Ingesting multi-satellite radiances to improve the predictability of regional NWP model

C. Balaji and C. Krishnamoorthy

Heat Transfer and Thermal Power Laboratory
Department of Mechanical Engineering
IIT Madras

Introduction

- Bjerknes (1911) - The necessary and sufficient conditions for a rational solution of the problem of meteorological prediction are the following,

  1.The state of atmosphere at a given time should be known with sufficient accuracy

  2.The laws according to which one state of the atmosphere develops from another should be known

  Weather prediction is an initial value problem

- Three components :

  1. Observation component

  2. Analysis/diagnostic component

  3. Prognostic component

- First two components ensures condition 1 is met, whereas the last component deals with future prediction of atmospheric state
- To resolve different atmospheric scales
- Numerical Weather Prediction models : Regional , Global
- Regional NWP model => IC and BC from Global model

Introduction

- Data deficiency over open ocean has been tackled by satellite based remote observations
- Use all observations to get best possible estimate of Initial Conditions
- Several methods available
  - Deterministic/Variational methods
  - Stochastic methods
- Deterministic methods : 3DVAR, 4DVAR
- Computationally very expensive
- Stochastic methods : Optimal Interpolation, EnKF
- Ensemble based methods have become very popular
- Single deterministic forecast is replaced with an ensemble of forecasts
- Both the atmospheric state and the error estimates can be obtained

Review of Literature

Ensemble Kalman Filters:

- Evensen (1994) – Developed the theory of EnKF => Kalman filter + Monte Carlo estimation
- Houtekamer and Mitchell (1998) demonstrated Ensemble Kalman Filter (EnKF) using a three level quasi geostrophic model
- Burgers et al (1998) proposed a perturbed observation scheme to improve the analysis variance
- Houtekamer and Mitchell (2001) proposed an efficient analysis update scheme for EnKF
- Anderson (2001) proposed Ensemble Adjustment Kalman Filter using Lorenz 69 model
- Local Ensemble Kalman Filter (LETKF) algorithm developed by Otto and Hunt (2007) is used in this study

EnKF methods for WRF

- Zhang et al. (2006) implemented EnKF for WRF under perfect model assumption. They assimilated only conventional observations
- Wang et al. (2008) developed a hybrid EnKF-3DVAR system for assimilation
- Zhang et al. (2016) Assimilated radiances from GOES-R imager into WRF and showed considerable improvement in the forecast states
- Dillion et al. (2016) operationally implemented WRF-LETKF assimilation system at the National Weather Service (NWS), Argentina.
- Jones et al. (2018) assimilated clear-sky water vapor radiances from GOES 13 into WRF and found a neutral to positive impact

Objectives of the present study

Based on the review of literature

(I) the performance of EnKF based methods is superior compared to deterministic methods

(ii) studies on radiance assimilation got attention only in the last decade

(iii) Attempts to assimilate multi-satellite radiances into regional model with EnKF are scarce

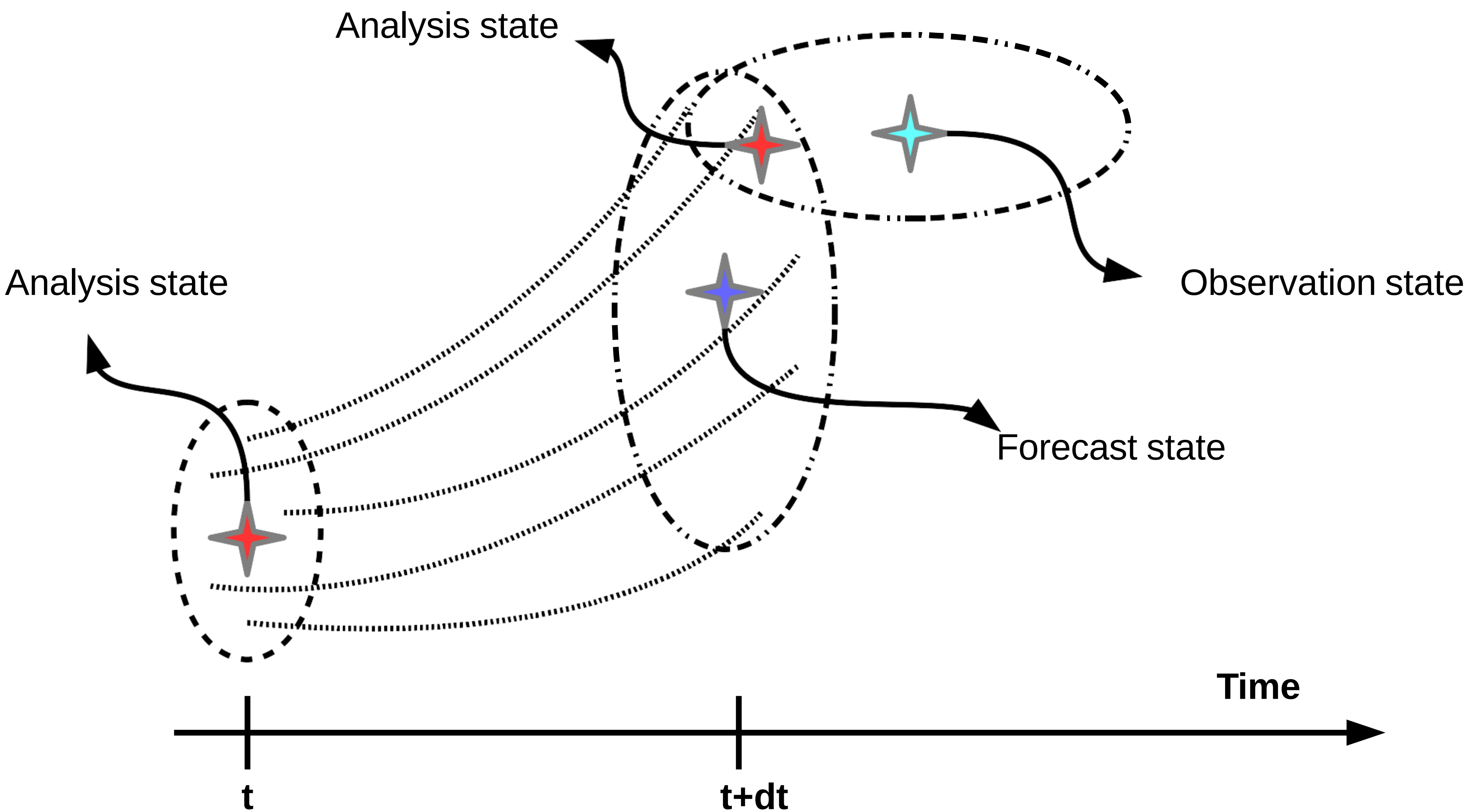
Objectives of the present study

(I) To develop a multi-satellite radiance assimilation framework to assimilate observations from INSAT 3D and SAPHIR into WRF model

(ii)To quantify the bias characteristics of INSAT 3D and SAPHIR sensors based on radiative transfer model simulations

(iii)To study the performance of the radiance assimilation system by ingesting radiances independently for several mesoscale events

