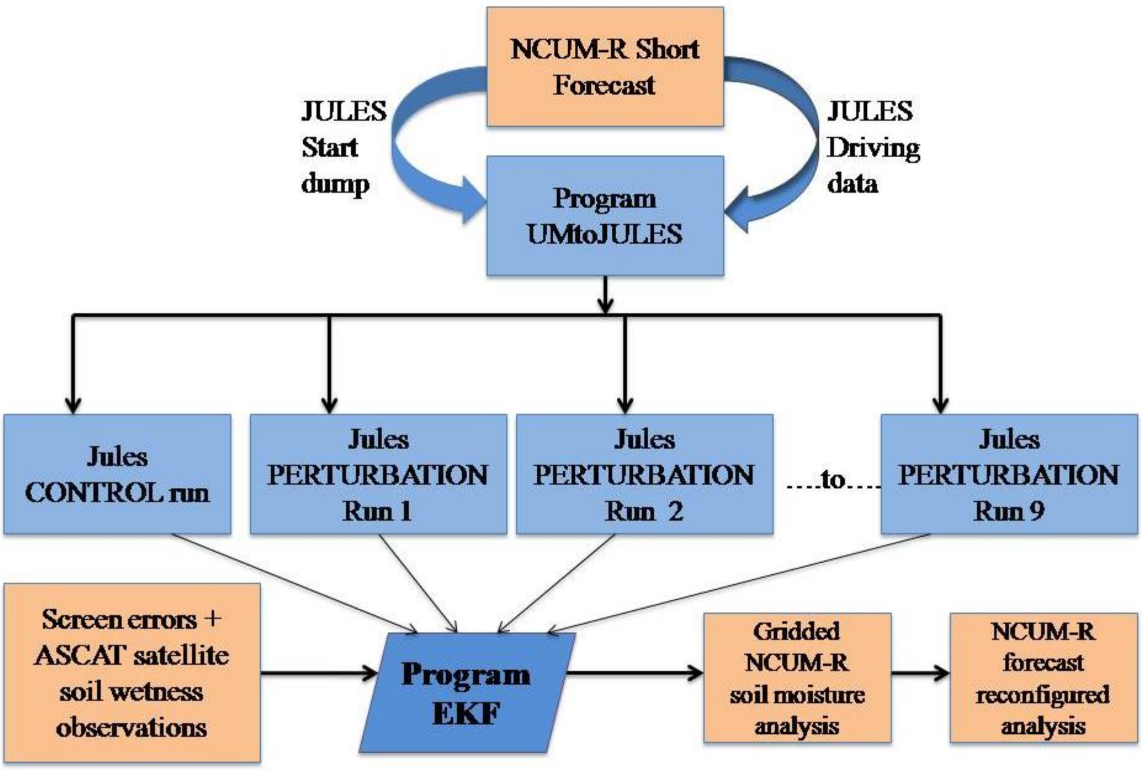

Figure 1: Schematic of the regional Simplified EKF soil moisture data assimilation system

The EKF program reads the ASCAT soil wetness; screen observations andJULESv5.1 model output to perform the task of data assimilation and produce the re-gridded soil moisture (Dharssi et al., 2011) over Indian region.

3. Observations Assimilated in the Regional LDAS

Regional land data assimilation makes use of ASCAT soil wetness observations from MetOp-A and B satellites and analysed screen-level variables (pseudo observations) of 2-metre temperature and relative humidityproduced by 3D-VAR screen analysis system. In the absence of a near-real time dense network providing soil moisture information over India, screen-level analysis of atmospheric variables, which can be related to soil moisture is a major source of information. It provides indirect, but relevant information to infer soil moisture conditions at all grid points of the model.

ASCAT on board of MetOp satellites is operationally providing soil moisture information. The ASCAT level 2 product (Bartalis et al., 2008, Brocca et al., 2017) of soil wetness is available in near real time at 25 km and 12.5 km resolutions.The 12.5 km resolution products are used in the regional LDAS for NCUM-R.

