# Initialization of Soil Moisture in Numerical Weather Prediction

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# Importance of Soil Moisture

- Soil moisture content is one of the most important variable that affect the water cycle and energy balance through land–atmosphere interactions.

- The Indian monsoon zone is a major ‘positive soil moisture feedback hot spot' where soil-moisture variations have a significant impact on the precipitation even on the synoptic timescale.

Boreal summer, ‘positive soil moisture feedback hot spots’ include central United States, North Africa, northern Brazil, western Eurasia. Hot spots for austral summer include Amazon, Congo, Australia, Indonesia, Mexico, and southwest United States.

# Soil Moisture in NWP

- The earth surface serves as a lower boundary condition for the Numerical Weather Prediction (NWP) model - So the surface boundary conditions have a very important influence on the weather forecast.
- Land Surface Models (LSM) provide surface boundary conditions to atmospheric models in the coupled NWP system. LSM determine the partitioning of the energy into latent and sensible heat fluxes - these fluxes provide the main link between the surface and the atmosphere.
- LSMs have been improved considerably over the years. Still there are a lot of uncertainties and errors in the models

# Soil Moisture Initialization in NWP

- Studies have shown that soil moisture initial condition has significant influence on the predictability from short-range to seasonal time scales – but often overlooked in the past.

- Land surface models simulate soil moisture (and other land surface variables). But more realistic estimates of soil moisture can be obtained by assimilating observations of soil moisture.

# Soil Moisture Assimilation

The success of the assimilation depends on the choice of the assimilation technique, the nature of the model, the assimilated observations and the characterization of model and observation errors.

# Observations

**Soil moisture is highly variable and depends on the precipitation, land cover, and soil texture.**

**For this reason, a satellite observation with a wide horizontal coverage is more useful than point data by in-situ measurements. In-situ measurements have the problem of representativity - associated to large land surface heterogeneity.**

Satellite Soil Moisture Estimates are currently available from:

- ASCAT in MetOp satellites
- SMOS
- AMSR2/GCOM-W1
- SMAP

# Soil Moisture Assimilation- Methods

- Extended Kalman Filter (EKF) is one of the popular data assimilation method used in Soil Moisture assimilation. NCMRWF uses a Simplified EKF system (UM based system) for Soil Moisture assimilation.
- This scheme takes in account non-linearities of the soil moisture observation operators. Furthermore, this system allows a wide range of satellite products to be used, combined with other observations.

The cornerstone of the EKF is the Jacobian of the observation operator. The Jacobian describes the sensitivity of the screen-level observations to changes in the soil prognostic variables. Mahfouf et al. (2009) suggest to calculate the Jacobian with a finite differences approach, using a reference run and one perturbed run for each of the soil prognostic variables.

# Soil Moisture Assimilation - NCUM

- **Two Soil Moisture estimates are being used in the NCUM assimilation system**

  - Satellite retrieved near-surface soil moisture.

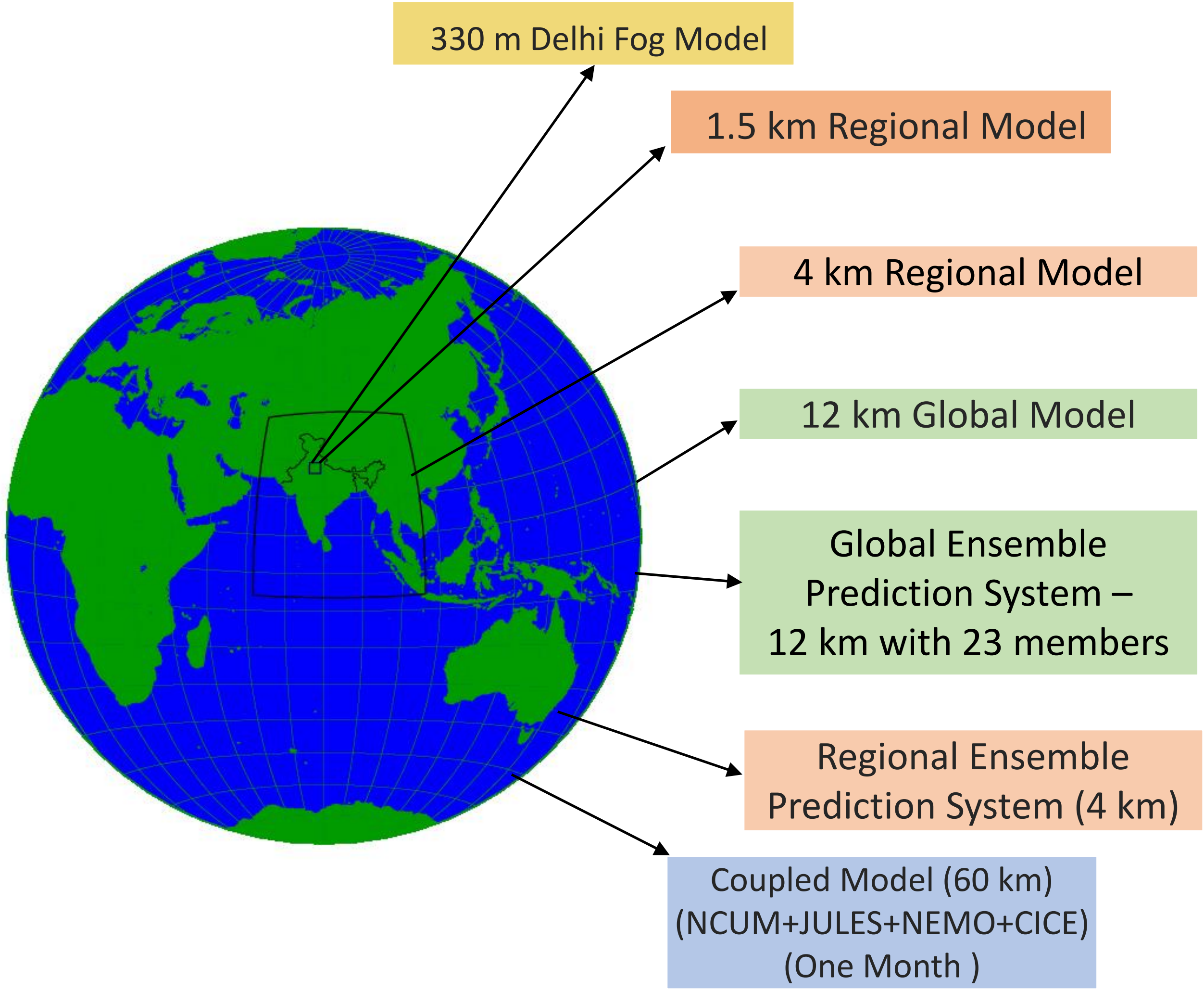
  - Pseudo-observation : Soil moisture information obtained from screen-level atmospheric observations of temperature and humidity.

Douville et al. (2000) suggests to use screen-level temperature and screen-level relative humidity as indirect observations for soil moisture content and soil temperature.

ASCAT retrieval data available in near-real time is widely used in operational NWP models (e.g. UM of UK Met office, IFS of ECMWF, NCMRWF NCUM etc)

Both the observations have near-global coverage.