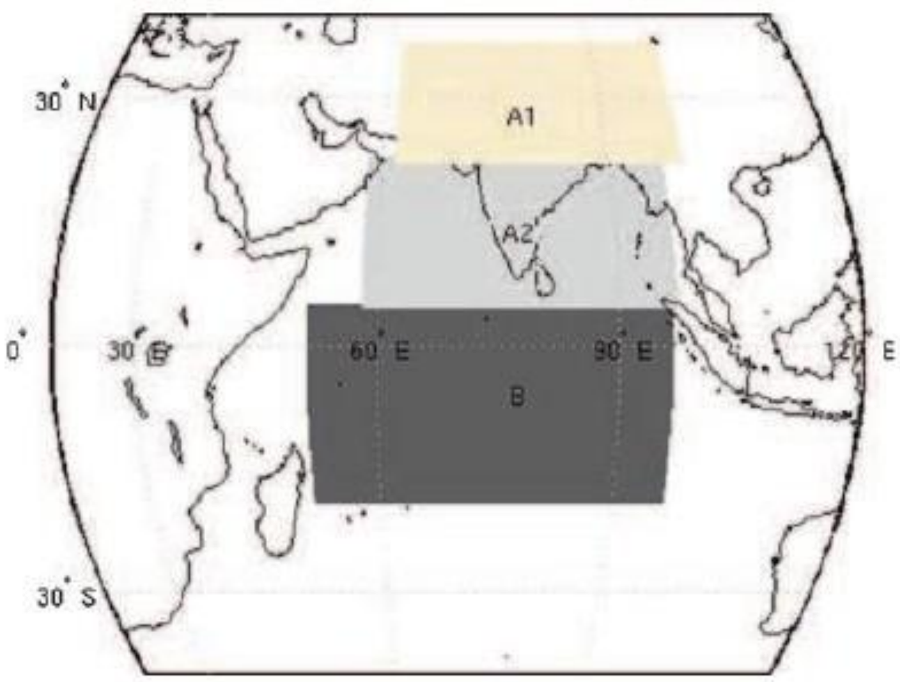
Data assimilation



Satellite and data description

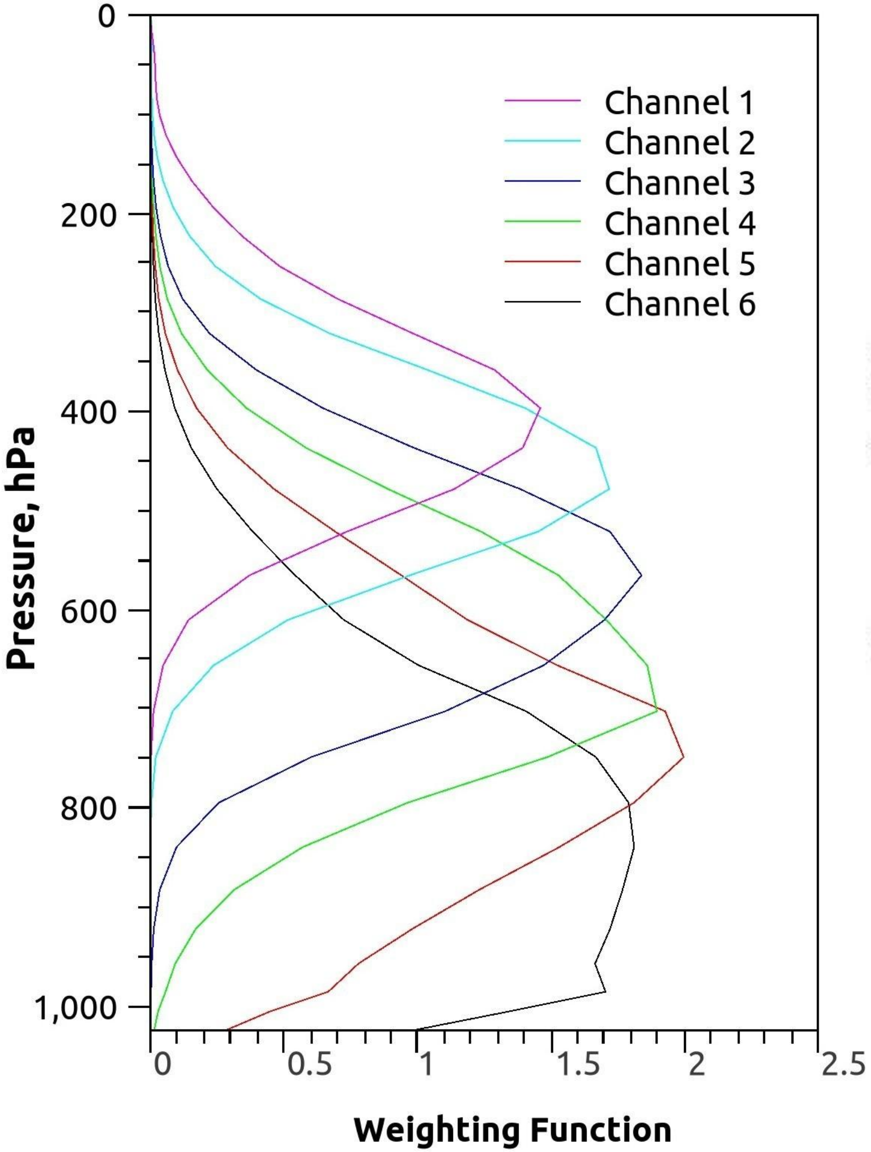
- SAPHIR – Microwave sounder - Six channels centered around the water vapor absorption line 183.31 GHz
- INSAT 3D – Infrared sounder – 18 Channels
- SAPHIR – Orbiting satellite , INSAT 3D – Geo-stationary satellite
- SAPHIR – sensitive to tropospheric humidity
- INSAT 3D – 5 water vapor channels sensitive to middle
- troposphere

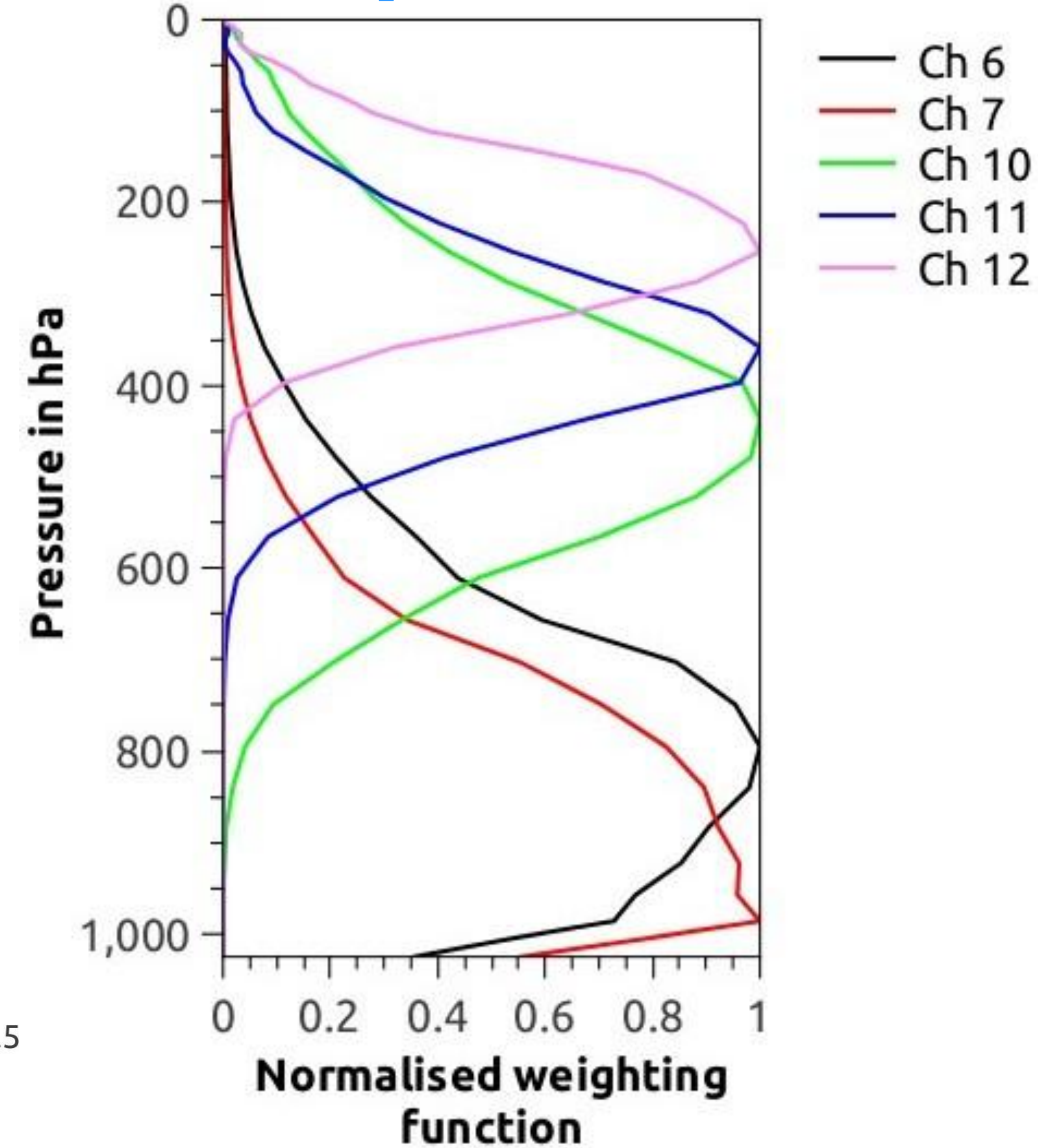
  Weighting functions – Plotted with standard atmospheric profile