4. Pre-processing of ASCAT Observations

ASCAT is a C band (5.255 GHz) scatterometer on-board Meteorological Operational MetOp series of satellites operated by EUMETSAT. Backscatter measurements of ASCAT are processed to get the information about the soil moisture content. The level-2 ASCAT soil moisture product is the surface soil wetness (m_s). Before its assimilation, ASCAT surface soil wetness (m_s)must be converted to surface volumetric soil moisture content (θ_{Ascat}).

$$\theta_{Ascat} = \theta_{NCUM} + b \times (m_s - m_{clm})$$

Where,

θ_{NCUM} is volumetric soil moisture calculated from the model short forecast

m_{clm} is the monthly climatology of ASCAT surface soil wetness.

b is the parameter, which can be estimated from the slope of the line of best fit through a scatter plot of θ_{NCUM}against m_{clm}.

This process is done with the help of “pre-processing” algorithm which gets the ASCAT retrievals and interpolates them to the Indian limited area model grid (rotated grid).

5. Forecast experiments: Impact of ASCAT assimilation

This section investigates the impact of the assimilation of the ASCAT soil moisture data in the regional LDAS on near surface predictionsgenerated byNCUM-R. For the case study, a monsoon low pressure system (25^{th} to 28^{th}September 2019) over northern plains of India is considered. The details of the synoptic conditions that prevailed during this periodis available at India Meteorological Department (IMD) Monsoon Report-2019.

The high resolution (4 km) NCUM-R analysis-forecast system (Domain size: 62^0E – 107^0E and 6^0S–42^0N; No. of points: 1200 × 1200; Vertical levels: 80) with soil moisture analysis produced by regional LDAS is used in this study. Impact of assimilation of ASCAT soil moisture data in the regional LDAS the simulation of a monsoon low pressure system (25^{th} to 28^{th} September 2019) is studied here. Details of the numerical experiments and observations used in the assimilation are given in Table 1. The high resolution 4D-VAR data assimilation system is used to produce atmospheric analysis for NCUM-R.

Table 1: Details of the numerical experiments carried out in this study

Sl. No.	Experiment Name	Observations used in LDAS	Initialization and forecast length
1	CTL	No ASCAT soil moisture data is used in the LDAS. Only screen level analysis increments of humidity and temperature (pseudo observations) are used.	NCUM-R 72 hour forecasts based on 06UTC initial condition (analysis) are made from 25^{th}-28^{th} September 2019 (Totalof four 72 hoursimulations. Two each for CTL and ASCAT experiments). Soil moisture analysis at 06 UTC is used in all simulations.
2	ASCAT	Both ASCAT soil moisture observations and screen level analysis increments of humidity and temperatures are used.	

The first experiment, called the control (CTL) run of region LDAS utilises only the surface (screen) level analysis of temperature and humidity in the land data assimilation. The second experiment, called the ASCAT, in which soil wetness from ASCAT is also used in this LDAS system in addition to the all observations used in CTL run. It is important to mentionhere that the ASCAT soil moisture observationsare received over India region daily twice as MetOp visits over region close to 06 UTC and 18 UTC time. Therefore, we used 06 UTCinitial conditions (both atmosphere and land) in these experiments. The lateral boundary conditions for the CTL and ASCAT experiments are from NCUM global (12km) forecasts, updated at every three hours. Details of the physical parameterization schemes employed for these experimentsare provided in Dutta et al., 2019. After quality control (QC), the observations are used in the LDAS system for generating the soil moisture analysis. Figure 2a shows the total number of surface(screen) level &ASCAT observations available andthe amount of observations assimilated after quality control. These numbers suggest that good numbers of observations are assimilated in the regional LDAS. Figure 2b represented the spatial distribution of the soil moisture over Indian region at 06 UTC 25th September 2019.