# NCMRWF Unified Model (NCUM) Assimilation-Forecast System (Unified Model based System)




- NCUM Global Model (12km) with **Hybrid 4D-Var Data Assimilation (Atmosphere)** and Extended Kalman Filter based Land Data Assimilation
- NCUM Regional Model (4 km) with **4D-Var Data Assimilation**
- Sri Amarnathji Yatra model (1.5 km) (Only during Yatra) (downscaled initial condition)
- 330 m Delhi fog model based on NCUM (Only during winter) (downscaled initial condition)
- NCMRWF Global Ensemble Prediction System (NEPS) (12 km / 22 +1 members) with **Ensemble Transform Kalman Filter (ETKF) for Initial condition perturbations**
- Regional NEPS (4 km /11 member)
- Coupled Model with **Data Assimilation for Atmosphere (Hybrid 4D-Var), Ocean (3D-Var),Sea Ice (3D -Var) and Land (EKF)**

# Global NCUM Global NWP System

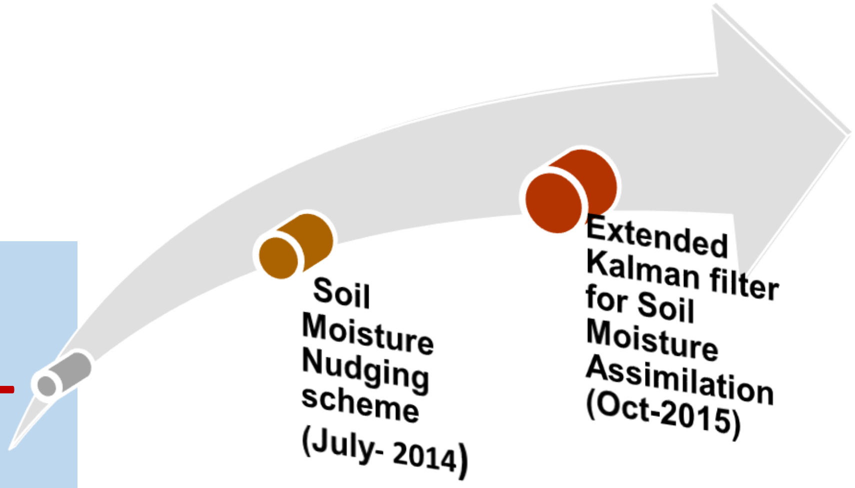
## Salient Features of NCUM Assimilation–Forecast System

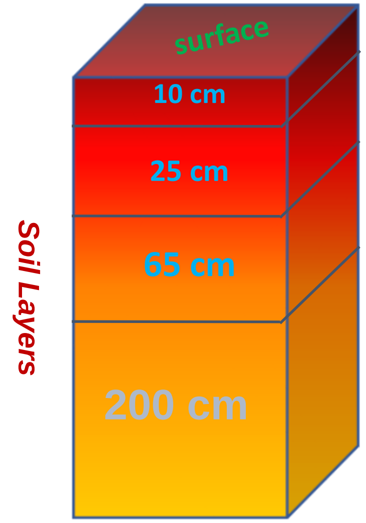
| Model | Atmospheric Data Assimilation | Surface Analysis |
|---|---|---|
| **Model:** Unified Model; Version 11.2<br>**Domain:** Global<br>**Resolution:** 12 km, Levels 70 (80 km height)<br>**No. of Grids:** 2048x1536<br>**Time Step:** 5 minutes<br>**Physical Parameterizations:** based on GA7.2(Walters et al)<br>**Dynamical Core:** ENDGame<br>**Operational Forecast length:** 10 days (based on daily 00 UTC and 12 UTC initial conditions) | **Method:** *Hybrid 4D-Var*<br>Hybrid incremental 4D-Var. Information on "errors of the day" is provided by NEPS forecast at every data assimilation cycle<br>**Data Assimilation Cycles:** ***4 analyses per day*** at 00, 06, 12 and 18 UTC. Observations within +/- 3 hrs from the cycle time is assimilated in respective DA cycle<br>**Observations:** ***Satellite & Conventional Observations***<br>• Observations received at NCMRWF from GTS (IMD) and various satellite data producers (NOAA/NESDIS, EUMETSAT, ISRO etc.) are used for assimilation.<br>• Observation Processing System does the quality control of observations. Variational bias correction is applied to satellite radiance. | Soil Moisture Analysis *Method:* Simplified Extended Kalman Filter (EKF)<br>*Analysis time:* 00, 06, 12 and 18 UTC<br>*Observations assimilated:* ASCAT soil wetness observations, Screen level Temperature and Humidity ( 3D-Var screen analysis)<br>**Sea Surface Temperature:** Updated at 12 UTC DA cycle with OSTIA based SST and sea-ice analysis<br>**Snow Analysis:** Satellite-derived snow analysis. Updated at 12 UTC DA cycle |

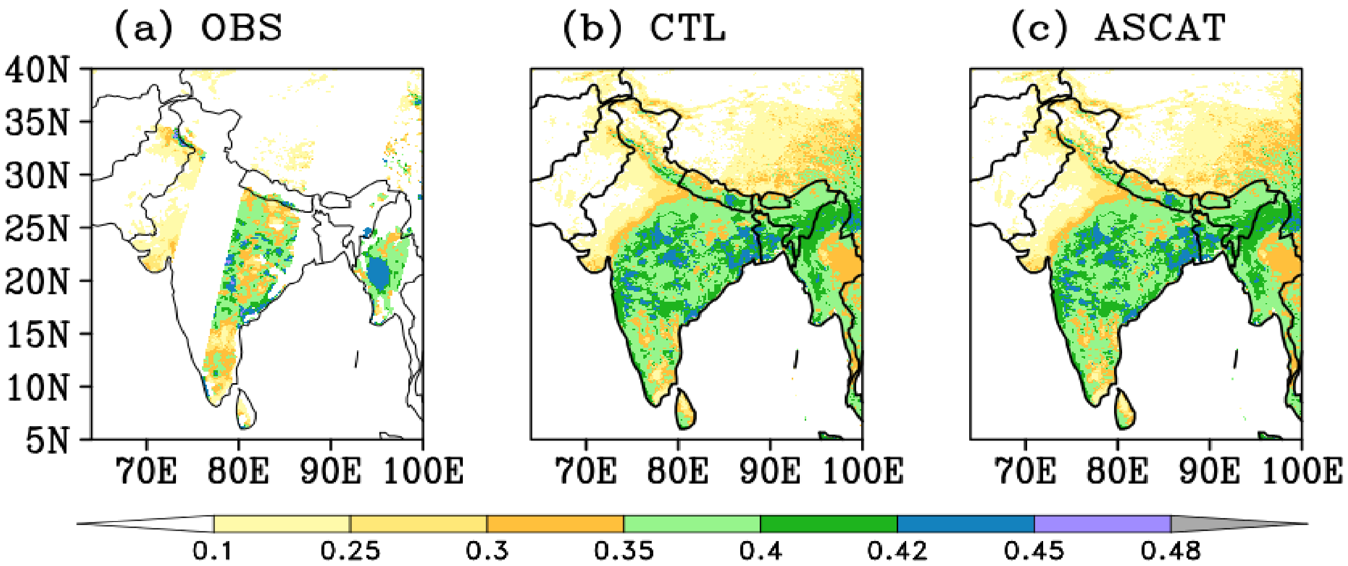
# Observations Assimilated in NCUM Global System