INSAT 3D Scanning geometry

Satellite and data description

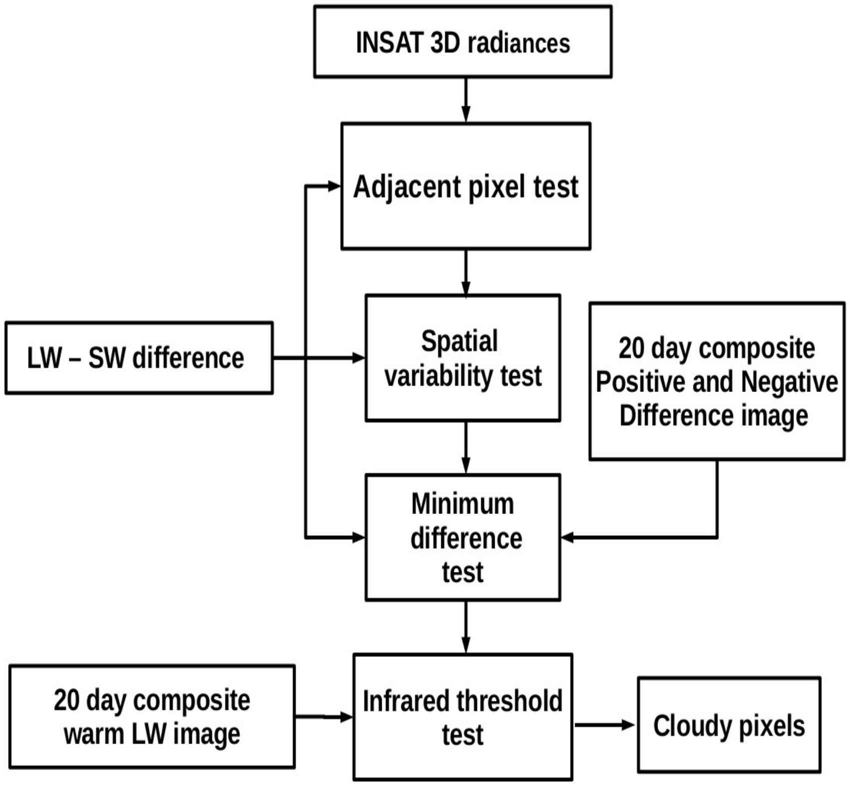


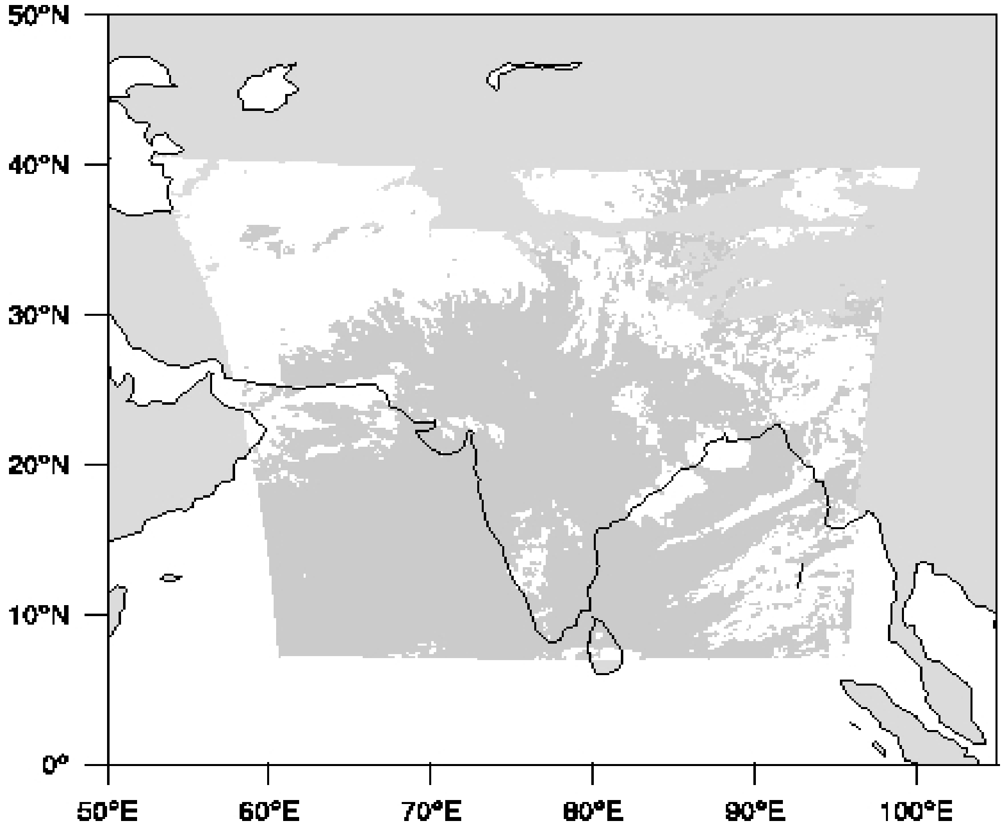


Weighting function corresponding to SAPHIR Channels

Weighting function corresponding to INSAT 3D Channels

Cloud screening methodology for INSAT 3D





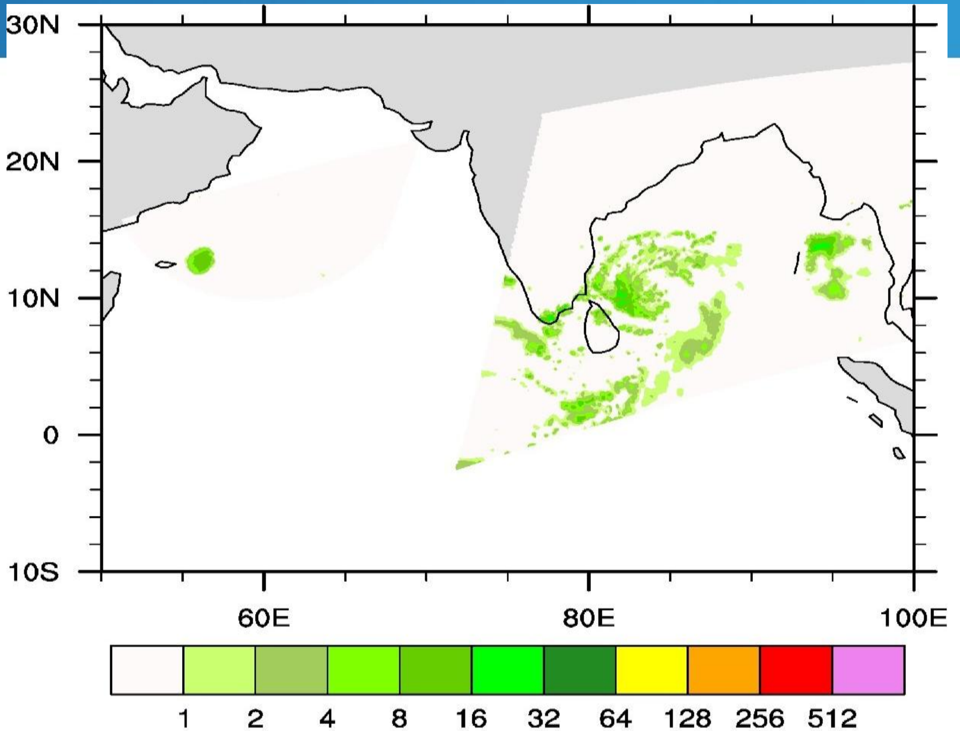
Derived cloud mask at 12 UTC of 01 April 2016

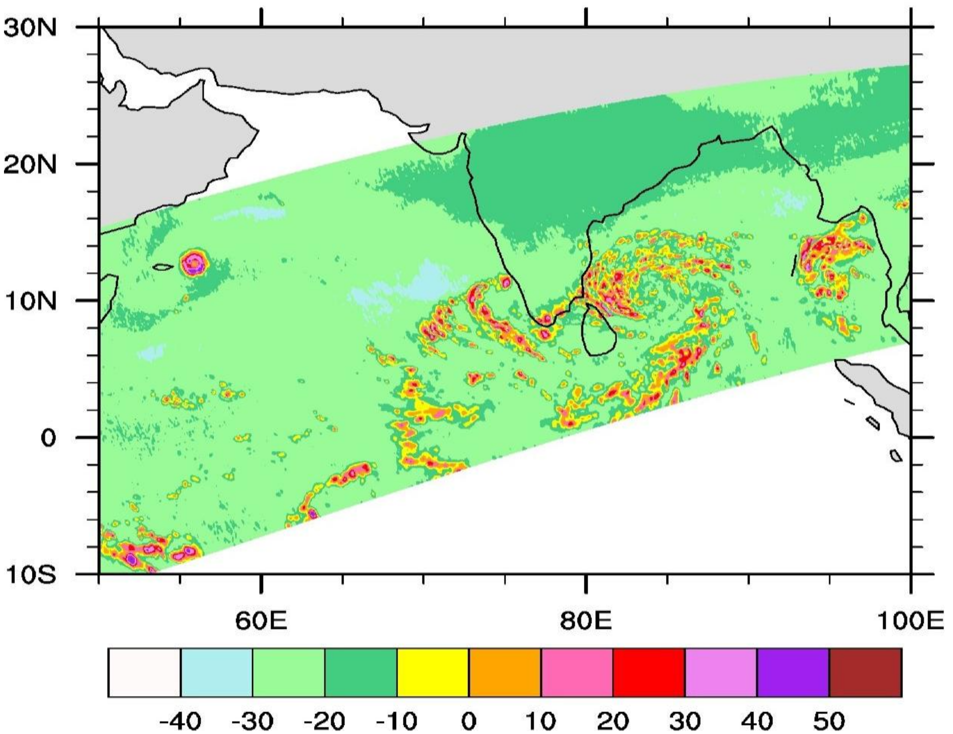
PP	0.82
HR	0.73
FAR	0.14
TSK	0.59

PP – Proportion of Perfect classification
HR – Hit Rate
FAR – False Alarm Rate
TSK – True Skill Score

Cloud screening for SAPHIR

- Rainy pixels were removed from the initial set of observations
- Only clear sky pixels were assimilated
- Rainy pixels were identified using threshold test proposed by *Funatsu et al* (Channel S1 – S5 BT diference)
- Difference > -8K
- Evaluated for a sample overpass
- Compared with GPM rainfall
- Limitation: Light rainfall pixels

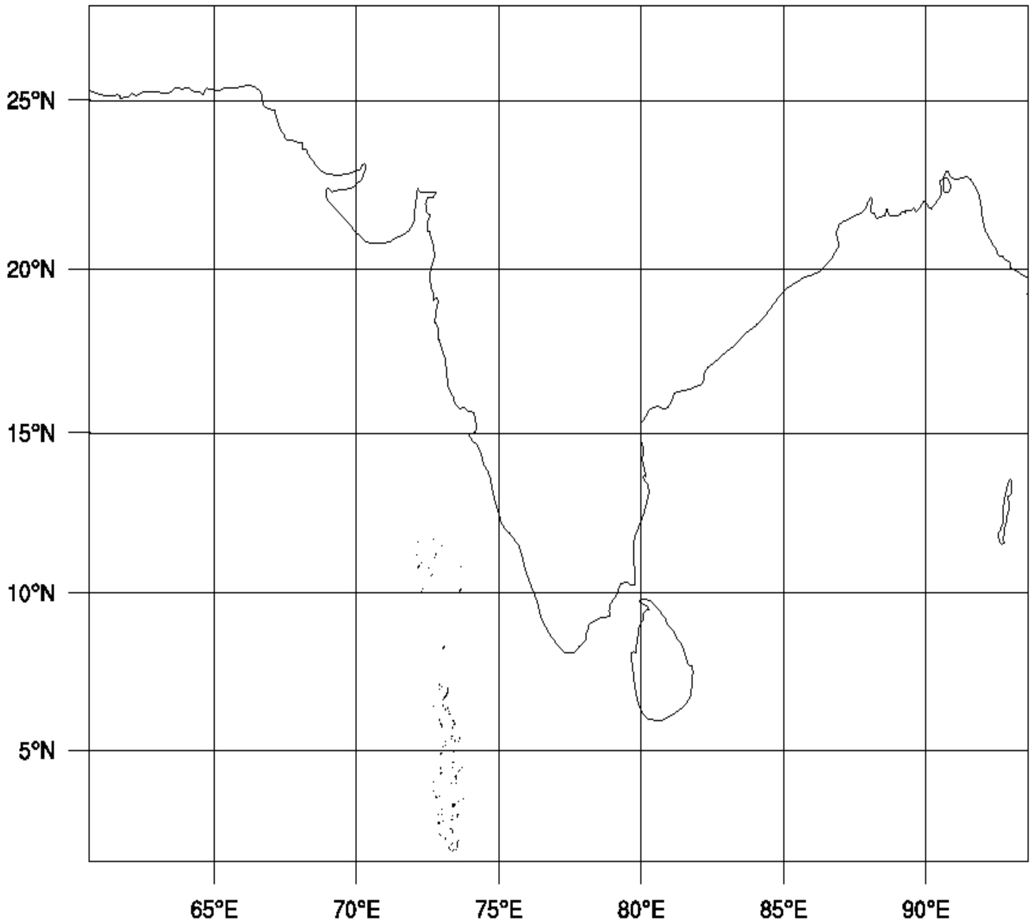




Forward RT and NWP model

- Radiative Transfer for the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (RTTOV)
- RTTOV v11.2 is used
- Representative profiles (43 TIGR profiles)
- Gas transmittance => Calculated for the representative profile
- Input to RTTOV for clear-sky simulation:
  - Pressure (hPa)
  - Temperature (K) Specific
  - Humidity(g/kg)
  - Other gas mixing ratios (g/kg)
- Atmospheric dynamics – simulated with WRF
- A community based weather model
- Uses Global model output for Initial and Boundary condition

Advanced Research WRF



WRF domain

Horizontal resolution : 15 km

Vertical resolution : 29 Levels

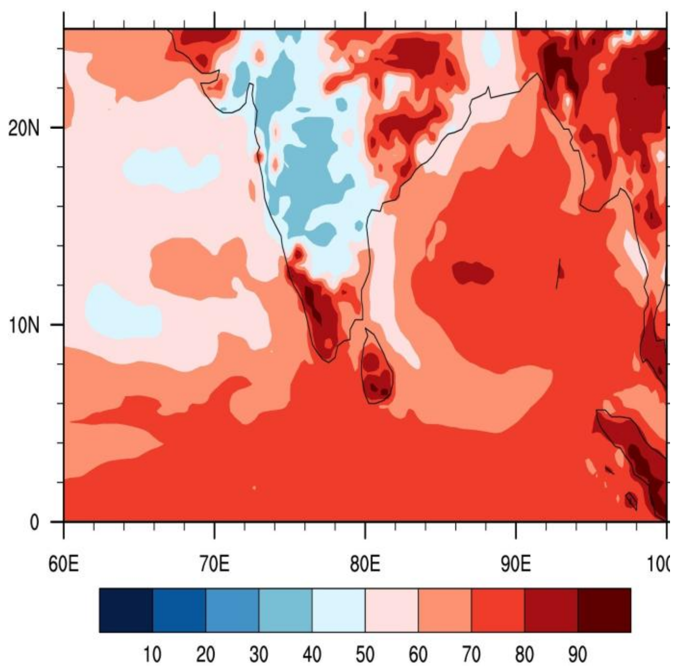
Cumulus parametrization: NSAS (New Simplified Arakawa Schubert scheme)