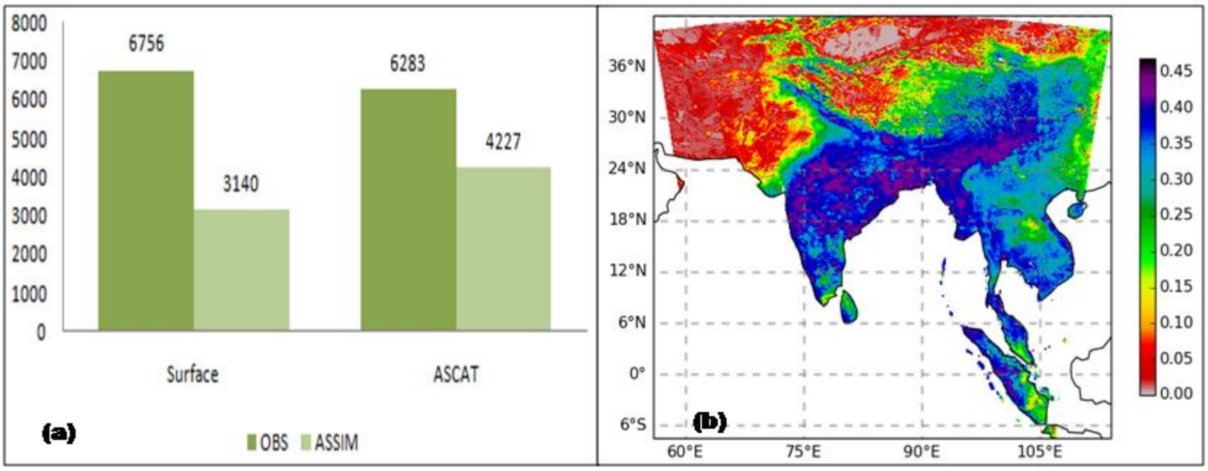

Figure 2: (a) Surface & ASCAT observations available (dark green) and assimilated (light green) in the regional LDAS and (b) Soil moisture analysis (m^3/m^3) of first 10 cm soil level close to surface produced by regional LDAS at 06 UTC 25th September 2019.

Bias in soil moisture analysis from CTL and ASCAT analyses are calculated with respect to European Centre for Medium-Range Weather Forecasts (ECMWF) Land Reanalysis (ERA5-land) data. (Copernicus Climate Change Service (C3S) (2019): C3S ERA5-Land reanalysis. Copernicus Climate Change Service, 2020-06-12 19:39:03 GMT. https://cds.climate.copernicus.eu/cdsapp#!/home). Figure 3 illustrates the bias in soil moisture analyses generated from the CTL and ASCAT experimentsover the monsoon trough region lying between 23^0N-26^0N and 83^0E- 86^0E. Small bias values indicate reasonable match of soil moisture analysis from CTL and ASCAT with ERA5 reanalysis. ASCAT has better match with ERA5 in all days.

Figure 4 and 5 shows the spatial distribution of top layer (i.e., 0-10cm) soil moisture (m^3/m^3); and soil temperature (LST; ^{0}C) from the CTL and ASCAT experiments (analysis) respectively for 06 UTC of 25th September 2019. On 25th September 2019, the ASCAT soil moisture analysis is drier over parts of northern India (Punjab, Haryana and western Rajasthan), whereas wetter over central (eastern Uttar Pradesh, Interior Maharashtra and Madhya Pradesh) and southern parts of India. The wetter land surface state over central India can be attributed to rainfall over the region, which is correctly captured in the ASCAT soil moisture observations. The difference between the soil temperature analysis shows opposite polarity over the same regions.