| | | | | |
|---|---|---|---|---|
| Conventional Observations | Surface | | | Land Synop (TAC, BUFR), Ship (TAC, BUFR), BUOY, TC BOGUS |
| | Profile | | | PILOT, TEMP (RS/RW- Both TAC and bufr), Wind Profiler Drop sonde (+ DWR VAD Winds) |
| | Aircraft | | | AMDAR, AIREP |
| Satellite Observations | HLOS Wind | | LEO | ALADIN (Aeolus) |
| | Satellite Wind | AMV | GEO | INSAT-3D, Meteosat-8, Meteosat-11, Himawari, GOES-16, GOES-17 |
| | | | LEO | MetOp-A, MetOp-B, NOAA-15, NOAA-19, NOAA-20, AQUA, TERRA, SNPP, |
| | Scatterometer wind | | LEO | ASCAT (MetOp-A), ASCAT (MetOp-B), ASCAT (MetOp-C), Scatsat, Windsat (Coriolis) |
| | Satellite radiance | IR | GEO | INSAT-3D Imager, SEVERI (Metosat-8), SEVERI (Metosat-11), GOES Imager (GOES-15), AHI (Himawari-8), INSAT-3D Sonder, ABI (GOES-R) |
| | | IR (HyS) | LEO | IASI (MetOp-B), IASI (MetOp-C), AIRS (AQUA), CrIS (SNPP), CrIS (NOAA-20) |
| | | MW | LEO | AMSU-A (MetOp-B), AMSU-A (MetOp-C), AMSU-A (NOAA-15), AMSU-A (NOAA-18), AMSU-A (NOAA-19), MHS (MetOp-B), MHS (MetOp-C), MHS (NOAA-19), MT-SAPHIR, ATMS (SNPP), SSMIS (DMSP-F17), AMSR-2 (GCOM-W1), FY3C, GMI (GPM), ATMS (NOAA-20) |
| | GPSRO | Bending angle | LEO | COSMIC-2, GRAS-A, GRAS-B, TanDEM-X, TerraSAR-X, FY-3C |

# Soil Moisture Assimilation Systems – Global NCUM

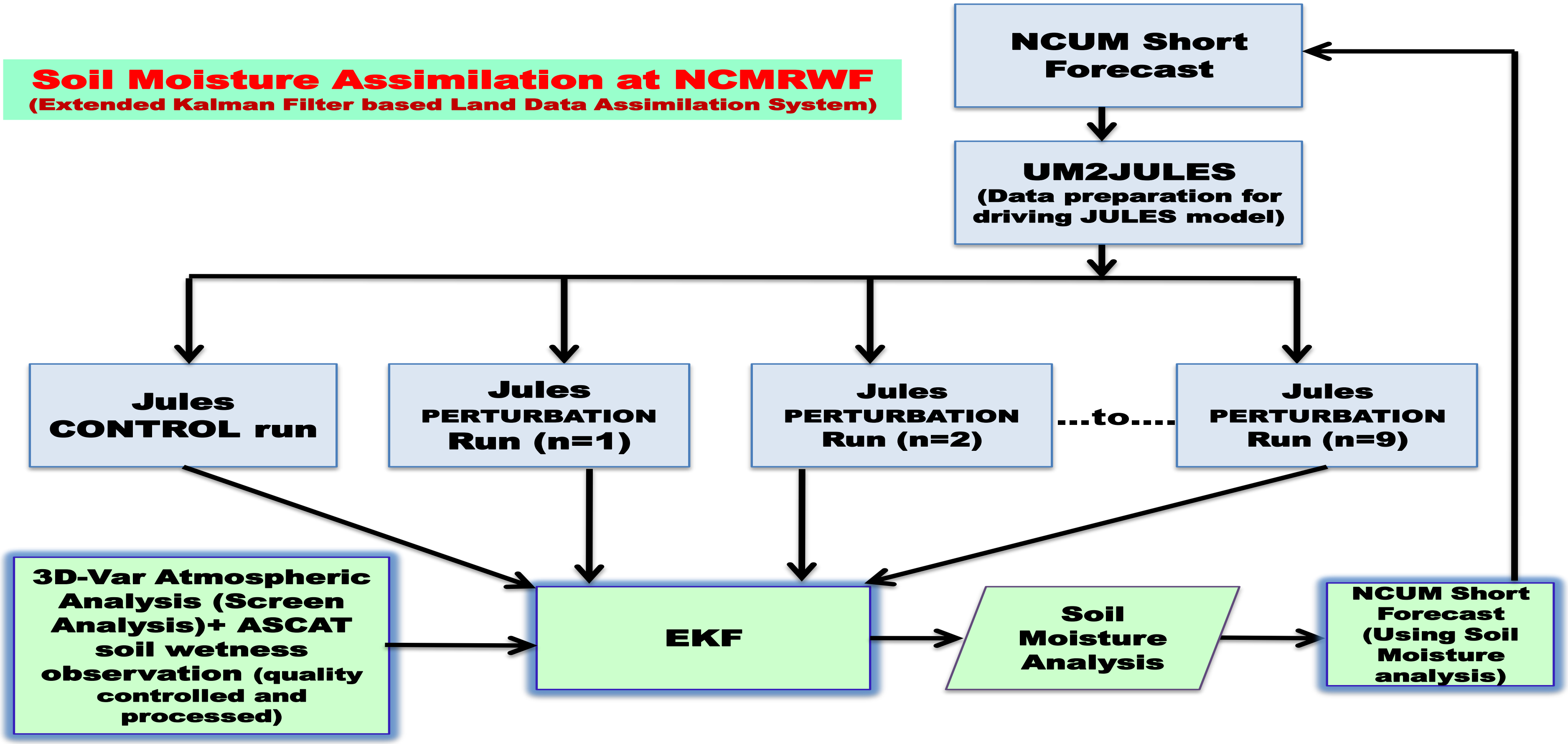


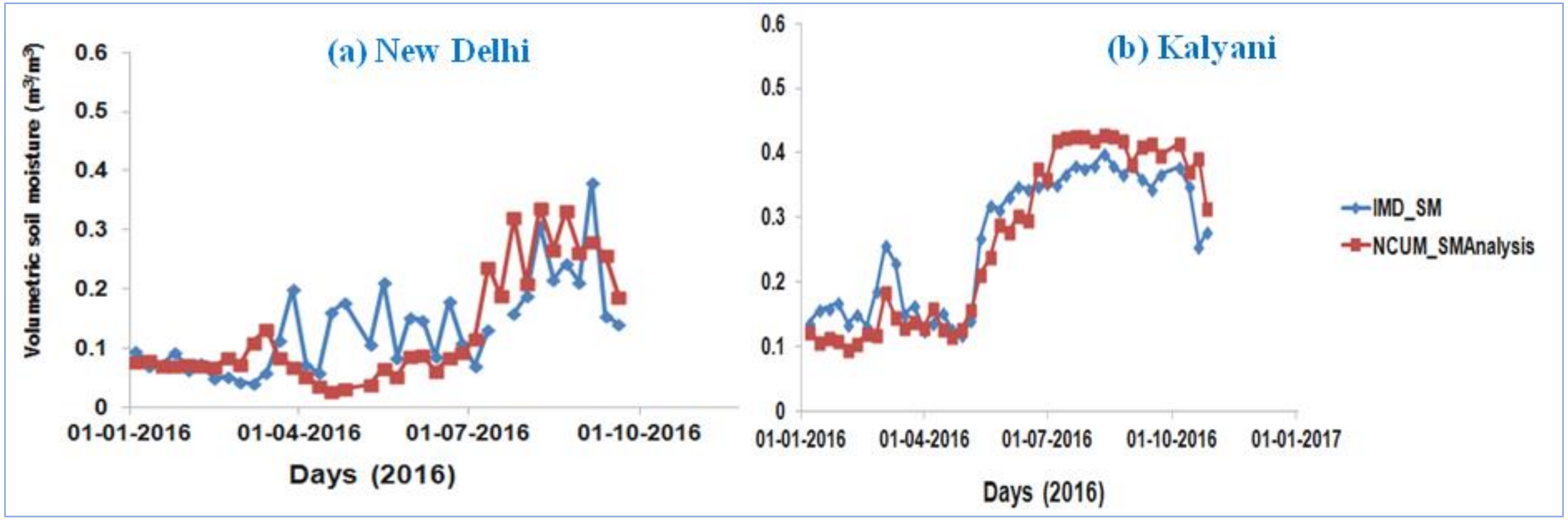

*Spatial distribution of soil moisture from (a) ASCAT observations (b) CTL analysis ($m^3/m^3$) (using only pseudo obs) (c) ASCAT analysis (pseudo + ASCAT) of first soil layer (10 cm) close to the surface valid for 06 UTC 25$^{th}$ September 2019.*