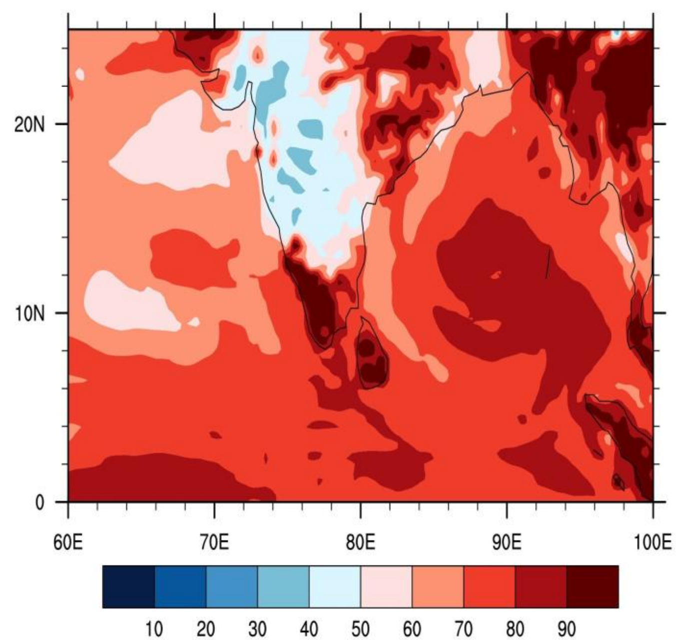
Microphysics parametrization : Kessler scheme

Projection : Mercator

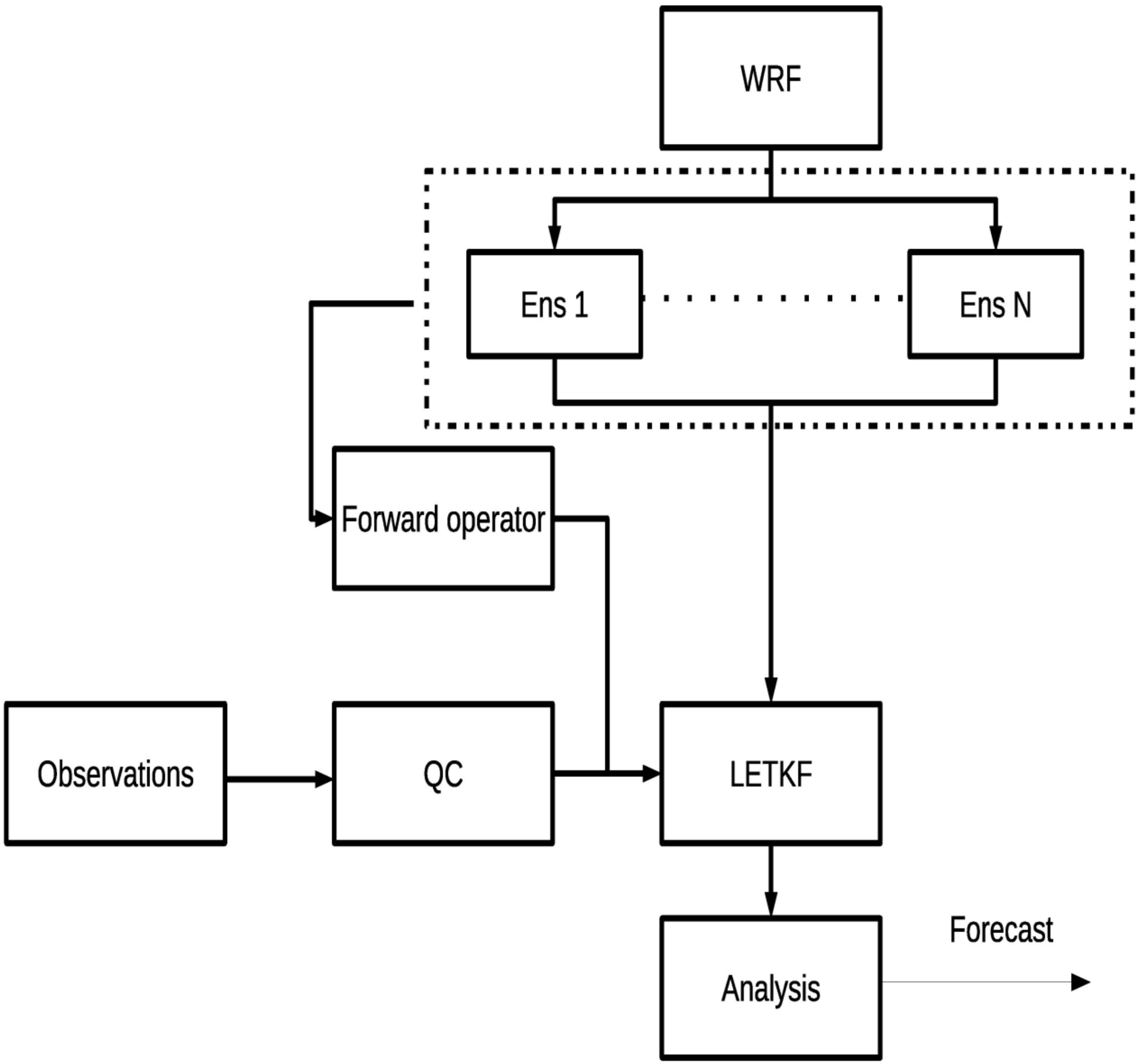
Ensemble generation and LETKF

- Initial population of atmospheric states / ensembles of initial conditions are required
- Empirical Orthogonal Function based perturbations were done to initial fields (Temperature and Humidity)
- Since eigen vectors and eigen values represents the principal direction in which the field varies
- Number of grid points O(10,000) => Iterative EOF generation by Van den Dool (2000) is used.
- Only Temperature and Humidity perturbations were performed





Two ensembles of Relative Humidity at first model level



Overview of LETKF algorithm

Several experiments were carried out to assess the performance of radiance assimilation.