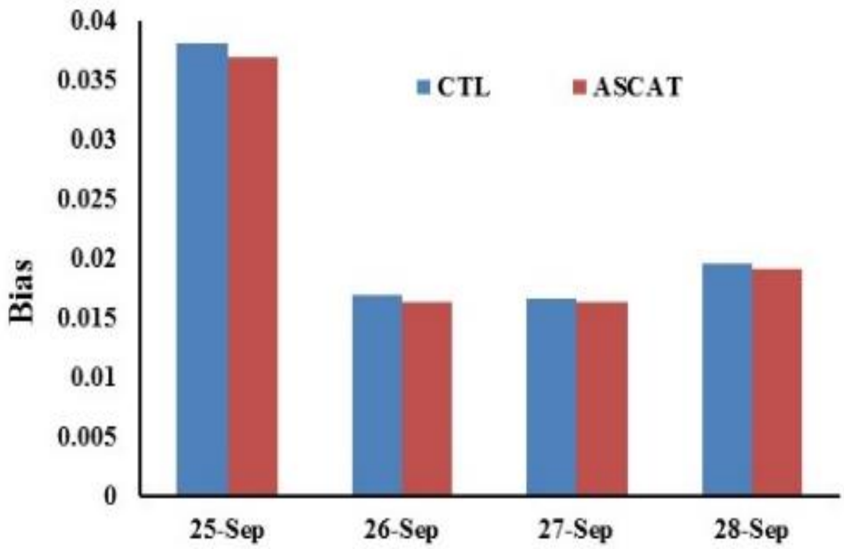

Figure 3: Bias of soil moisture analysis (over the monsoon trough region between 23^0N-26^0N and 83^0E- 86^0E) from CTL and ASCAT with respect to ERA5 reanalysis.

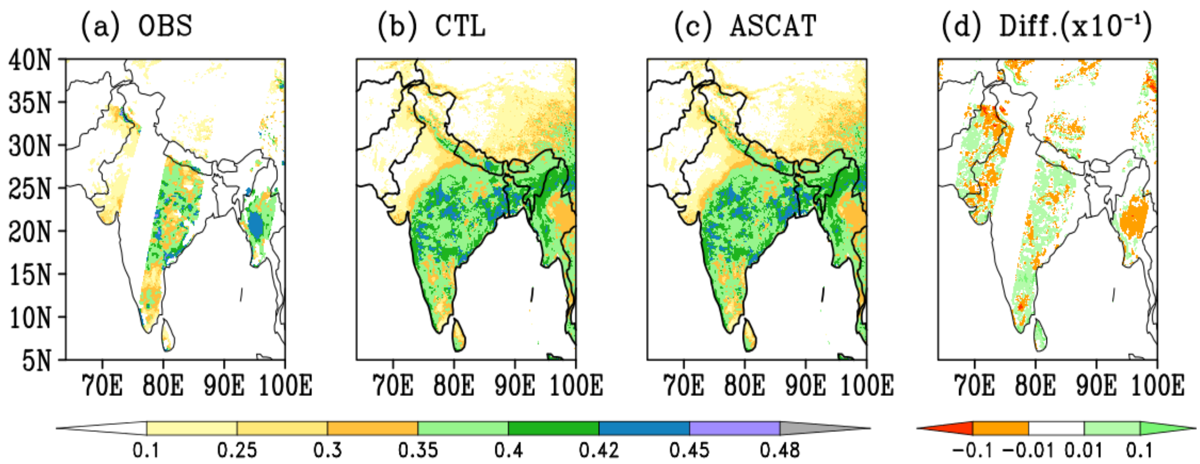

Figure 4: Spatial distribution of soil moisture from (a) ASCAT observations (b) CTL analysis (m^3/m^3) (c) ASCAT analysis and (d) difference between ASCAT and CTL analysis of first soil level close to the surface for 06 UTC 25th September 2019.