# Schematic of EKF based Land data assimilation system at NCMRWF



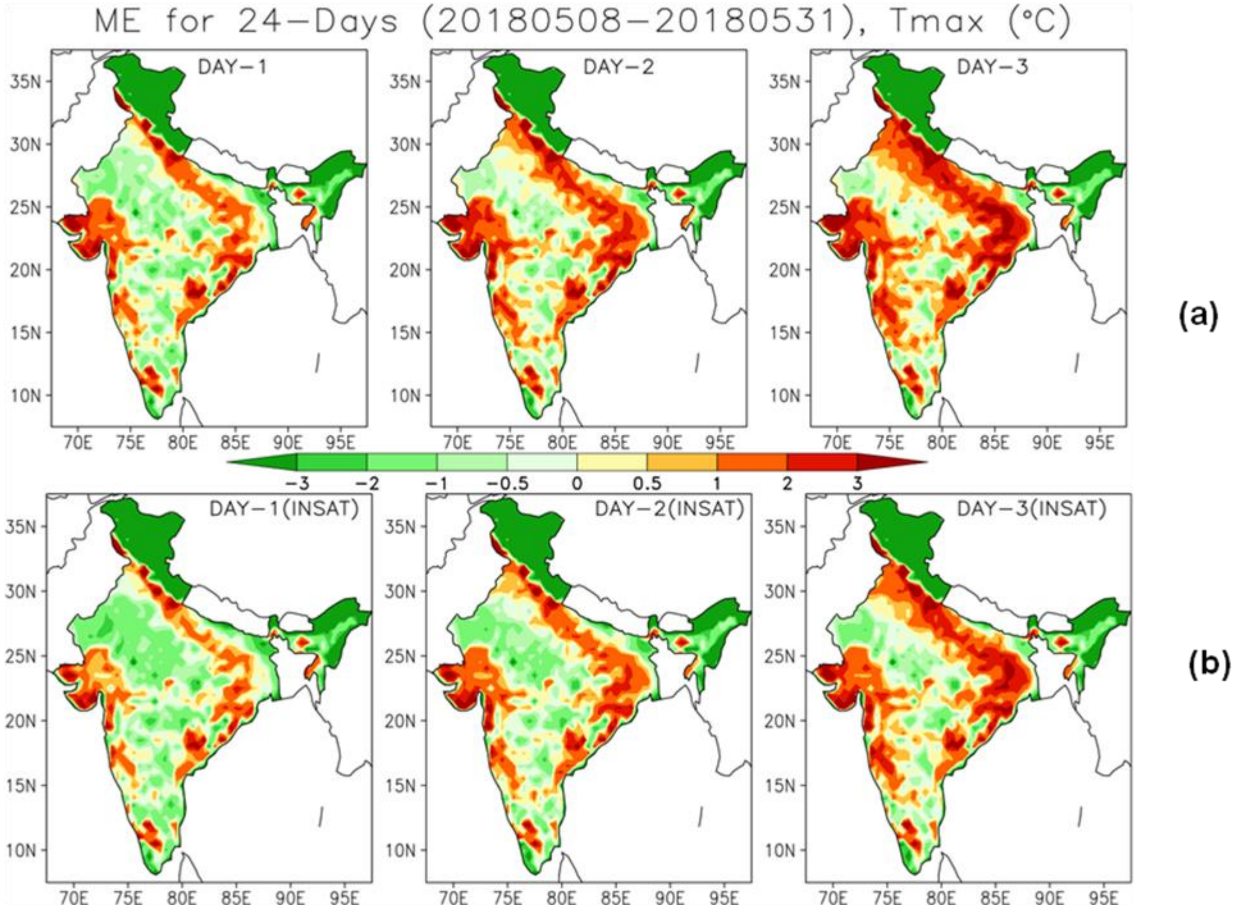

(JULES: the Joint UK Land Environment Simulator)

# *Verification of Soil Moisture Analysis (EKF system with ASCAT and Screen Obs) against in-situ observations*



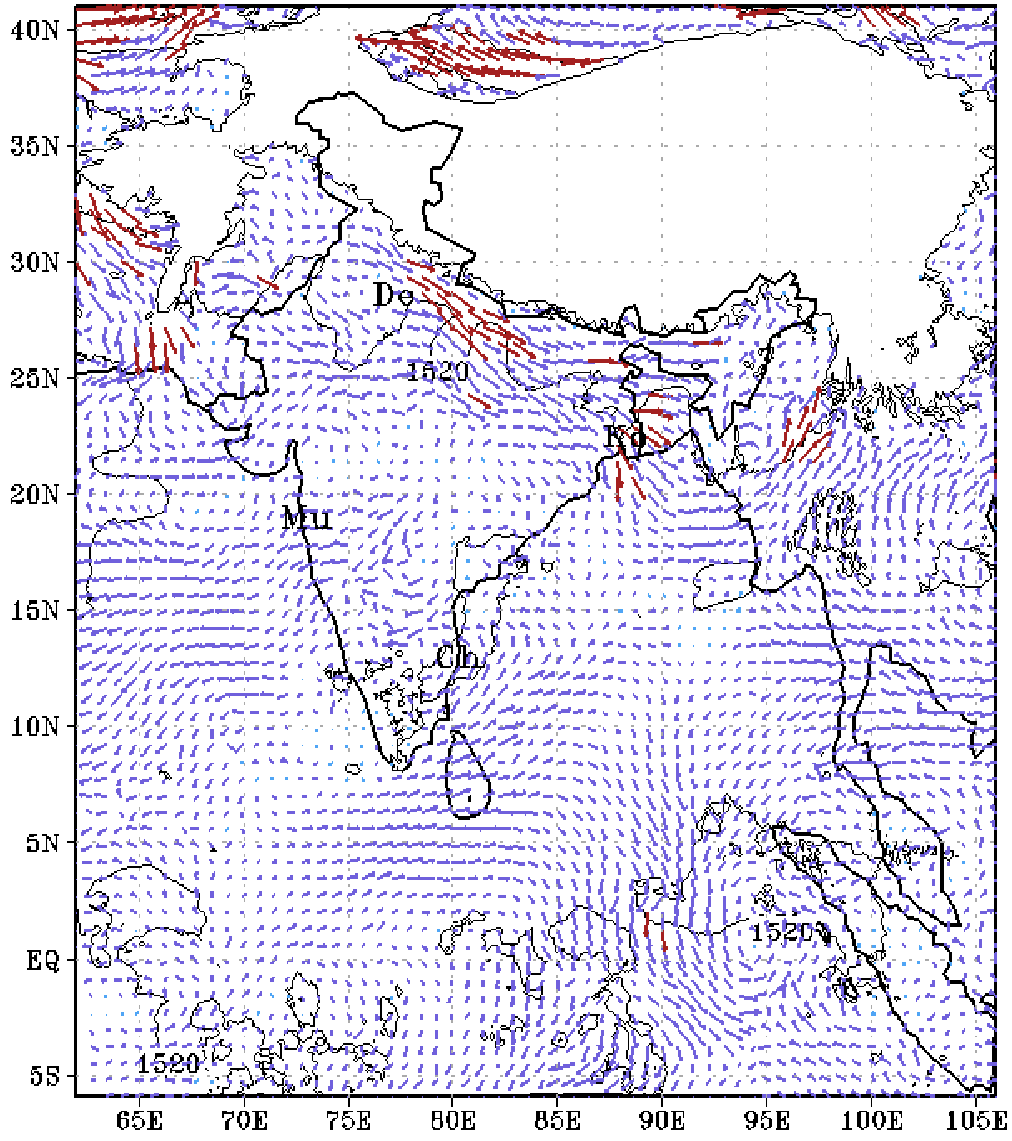
## Land Surface Temperature (Skin Temperature) assimilation