1) Cyclone VARDAH

2)Three episodes of heavy rainfall events

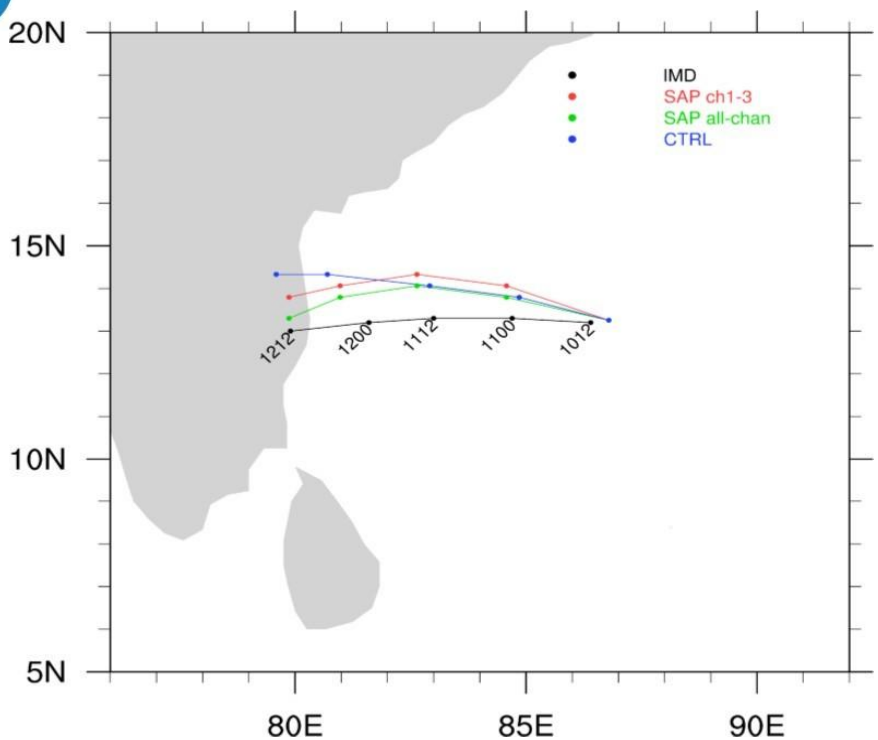
Three experimental setup, namely,

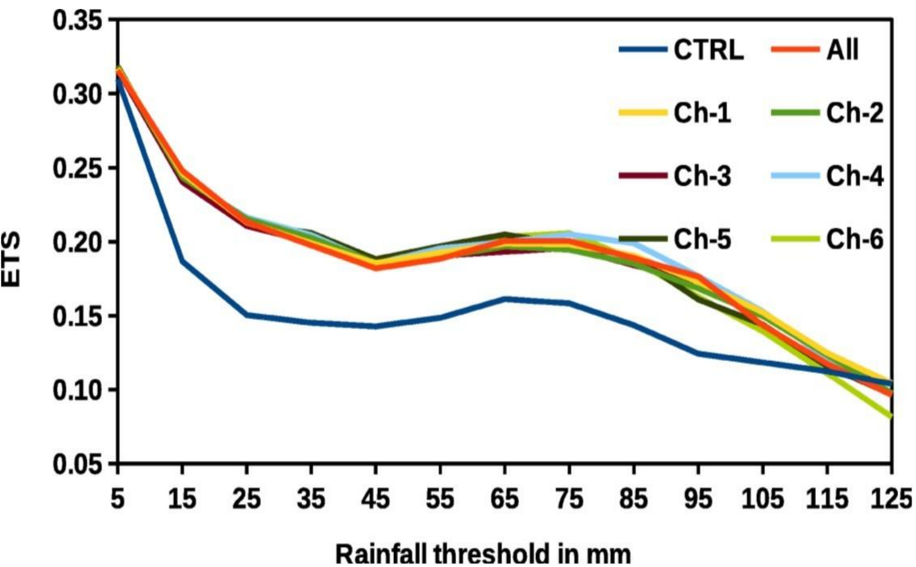
1) only SAPHIR

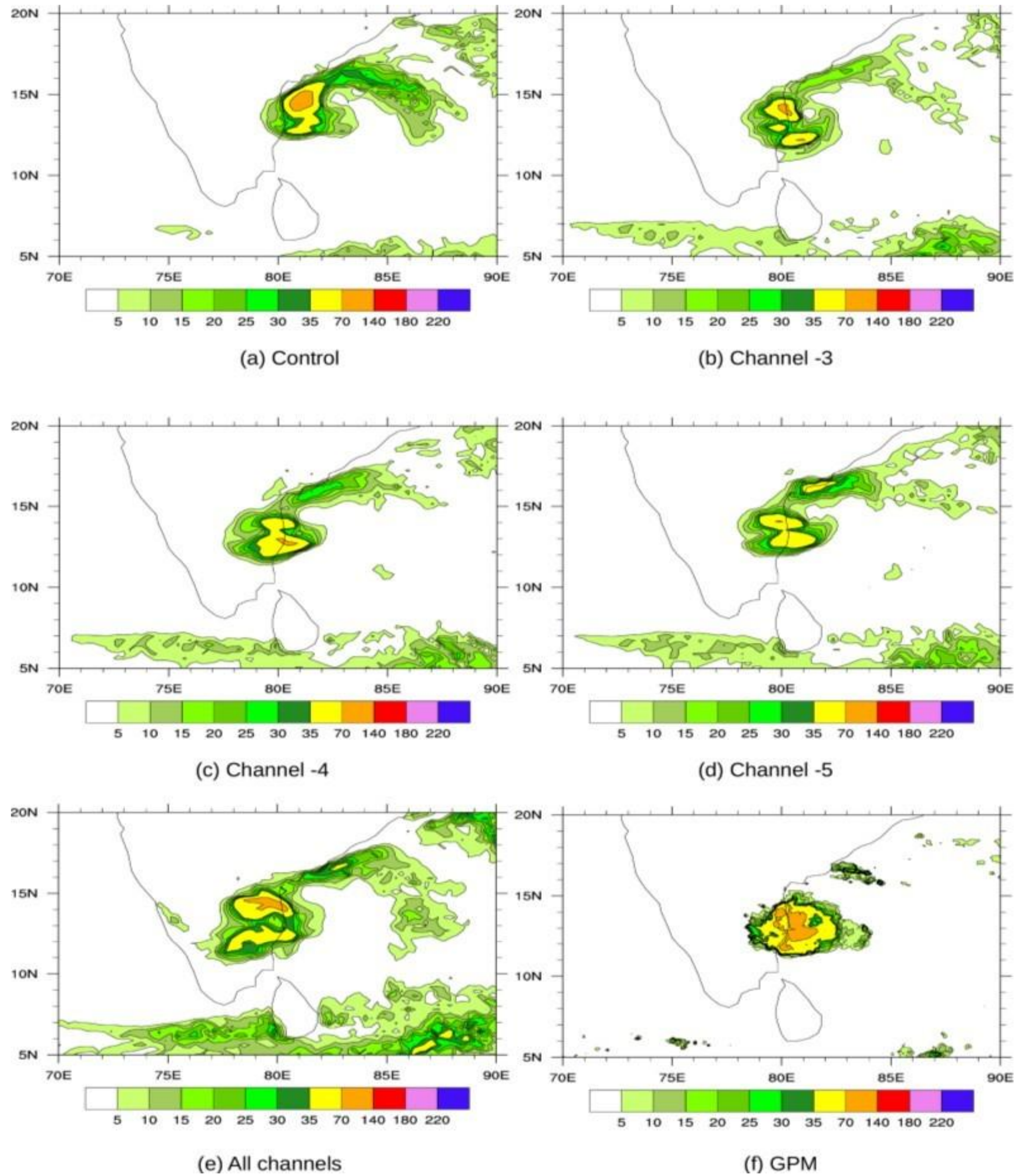
2) only INSAT 3D

3) SAPHIR + INSAT 3D

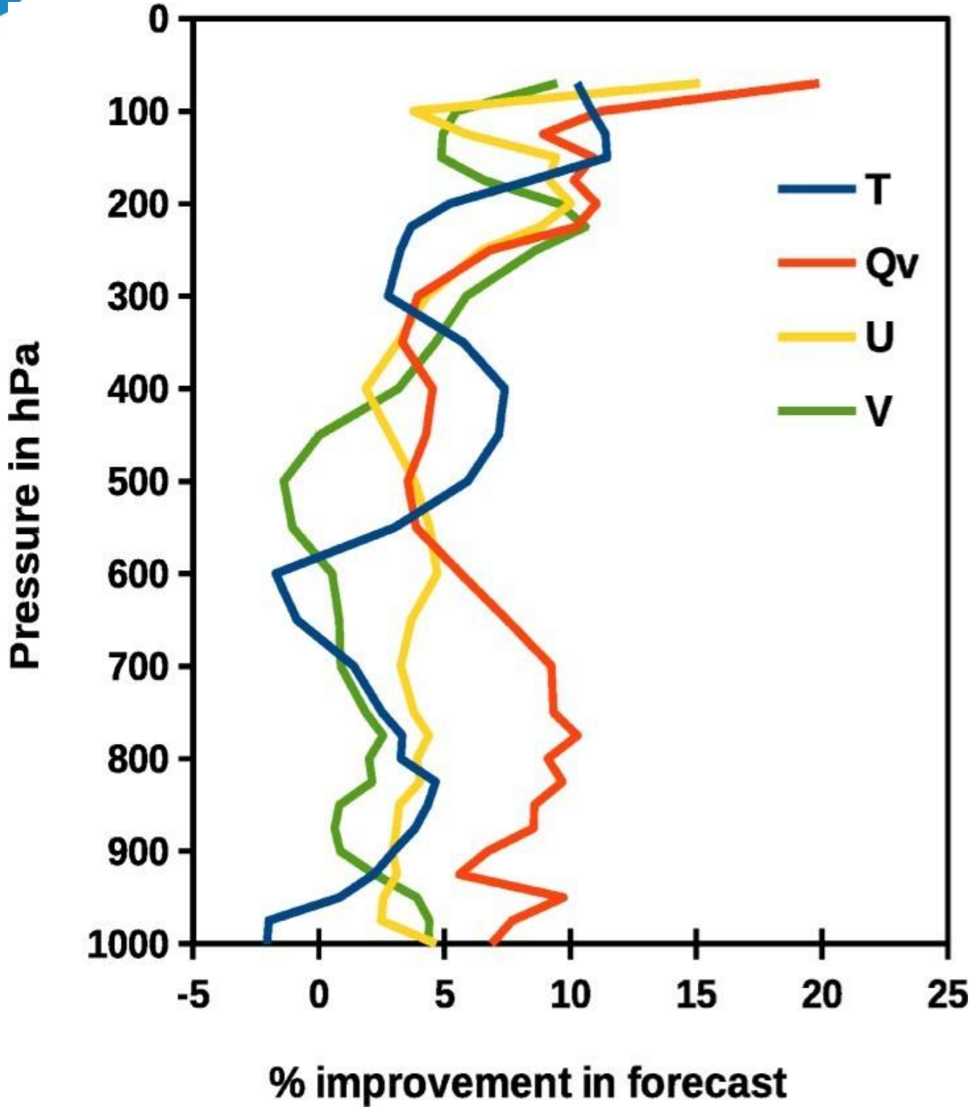
Results from SAPHIR assimilation



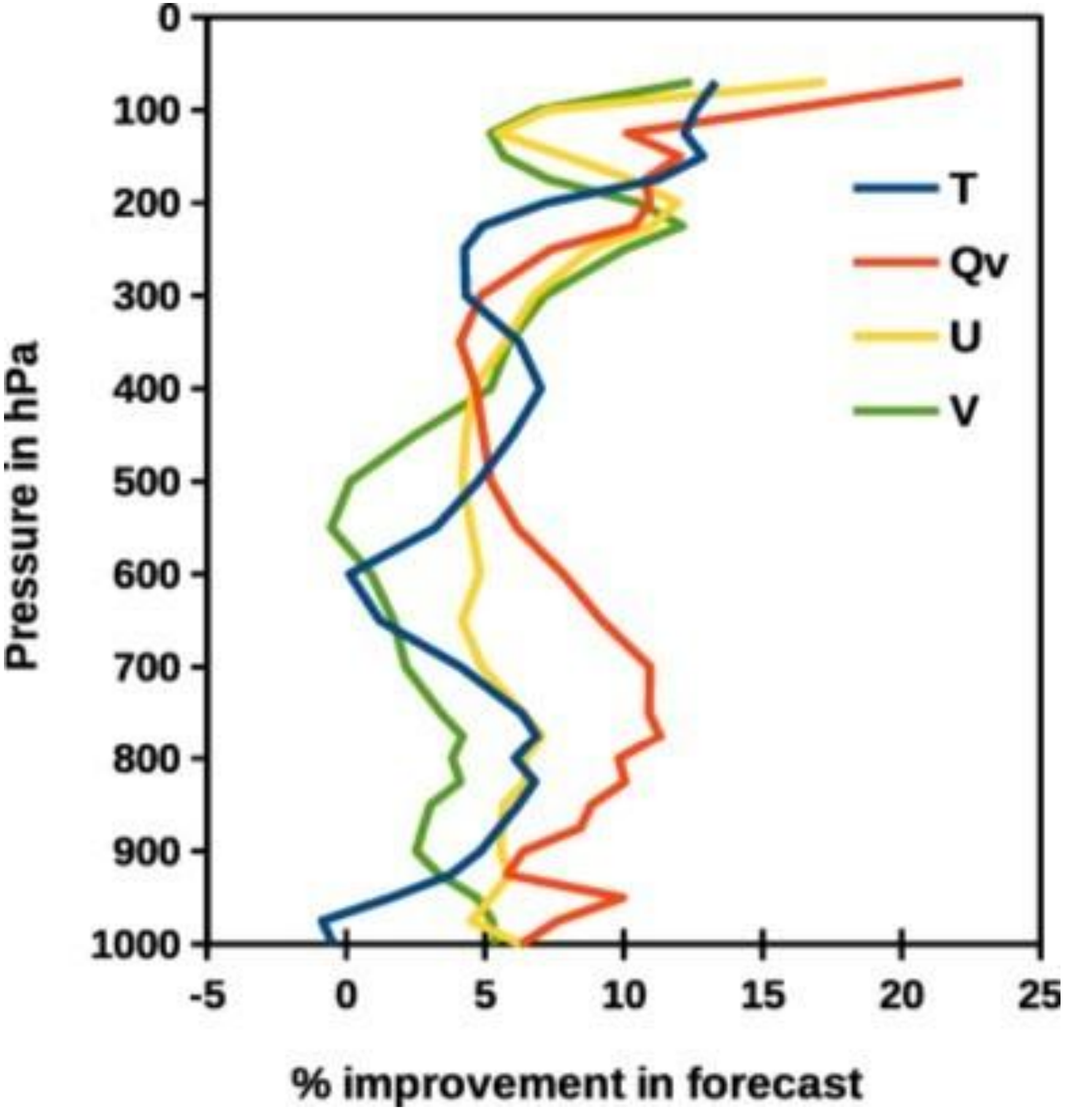




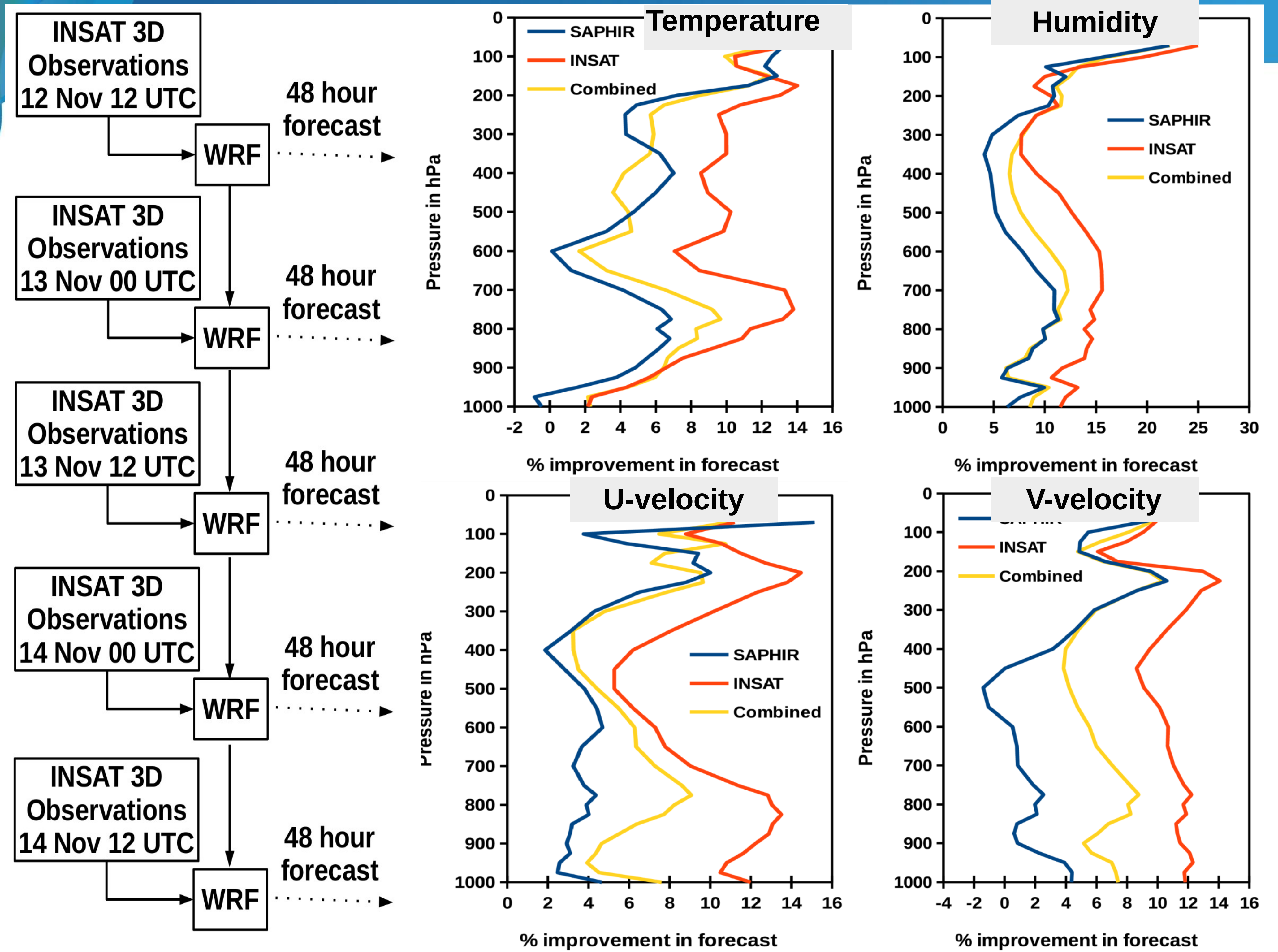