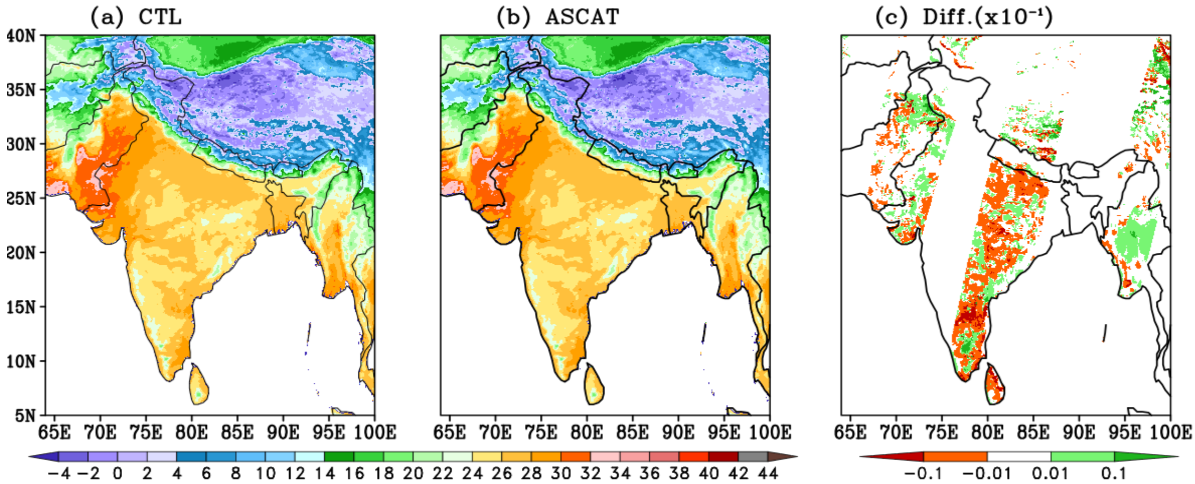

Figure 5: Spatial distribution of soil temperature (°C) from (a) CTL analysis (b) ASCAT analysis and (c) difference between ASCAT and CTL analysis of first soil level close to surface for 06UTC 25th September 2019.

Figures 6 and 7 shows the time series of model simulated 2m level temperature (T_{2m}) and dew point temperature (T_d) for 0-24 hour forecast valid for Delhi (Indira Gandhi International airport (IGI), New Delhi) compared with the IMD observations at IGI, Delhi. The forecast is based on the initial condition of 06 UTC of 25th September 2019. The simulated diurnal variation of 2m level temperature (Figure 6) and dew point temperature (Figure 7) from the ASCAT experiment matches reasonably well with the IMD surface (METAR) observations as compared to that from CTL simulation. In the CTL experiment there is an underestimation of the surface dew point temperature throughout the forecast period. The correlation and root mean square error (RMSE) are significantly improved in the ASCAT experiment as compared to the CTL experiment. Validation of the model simulated near surface meteorological variables reveals that assimilation of ASCAT soil moisture observations in the NCUM-R system reduced bias of the predicted near surface variables and improved the correlation with observations. These preliminary results indicate a beneficial impact of the assimilation of ASCAT soil moisture in the regional LDAS on the prediction ofnear surface variables by NCUM-R.