### Assimilation of INSAT-3D skin temperature in EKF assimilation system




***Spatial distribution of mean error in surface maximum temperature for (a) CONTROL experiment and (b) for INSAT sensitivity experiment for 24 days from 20180508 to 20180531.***

# High Resolution (4km) Regional NCUM




| Regional NCUM System | |
|---|---|
| Model Resolution | 4 km |
| Grid | 1200 X 1200(50-110°E, 5-45°N) |
| Vertical Levels | 80 (Top ~38.5 km) |
| Forecast Length | 72 hours |
| Data Assimilation (DA) Method | Incremental 4D-Var |
| Observation | Satellite, Radar and Conventional Observations |

| Soil Moisture Assimilation | |
|---|---|
| Soil Levels | 4 |
| Data Assimilation (DA) Method | Simplified Extended Kalman Filter method |
| DA Frequency | 6 hours |
| Observation | Satellite: ASCAT Soil Moisture (MetOp-A and MetOp -B)<br>Pseudo observations: Screen level Temperature and Humidity |

# Sensitivity of ASCAT observations on the forecast of Monsoon Depressions: Case studies

Impact of ASCAT soil wetness/soil moisture data on the simulation of inland moving monsoon depressions over Indian region using high resolution NCUM-R regional forecast system is studied.

Monsoon Depression (MD) is a synoptic scale cyclonic circulation forms during Indian summer monsoon season (June to September) (~ 6 per season) (having surface wind speed of 17 - 27 kts), which leads to heavy to very heavy rainfall events.

The MDs and monsoon lows are major contributors to monsoon rainfall due to their frequencies, strength and longevity

**Three Monsoon Depression are studied:**

**Case 1: 21-23 July 2018**

**Case 2: 15-18 August 2018**

**Case 3: 4-8 August 2019**

# Details of the Study

The soil moisture initial conditions for NCUM-R has been created using the EKF assimilation system

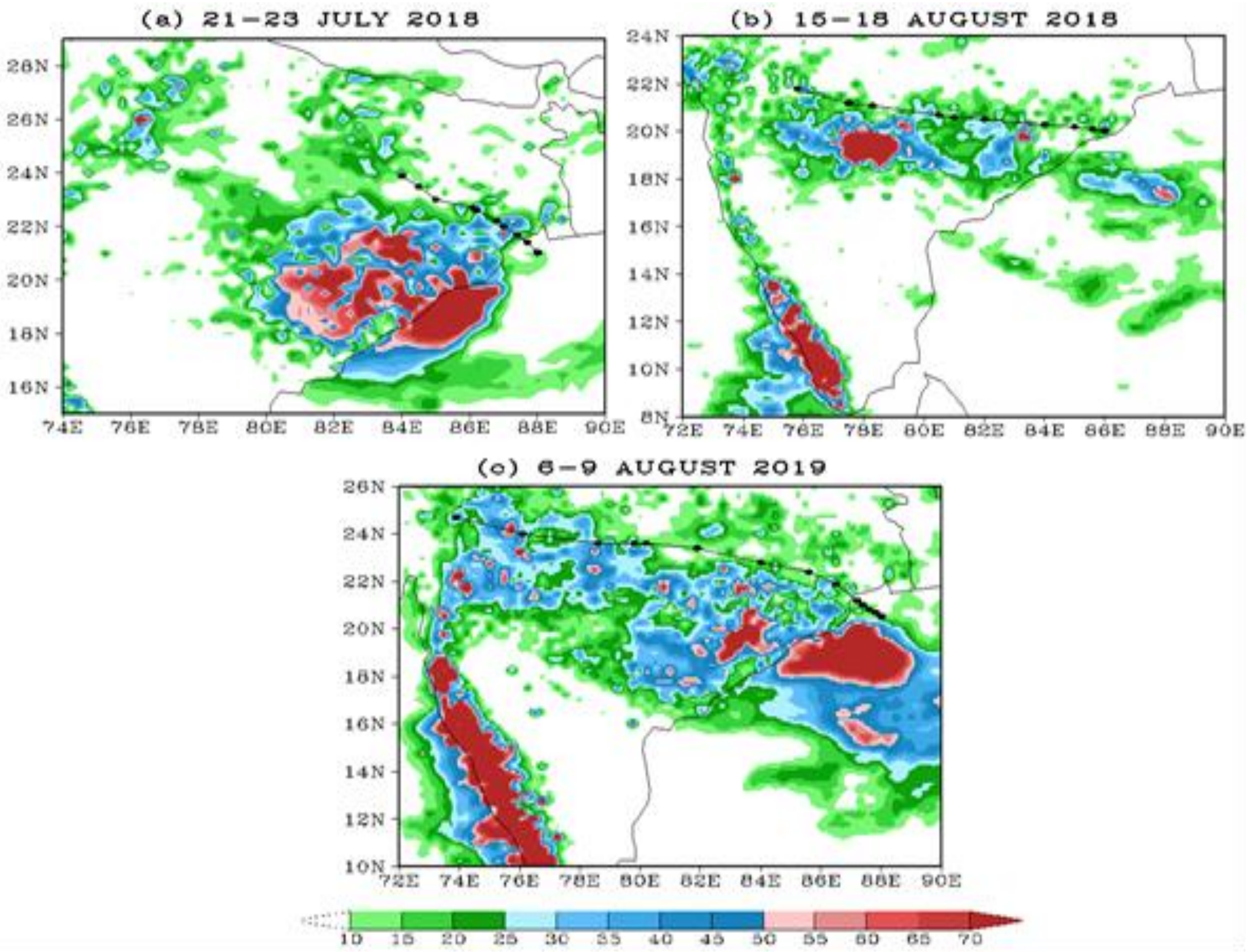
Two numerical experiments namely

**CTL (assimilating only screen level observations) and**

**ASCAT (both ASCAT and screen level observations in assimilation)**

Identical atmospheric initial condition prepared using incremental 4D-VAR data assimilation system is used in both experiments.

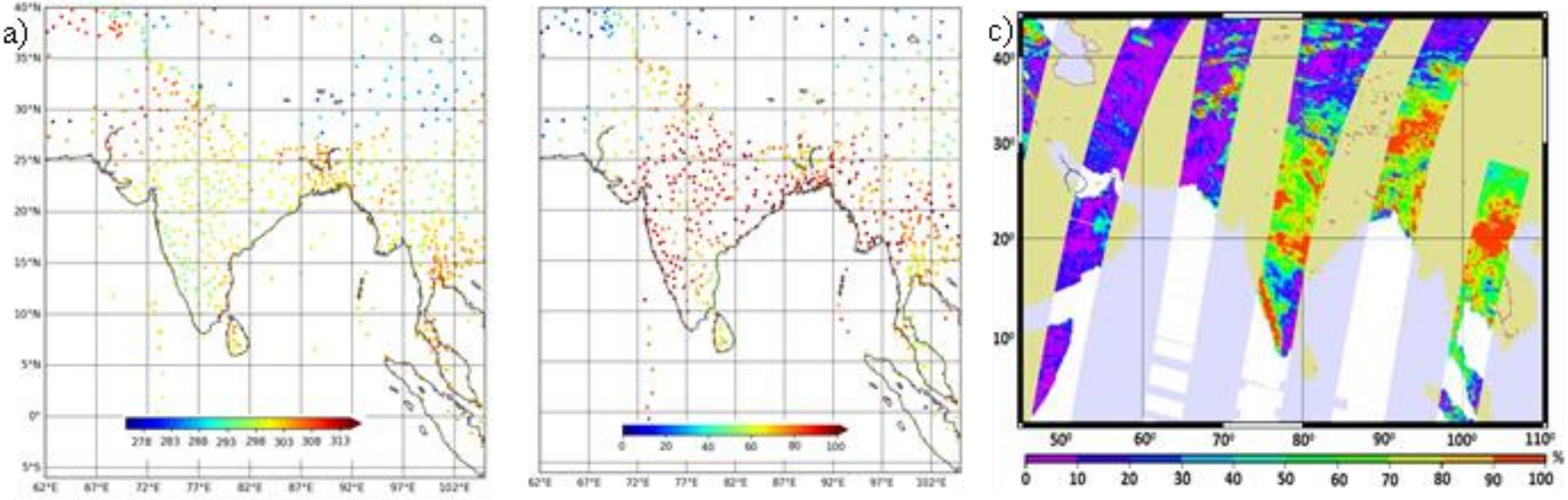
# Monsoon Depression-Track & Rainfall from Observations