Results from SAPHIR assimilation



24 hour average

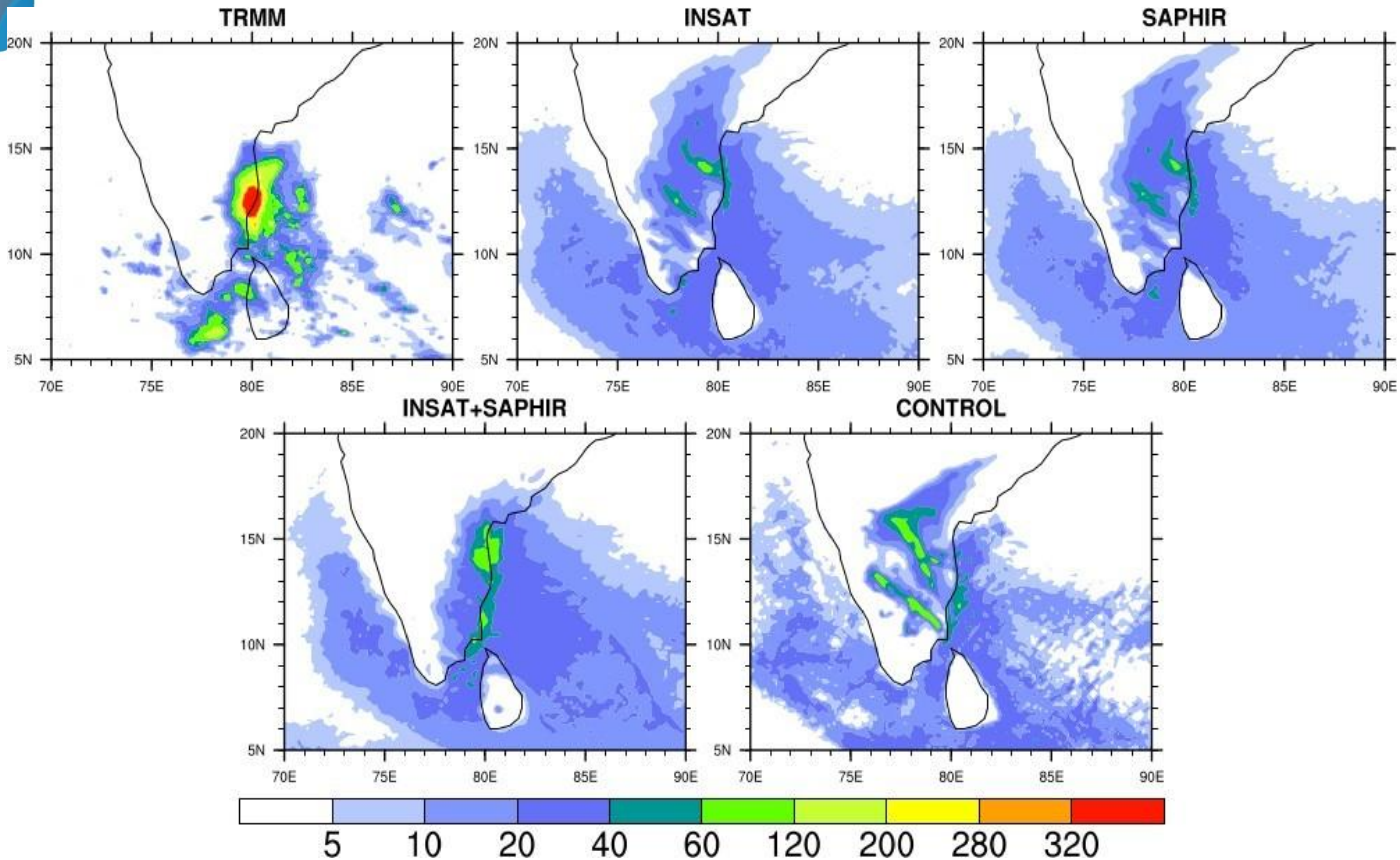


48 hour average



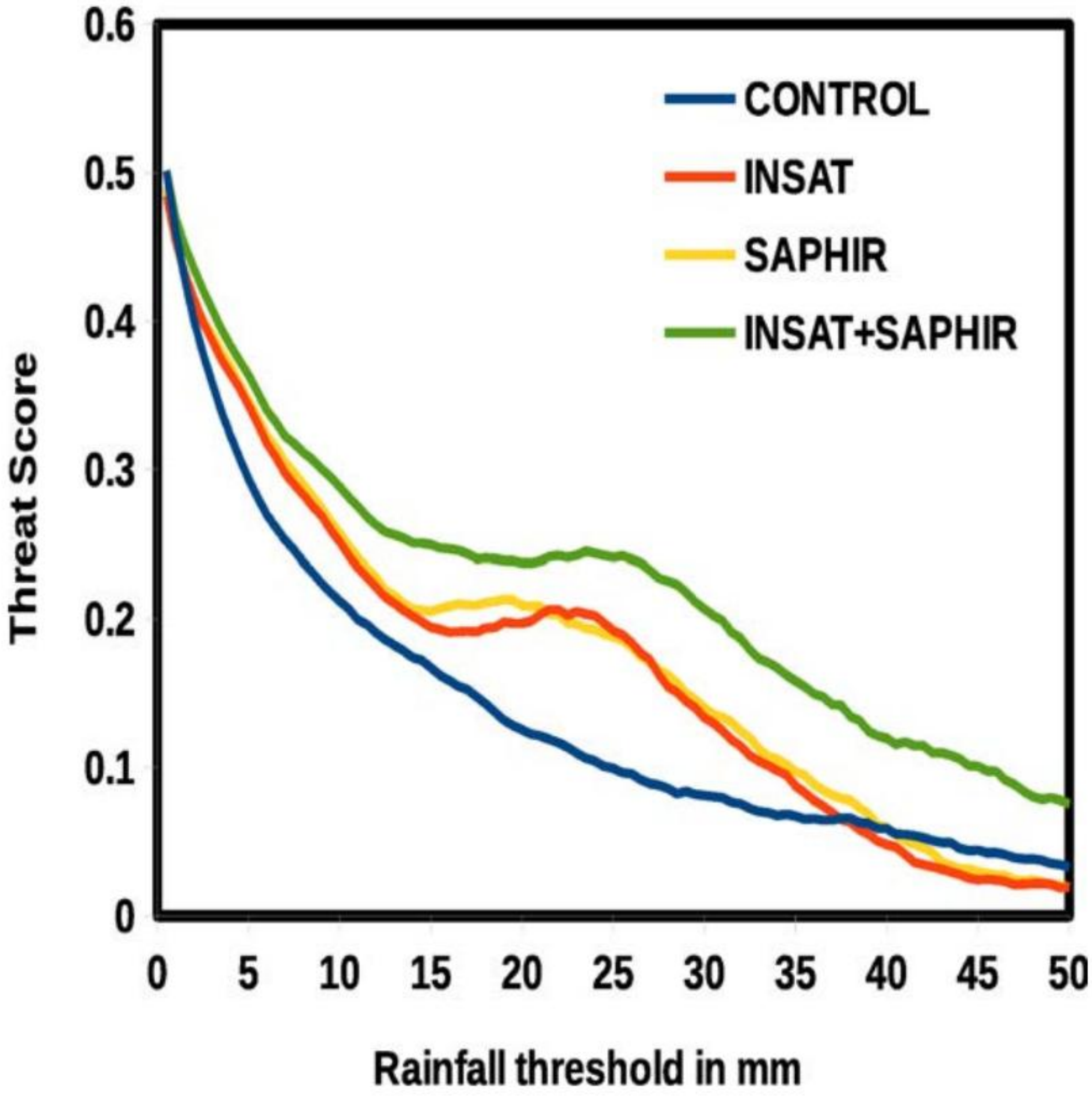
INSAT 3D Observations 12 Nov 12 UTC
INSAT 3D Observations 13 Nov 00 UTC
INSAT 3D Observations 13 Nov 12 UTC
INSAT 3D Observations 14 Nov 00 UTC
INSAT 3D Observations 14 Nov 12 UTC
WRF
48 hour forecast
Temperature
Humidity
U-velocity
V-velocity
SAPHIR
INSAT
Combined
Pressure in hPa
% improvement in forecast