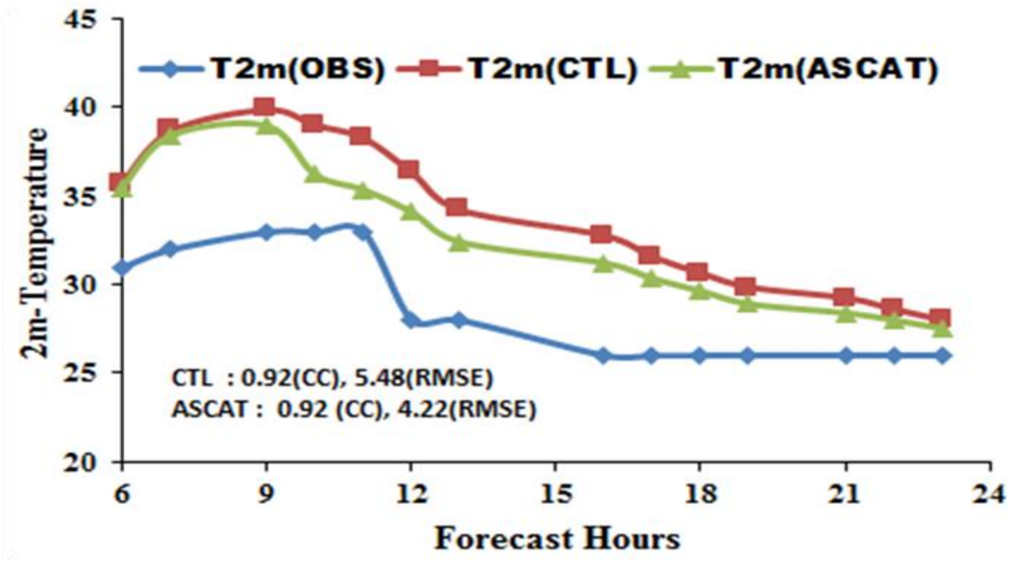

Figure 6: Hourly Time series of NCUM-R simulated 2-metre (atmospheric) temperature (T_{2m}; ^{0}C) from CTL and ASCAT experiments for 0-24 hour forecast based on the initial condition of 06 UTC of 25thSeptember 2019 and corresponding surface meteorological observations of IMD (IGI airport, New Delhi).

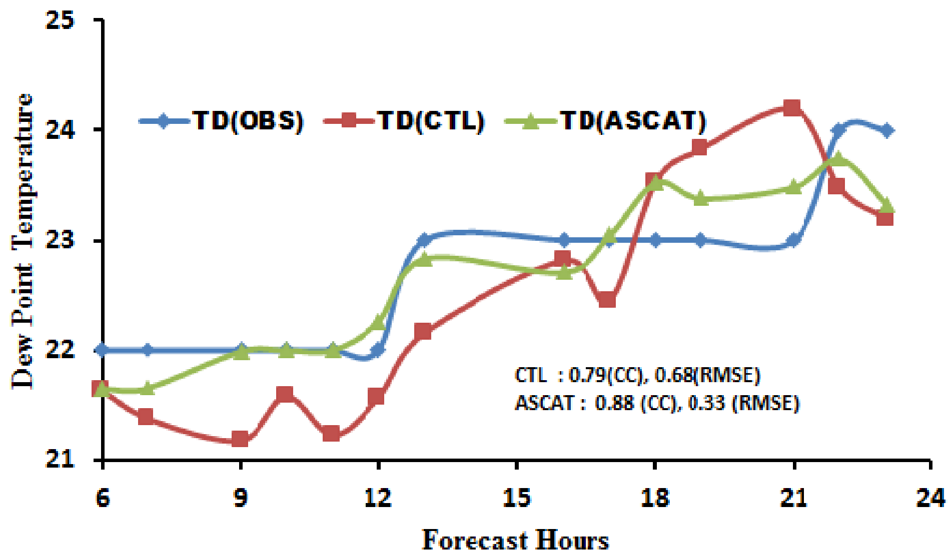

Figure 7: Same as Figure-6 but for dew point temperature (T_d; ^{0}C).

The spatial distribution of mean errors of the maximum temperature forecasts (Day-1, Day-2 & Day-3) from CTL and ASCAT experiments based on 06 UTC of 25th September, 2019 initial condition is depicted in Figure-8. The mean error in the temperature forecasts is calculated with respect togridded IMD maximum temperature observations(available over Indian region). The mean error of ASCAT experiment is slightlyreduced, in general, in all days of forecast compared to CTL simulations. However, the reduction of the error is more prominent in the Day-1 forecast than Day-2 and Day-3 forecasts. It can be concluded that the beneficial impact of the assimilation of the ASCAT soil moisture is retained only in the short range forecasts of maximum temperature and gradually reduced with increase of forecast lead time.