Tracks of the MD and the accumulated observed rainfall for 3 days associated with the system.

# Observations Assimilated (Case 1)

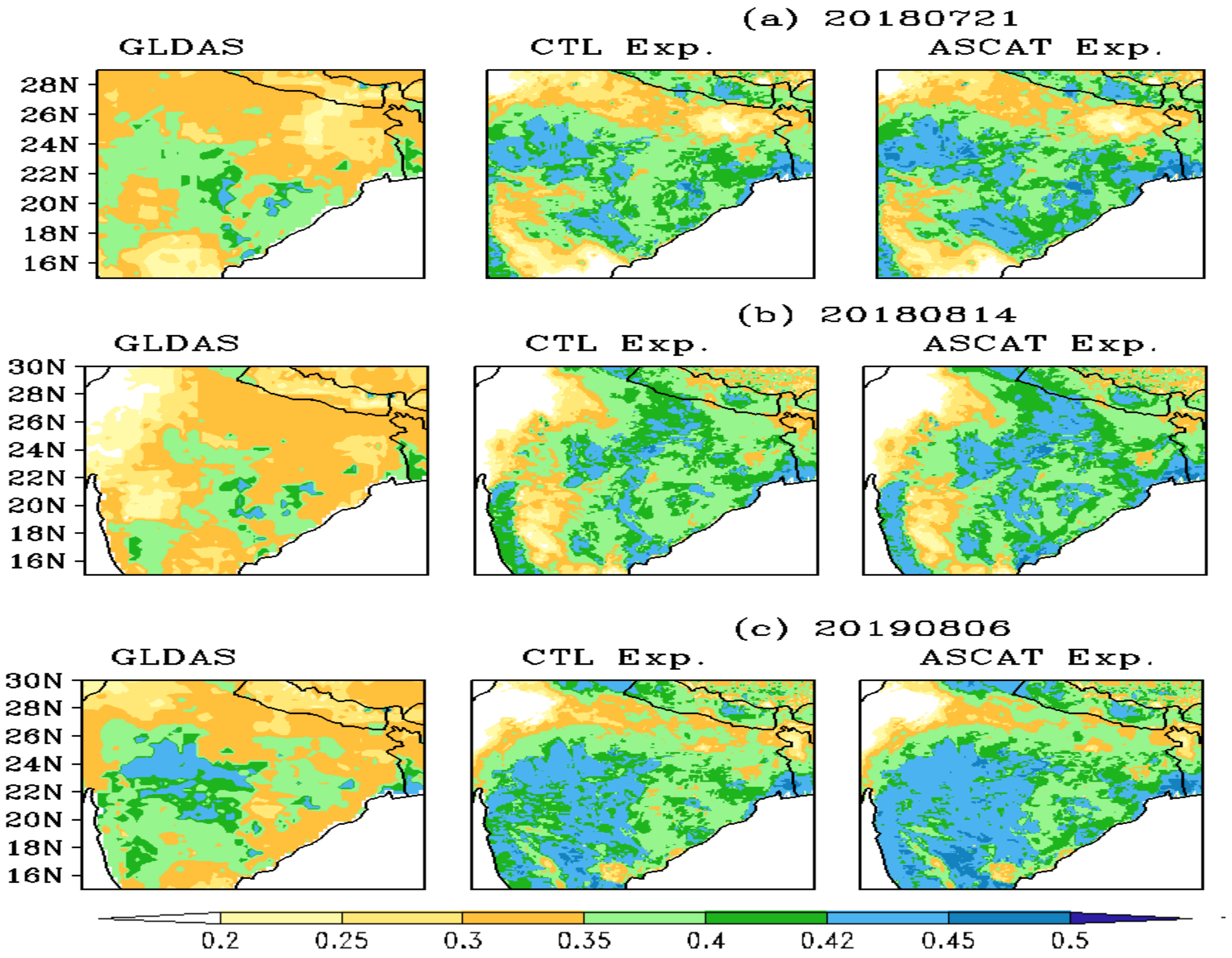
**(06 UTC 21$^{st}$ July 2018)**




Spatial distribution of a) Temperature (K); b) Relative humidity (%) at near-surface level from SYNOP observations and c) Soil moisture (SM) from ASCAT satellite

# Soil Moisture Analysis – Comparison

**The spatial distribution of top layer (0-10 cm) SM ($m^3/m^3$) from both the analyses (CTL and ASCAT) are compared with the Global Land Data Assimilation System (GLDAS) analysis for all cases**