Multi-satellite assimilation for heavy rainfall forecast



24 hour accumulated precipitation from 01 – 02 Dec 2015 00 UTC

Equitable Threat Score Comparison



Conclusions based on the present study

Assimilation of SAPHIR radiances

- Assimilation of individual channels from SAPHIR did not significantly improve results
- All 6 channel radiances has been proved to improve the forecast.
- The average 24 and 48 hour forecast improvements show a maximum of 5% in the temperature and 10% in the humidity with the peak values in the layer between 600-1000 hPa i.e in the lower troposphere.

Assimilation of INSAT 3D radiances

- An improvement of about 11% was found in humidity between 400-1000 hPa, whereas for temperature the improvements near the surface layers are very feeble.
- Additionally, 24 hour accumulated rainfall from all the 15 forecasts were compared with GPM IMERG data and it showed a huge positive impact in the rainfall range of 5 to 40 mm.

Assimilation of multi-satellite radiances

- The improvements in the tropospheric moisture between 600 - 900 hPa is about 15% when the improvement due to assimilation of SAPHIR is just about 10%.
- The improvement from the multi-satellite assimilation tends to neutralize the degradation of forecast due to SAPHIR microwave sounder.

Limitations of the study

- The present study looks only at clear-sky radiance assimilation due to the difficulties in simulating the cloudy radiances with specified hydrometeor content.
- The inability to characterize the land surface led to the assimilation of observations over open ocean
- The spatial observation error correlations for both INSAT3D and SAPHIR were not considered in this study, this could be the reason for degradation of certain analysis / forecast parameters
- Considering a fully correlated observation error Is still an active area of research and its implementation is computationally expensive.

Scope for future work

- All sky radiance simulations using fast RT model to access the bias characteristics of microwave sounder (SAPHIR)
- Extending the radiance assimilation system for other sensors like GMI (from GPM)
- Techniques to model the spatial observation error covariances
- Studying the impact of assimilating different observation on the forecast (Forecast Sensitivity to Observations)
- The results presented above looks only at short range forecasts but these can be extended for long range forecasts of Indian Summer Monsoon onset

Ongoing work

- The accurate prediction of the ISM rainfall is of paramount importance as it impacts agriculture, which is an integral part of the Indian economy.
- Short-range prediction (3-4 days) of ISM is important as there is an increase in the extreme rainfall events during the ISM in the recent years (Dash et al., 2009).
- Numerical Weather Prediction (NWP) models are imperative in providing accurate precipitation forecasts.
- Default values for many model parameters are generally assigned based on theoretical or empirical considerations by scheme developers.
- The objective of this study is to reduce the ISM rainfall prediction error by identifying and calibrating the sensitive parameters.

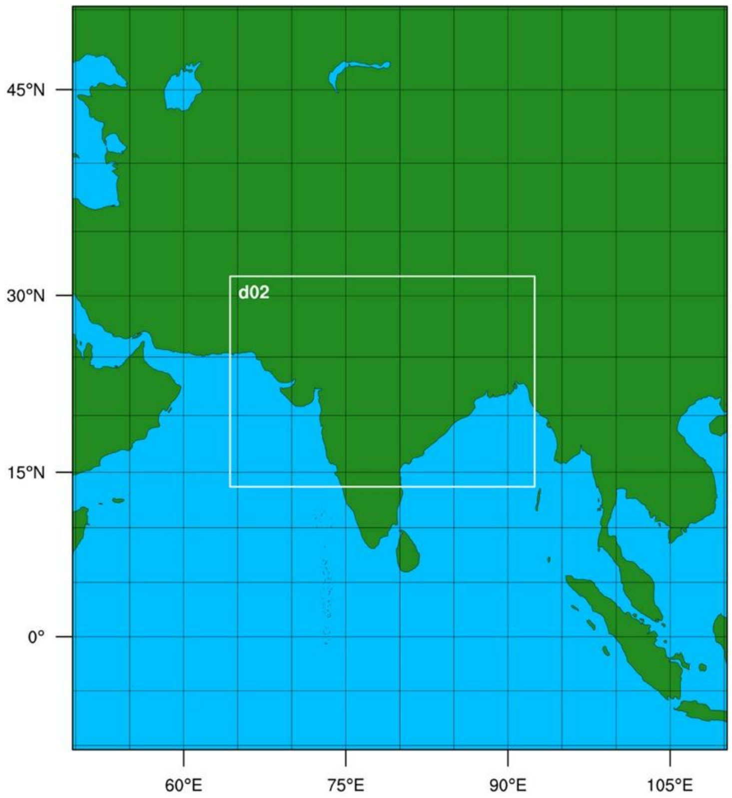
Set of adjustable parameters in the WRF model

Index	Scheme	Parameter	Default	Range	Description
P1	Surface layer	xka	2.4e-5	[1.2e-5 5e-5]	The parameter for heat/moisture exchange coefficient (sm^{-2})
P2		czo_fac	0.0185	[0.01 0.037]	The coefficient for converting wind speed to roughness length over the water
P3	Cumulus	pd	1	[0.5 2]	The multiplier for downdraft mass flux rate
P4		pe	1	[0.5 2]	The multiplier for entrainment mass flux rate
P5		ph_usl	150	[50 350]	Starting height of downdraft over USL (hPa)
P6		timec	2700	[1800 3600]	Mean consumption time of CAPE (s)
P7		tkemax	5	[3 12]	The maximum turbulent kinetic energy (TKE) value in sub-cloud layer (m^2s^{-2})
P8	Microphysics	ice_stokes	14900	[8e3 3e4]	Scaling factor applied to ice fall velocity (s^{-1})
P9		n0r	8e+6	[5e6 1.2e7]	Intercept parameter of rain (m^{-4})
P10		dimax	5e-4	[3e-4 8e-4]	Limited maximum value for the cloud-ice diameter (m)
P11		peaut	0.55	[0.35 0.85]	Collection efficiency from cloud to rain auto conversion

Set of adjustable parameters in the WRF model

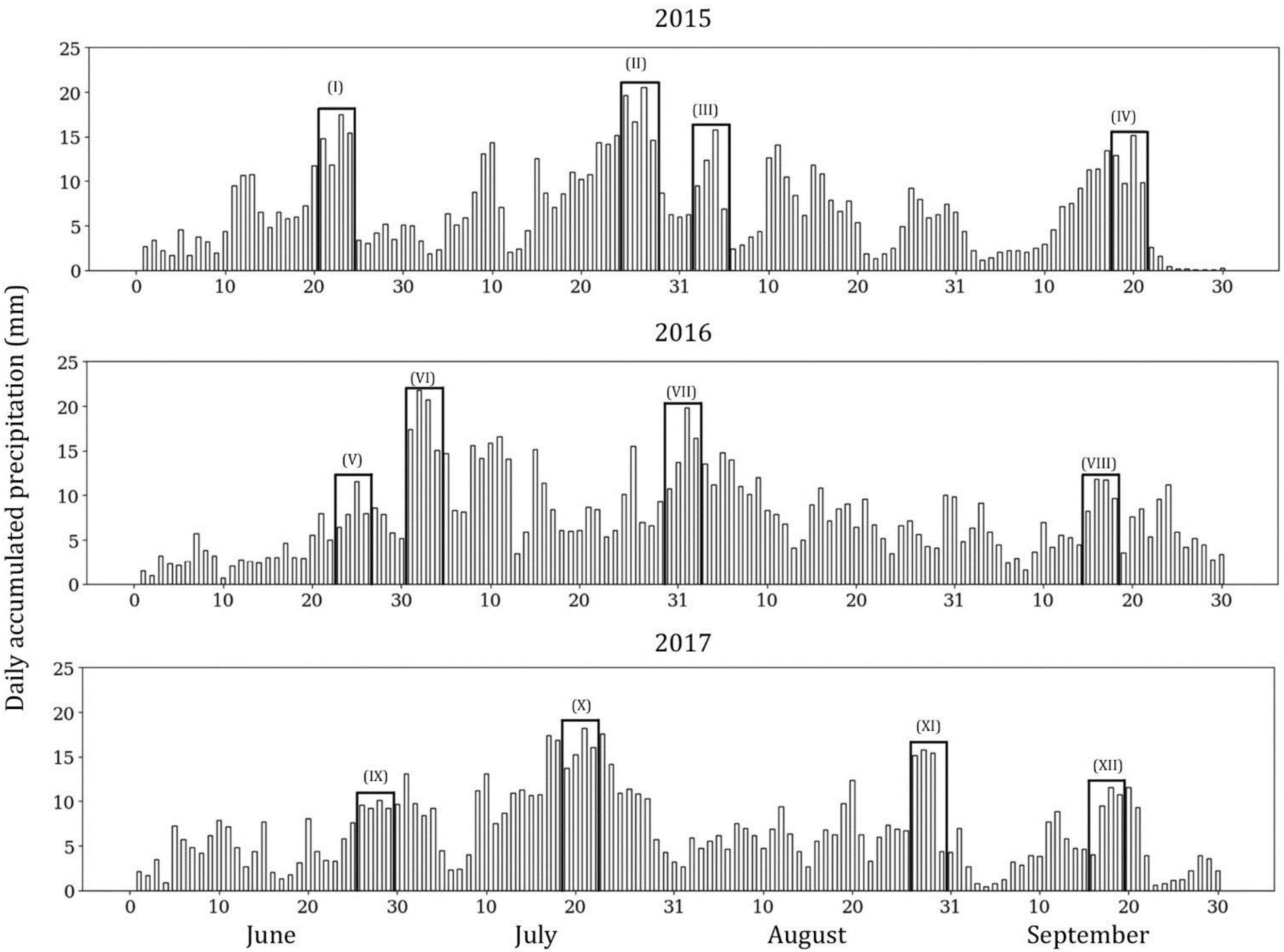
Index	Scheme	Parameter	Default	Range	Description
P12	Short-wave	cssca_fac	1e-5	[5e-6 2e-5]	Scattering tuning parameter (m^2kg^{-1})
P13		Beta_p	0.4	[0.2 0.8]	Aerosol scattering tuning parameter (m^2kg^{-1})
P14	Long-wave	Secang	1.66	[1.55 1.75]	Diffusivity angle for cloud optical depth computation
P15	Land surface	hksati	1	[0.5 2]	Multiplier for hydraulic conductivity at saturation
P16		porsl	1	[0.5 2]	Multiplier for the saturated soil water content
P17		phi0	1	[0.5 2]	Multiplier for minimum soil suction
P18		bsw	1	[0.5 2]	Multiplier for Clapp and Hornbereger 'b' parameter
P19	Planetary boundary layer	Brcr_sbrob	0.3	[0.15 0.6]	Critical Richardson number for boundary layer of water
P20		Brcr_sb	0.25	[0.125 0.5]	Critical Richardson number for boundary layer of land
P21		pfac	2	[1 3]	Profile shape exponent for calculating the momentum diffusivity coefficient
P22		bfac	6.8	[3.4 13.6]	Coefficient for Prandtl number at the top of the surface layer
P23		sm	15.9	[12 20]	Countergradient proportional coefficient of non-local flux of momentum