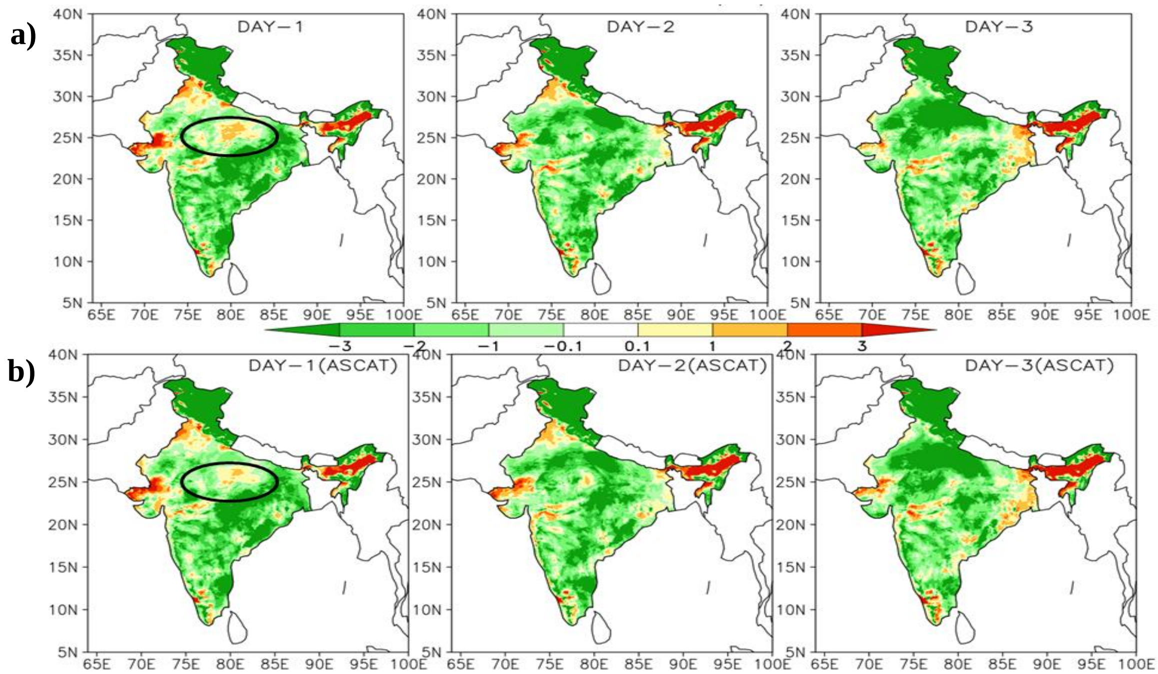

Figure 8: Spatial distribution of mean error of maximum temperature forecast of 26th, 27th and 28thSeptember 2019 respectively (Day-1, Day-2 and Day-3) based on 06UTC, 25th September 2019analysis for (a) CTL and (b) ASCAT experiment.

The vertical structure of vorticity in the three day forecastsfrom CTL and ASCAT experiments based on 06 UTC of 26thand 28th September, 2019 initial condition is depicted in Figure 9. Figure 9a shows that the monsoon low extends in the vertical upto 400 hPa level in the ERA5 reanalysis (Hersbach et al., 2020) with vorticity 2.5-3 $\times 10^{-5} s^{-1}$ on 18 UTC 27th September 2019. The CTL and ASCAT experiment results (Figure 9b and c) show that vorticity with 2 $\times 10^{-5} s^{-1}$ extends upto 500 hPa on 18 UTC 26th September 2019, but the magnitude of the vorticity is higher in the ASCAT, closer to ERA5. From the forecasts based on initial condition of 06 UTC 28th September 2019 (Figure 9e-f), it can be seen that once the easterlies are set over the domain (19^0N-26^0N and 75^0E- 86^0E), the core of the cyclonic vorticity (>3 $\times 10^{-5}$ s^{-1}) extends upto 300 hPa similar to that seen in ERA5 reanalysis (Figure 9d). In the lower levels also, the structure of vorticity in ASCAT forecast is closer to the ERA5 reanalysis.