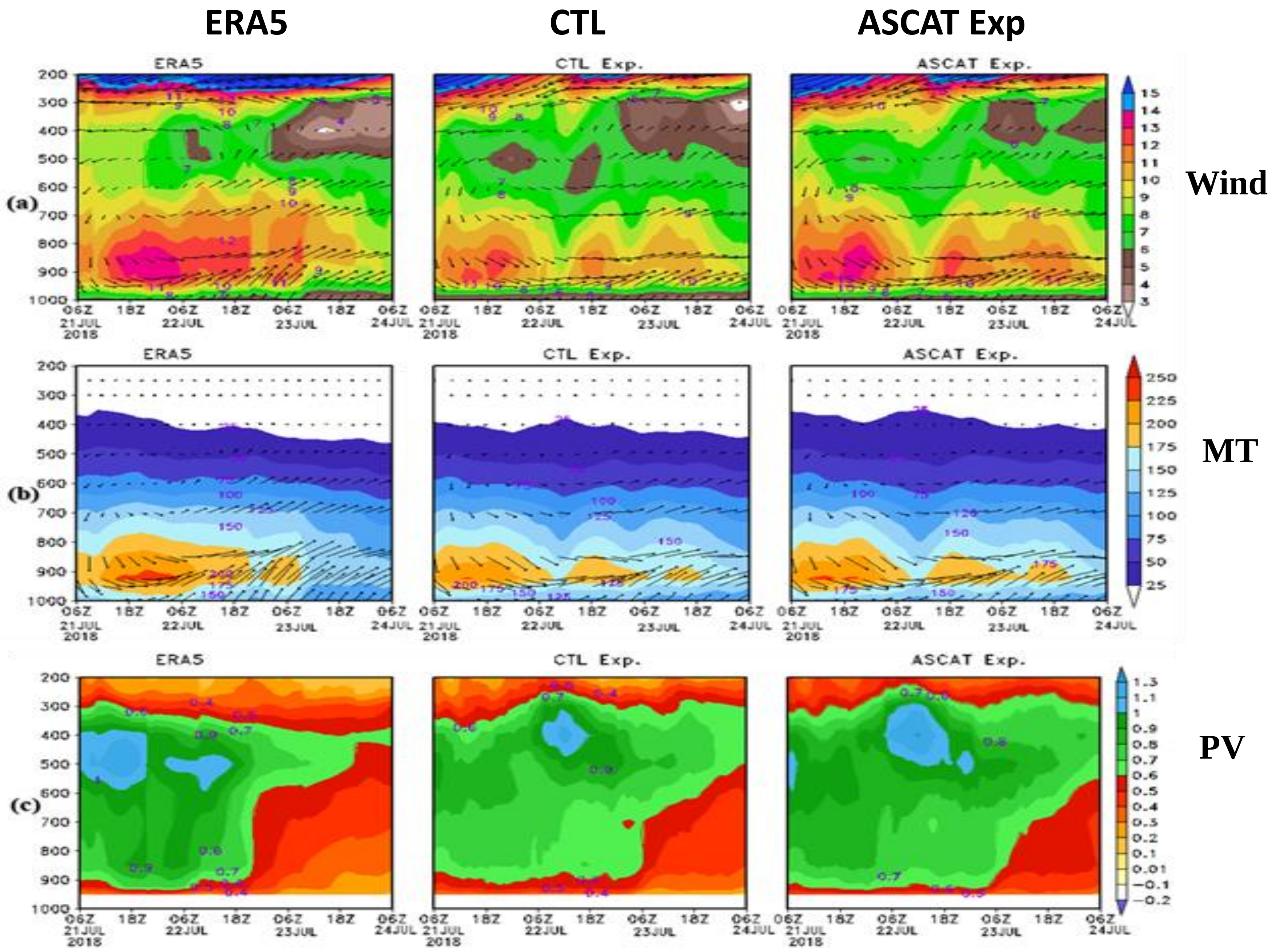


# Simulation Results

**The spatial averaged (19-24°N and 83-88°E) time-level cross section** of wind ($m.s^{-1}$); moisture transport ($g.\ kg^{-1}.\ m.\ s^{-1}$) and potential vorticity ($\times 10^{-6}\ K\ m^2\ kg^{-1}\ s^{-1}$) from ERA5, CTL and ASCAT simulations (72 hr mean)

Initial Condition for the simulation: 06 UTC of 21st July 2018

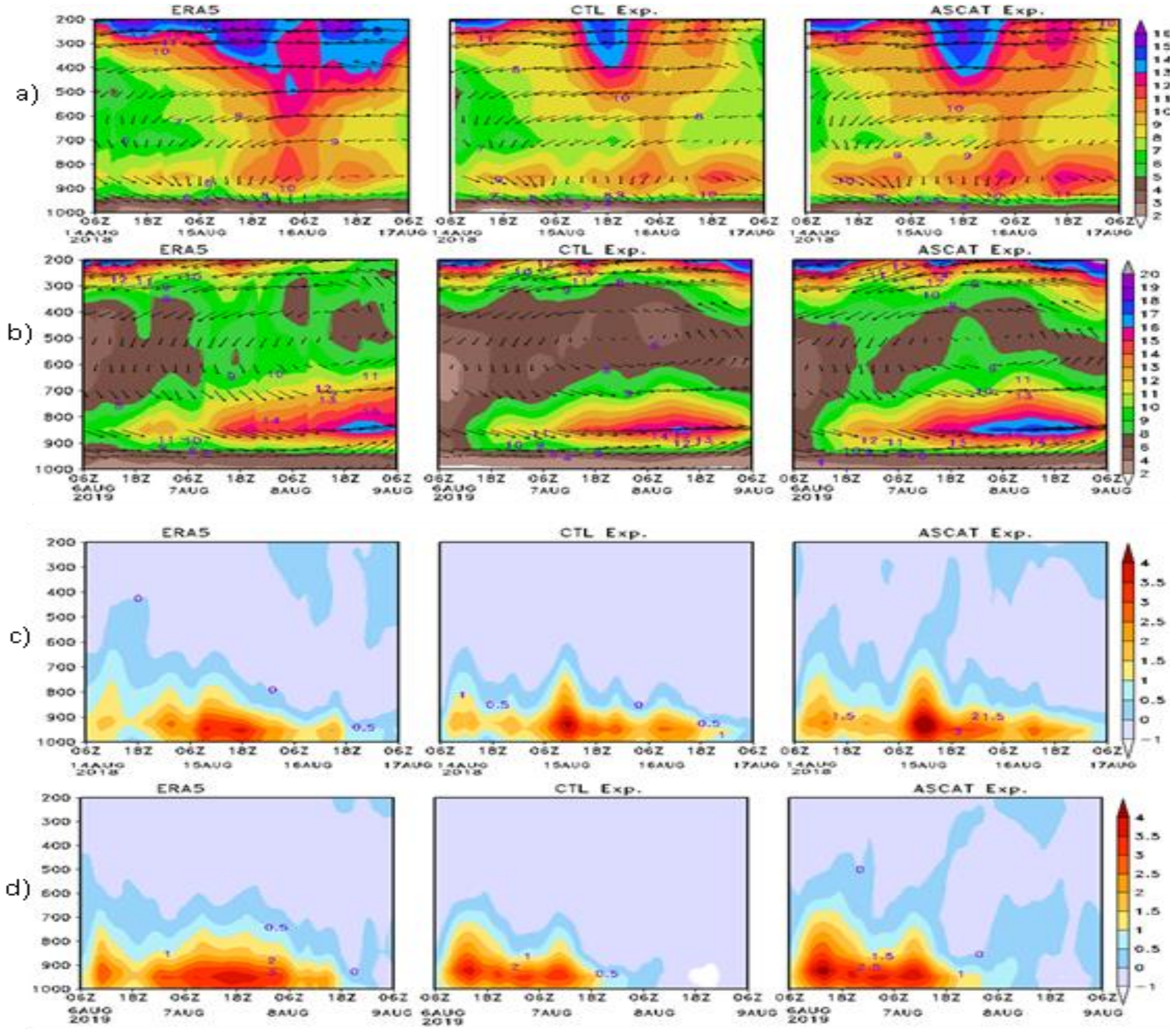
As per IMD report, the LPA was intensified into a depression on 21st July and maintained the same intensity up to early hours of 23rd July