Model domain and configuration



Model configuration	Details
Initial and lateral boundary conditions	NCEP FNL Global Analysis data
Horizontal resolution	36 × 36 km domain 1 (d01)
	12 × 12 km domain 2 (d02)
Central point for d01	80^oN, 23.22^oE
Grid points in X and Y directions	188 × 213 (d01)
	262 × 181 (d02)
Time step	120 sec (d01) and 40 sec (d02)

Events Simulated



Event	Year	Dates
1	2015	Jun 21 - Jun 24
2		Jul 25 - Jul 28
3		Aug 2 - Aug 5
4		Sep 18 - Sep 21
5	2016	Jun 23 - Jun 26
6		Jul 1 - Jul 5
7		Jul 30 - Aug 2
8		Sep 15 - Sep 18
9	2017	Jun 26 - Jun 29
10		Jul 19 - Jul 22
11		Aug 27 - Aug 30
12		Sep 16 - Sep 19

Morris One At a Time (MOAT) method

Consider a model with m-dimensional inputs. $\mathbf{X} = (x_1, x_2, ..., x_m)$.

All the ranges of parameters are mapped to [0,1] and are divided into p equally spaced intervals.

A base parameter set x^0 is randomly selected in the p-level grid.

Δ_i, a multiple of $\pm 1/(p-1)$, is added to one of the components of the x^{i-1} vector which has not been perturbed.

Finding all the m+1 points completes the full MOAT trajectory.

The elementary effect corresponding to the i^{th} parameter, when x_i^{j+1} and x_i^j of j^{th} trajectory differ by Δ_i in their i^{th} component is

$$EE_i^j = \frac{[y(x_1^{(j)}, .., x_i^{(j)} + \Delta_i, .., x_m^{(j)}) - y(x_1^{(j-1)}, .., x_i^{(j-1)}, .., x_m^{(j-1)})]}{\Delta_i}$$

Sensitivity measures

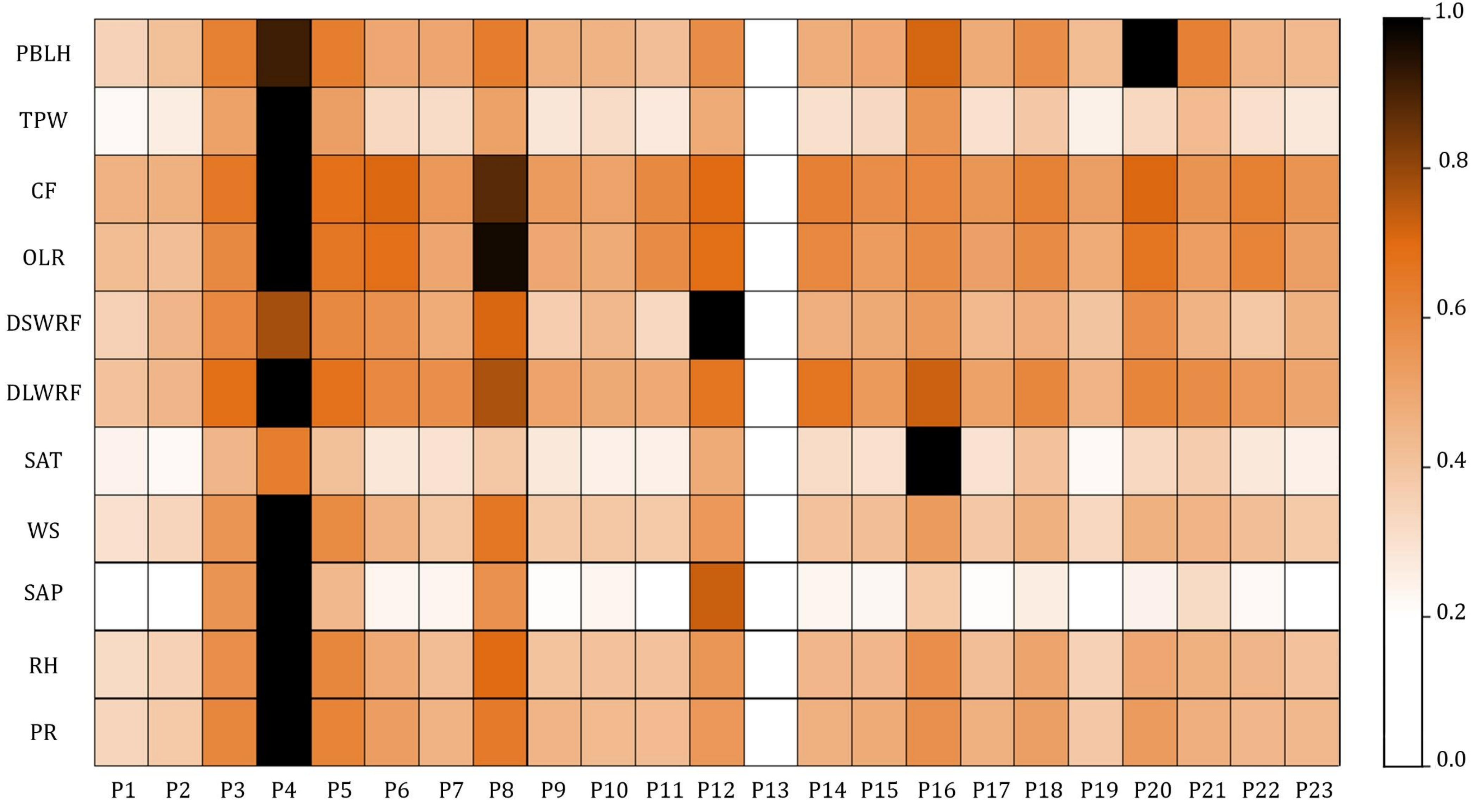
The sensitivity measures MOAT Mean, μ_i and MOAT standard deviation, σ_i after r MOAT replications are evaluated as follows:

$$\mu_i = \frac{1}{r}\sum_{j=1}^{r} \mid EE_i^j \mid$$

$$\sigma_i^2 = \frac{1}{r-1}\sum_{j=1}^{r} \left(EE_i^j - \mu_i\right)^2$$

- A large value of the μ_i implies that the parameter is sensitive.
- A large value of the σ_i implies a higher interaction of the parameter with other parameters.

Parameter Sensitivity



Conclusions

- A sensitivity study is performed to choose the most sensitive parameters out of the 23 adjustable parameters selected in this study.

- P4 has the highest impact on the model outcome; P13 is observed to have no impact on all the output variables while simulating ISM.

- Nine sensitive parameters are identified that have the most profound influence on the output variables.

- The sensitive parameters obtained will be calibrated using the Adaptive surrogate model-based optimization method to reduce the precipitation error corresponding to the Indian summer monsoon.

Publications based on the research

Journals:

Balaji, C., C. Krishnamoorthy, and R. Chandrasekar. "On the possibility of retrieving near-surface rain rate from the microwave sounder SAPHIR of the Megha-Tropiques mission." CURRENT SCIENCE 106.4 (2014): 587

Krishnamoorthy, C., Deo Kumar, and C. Balaji. "Retrieval of humidity and temperature profiles over the oceans from INSAT 3D satellite radiances." Journal of Earth System Science 125.2 (2016): 217-230.

Krishnamoorthy C and C. Balaji, "Ingesting microwave sounder radiances for improvement in track forecast of cyclone VARDAH." Journal of Applied Remote Sensing 12, no 2 (2018): 026015

Conferences:

Krishnamoorthy, C., and C. Balaji. "The Effect of Assimilating Clear-Sky INSAT 3D Radiances on Heavy Rainfall Prediction over Indian Region." AMS conference on Mesoscale Processes, 2017

Krishnamoorthy, C., and C. Balajia. "Impact of horizontal and vertical localization scales on microwave sounder SAPHIR radiance assimilation." SPIE Asia-Pacific Remote Sensing. International Society for Optics and Photonics, 2016.

Krishnamoorthy, C., and C. Balaji. "Variational retrieval of atmospheric humidity profiles from microwave sounder SAPHIR of Megha-Tropiques." Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International. IEEE, 2015.

Thank you !