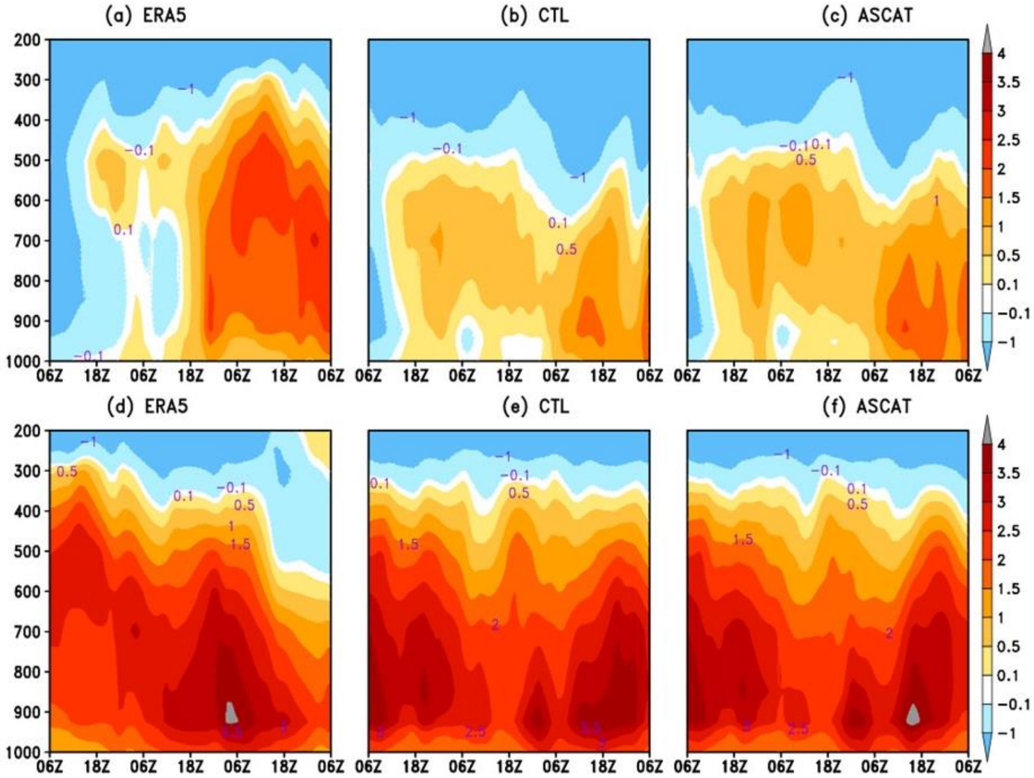

Figure 9: Time-pressure cross section vorticity (x $10^{-5}s^{-1}$) over the domain, 19^0N-26^0N and 75^0E- 86^0E, (a) ERA5 reanalysis; (b) CTL and (c) ASCAT for forecast based on 06 UTC of 26th September 2019 (Abscissa: Forecast period of 06 UTC of 26th to 29th September 2019). (d-f) are same as (a-c) but for forecast based on 06 UTC of 28th September 2019(Abscissa: Forecast period of 00 UTC of 28thSeptember to 1st October 2019.

6. Conclusions

A regional Land Data Assimilation System based on Simplified Extended Kalman Filter method is developed at NCMRWF for its high resolution regional model (NCUM-R). Currently this system is capable to produce soil moisture analysis, using ASCAT satellite observations and screen analysis. Impact of assimilation of ASCAT soil observations in this regional LDAS system on NCUM-R forecast during a monsoon trough period is also investigated and presented. Results from numerical experiments (with and without assimilation of ASCAT soil moisture in the regional land assimilation system) indicatethat near surface forecasts are improved with the use of ASCAT in the land data assimilation. It is also seen that NCUM-R forecast of large scale monsoon conditions in ASCAT experiments has a better match with ERA5 reanalysis. The results of the experiments show positive impact of the use of remotely sensed soil moisture observations on high resolution numerical weather forecasts.

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