# Simulation Results

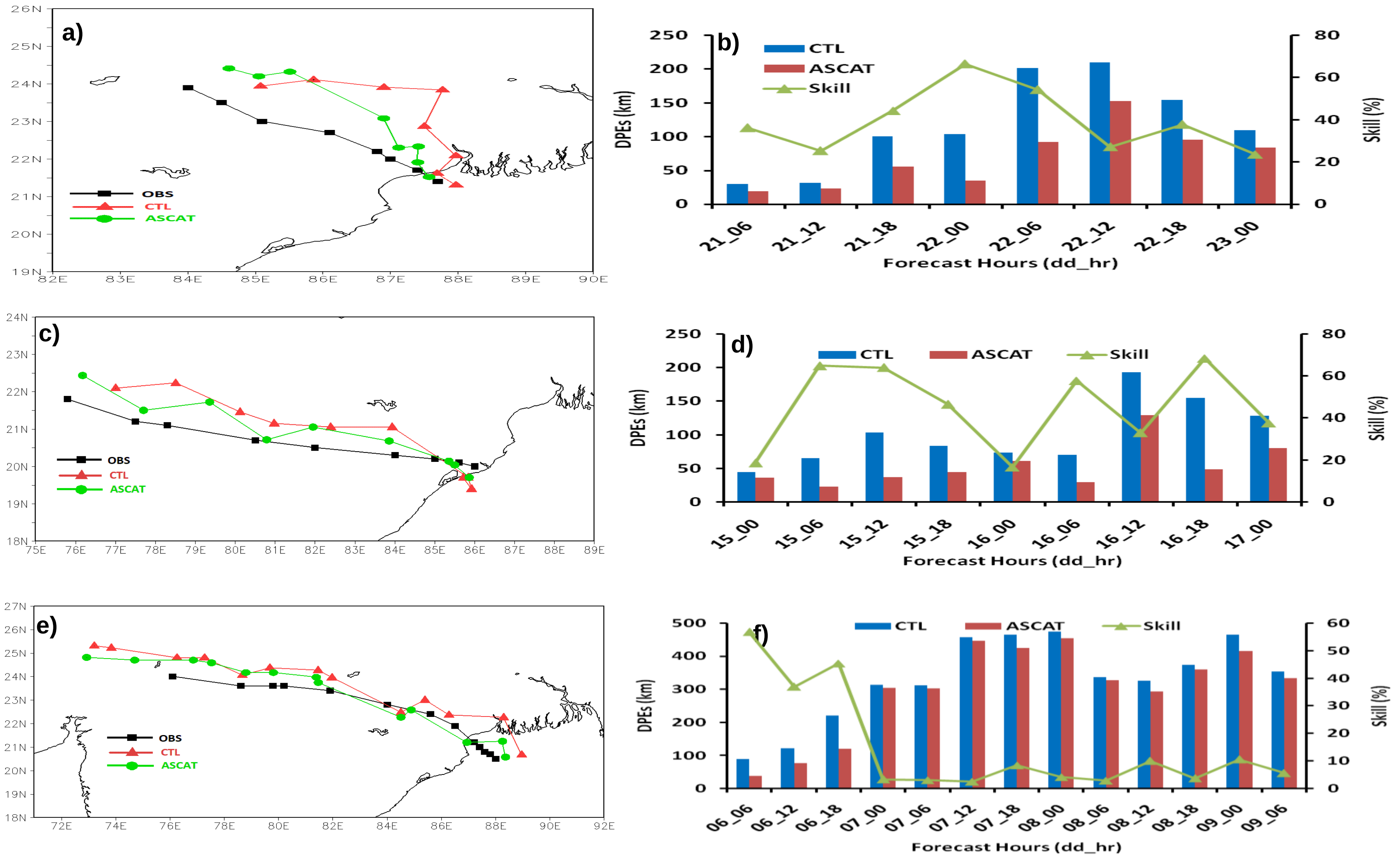
Area averaged time-pressure cross section of wind ($m.s^{-1}$; vector and magnitude in shaded) from ERA5, CTL and ASCAT simulations for (a) Case 2 and (b) Case 3.

Lower panels are for moisture convergence ($\times 10^{-5}$ g. $kg^{-1}$ $s^{-1}$).



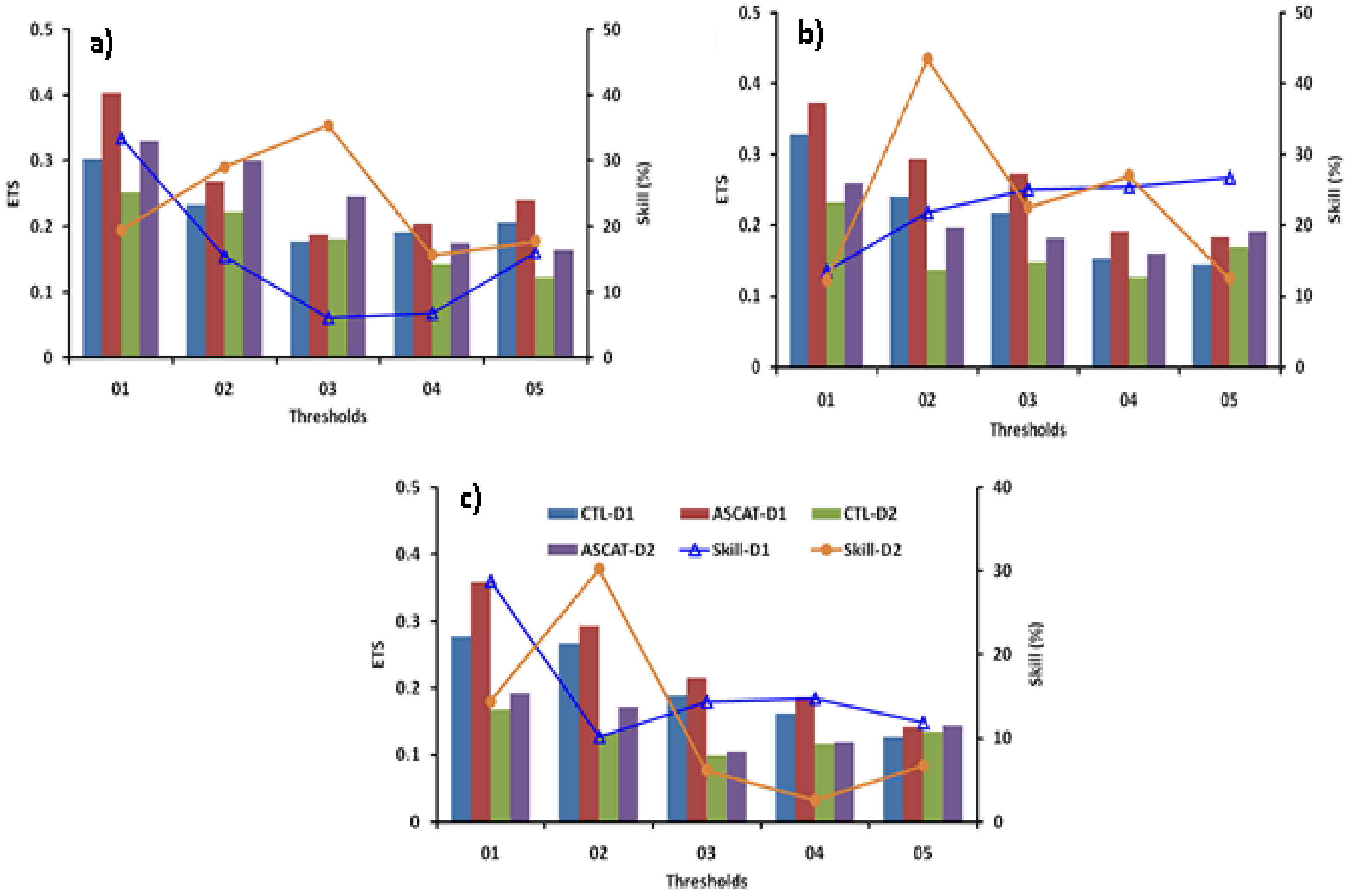
# Monsoon Depression – Track Forecast

Model simulated and IMD best estimated tracks and direct position errors (km) for a) Track and b) DPEs for Case1. Similarly, (c-d) and (e-f) are for Case 2 and Case 3 respectively.



# Rainfall Forecast Verification

Equitable threat score (ETS) at different rainfall thresholds (cm) from both the simulations of day-1 (D1) and day-2 (D2) along with % of improvement of ASCAT over CTL for a) Case 1; b) Case 2 and c) Case 3




Equitable Threat Score (ETS) = (hts-hts_random)/(hits+misses+false_alarm-hits_random) where hits_random=(hits+misses)*(hits+false_alarm)/total

# Summary

- Studies have indicated that SM analysis improve the NWP forecast, especially the surface weather and hydrological cycle. So NCMRWF is operationally assimilating SM in its Global & Regional NWP systems.

- Monsoon Depression study present here shows that Assimilation of remotely sensed SM has a beneficial impact on Monsoon Depression simulation - its movement, structure and associated precipitation.

# Thank You