MAUSAM, **72**, 1 (January 2021), 107-118

551.515.2 : 551.509.32 (267)

Assimilation of satellite and other data for the forecasting of tropical cyclones over NIO

V. S. PRASAD, SURYAKANTI DUTTA, SUJATA PATTANAYAK, C. J. JOHNY,

JOHN P. GEORGE, SUMIT KUMAR and S. INDIRA RANI

National Centre for Medium Range Weather Forecasting (NCMRWF),

MoES, A-50, Sector 62, NOIDA,UP

e mail : vsprasad@ncmrwf.gov.in

सार – उत्तर हिंद महासागर (NIO) में आने वाले उष्णकटिबंधीय चक्रवात अन्य समुद्री बेसिन की तुलना में गर्म कोर, अत्यधिक विनाशकारी और कम अवधि तक रहने वाले होते हैं। इन चक्रवातों के संख्यात्मक पूर्वानुमान में प्रारंभिक मान की मुख्य समस्या होती है। प्रारंभिकस्थिति की सटीकता मुख्य रूप से पूर्वानुमान मॉडल, घनत्व और प्रेक्षणों की गुणवत्ता तथा आंकड़ों के समावेश करने की योजना पर निर्भर करती है। नवीनतम संख्यात्मक मॉडलिंग प्रणाली अधिकांशतः चक्रवाती प्रणाली की उत्पत्ति का यथोचित पूर्वानुमान करने में सक्षम है, परन्तु अक्सर, वे सही स्थिति और तीव्रता को बनाए रखने में विफल रहते हैं। चक्रवात के पूर्वानुमान मेंउपग्रह प्रेक्षण महत्वपूर्ण भूमिका निभाते हैं क्योंकि वे खुले महासागर के विरल आंकड़ों को भी समाहित करते हैं। अक्सर इन प्रणालियोंकी तीव्रता और संरचनात्मक विशेषताओं को दूरस्थ संवेदी आंकड़ों से अनुमान लगाने की आवश्यकता होती है। उष्णकटिबंधीय चक्रवातों के स्थान और तीव्रता को बेहतर बनाने के लिए संख्यात्मक मौसम पूर्वानुमान प्रणाली (NWP) में उपग्रहप्रेक्षणों का तेजी से उपयोग किया जा रहा है। प्रस्तुत अध्ययन में भारत में विभिन्न स्रोतों से उपग्रह और अन्य विविध प्रेक्षणों की प्राप्ति और समावेशन में किए गए प्रयासों पर प्रकाश डाला गया है। प्रेक्षण प्रणालीप्रयोग (OSE) करके तथा पूर्वानुमान संवेदनशीलता प्रेक्षण प्रभाव (FSOI) अध्ययन के माध्यम से इन प्रेक्षणों के प्रभावों का अध्ययन किया गया है। उत्तर हिन्द महासागर में उष्णकटिबंधीय चक्रवातों पर हाल के कुछ OSE तथा FSOI के माध्यम से अधिक लाभकारी प्रेक्षणों की एक सूची इस शोध पत्र में प्रस्तुत की गई है।

ABSTRACT. Tropical Cyclones that occur over the North Indian Ocean (NIO) are warm cored, highly devastating and short-lived compared to other oceanic basins. Numerical prediction of these cyclones is mainly an initial value problem. Accuracy of the initial position largely depends on forecasting model, density & quality of observations and data assimilation scheme. State of the art numerical modeling systems are able to predict the genesis of most cyclonic systems reasonably well, but often, they fail to maintain the correct position and intensity. Satellite observations play an important role in cyclone prediction as they also cover data sparse open ocean. Often intensity and structural characteristics of these systems need to be inferred from the remotely sensed data. Satellite observations are increasingly being used to better initialize the tropical cyclones' location and intensity in the NWP systems. This study highlights India's efforts in the reception and assimilation of satellite and various other observations from different sources. The impacts of these observations are studied by carrying out Observing System Experiment (OSE) and through Forecast Sensitivity Observation Impact (FSOI) studies. Some of the recent OSEs on Tropical Cyclones over the NIO and a list of more beneficial observations through FSOI are presented in this paper.

Keywords – OSE, FSOI, Tropical cyclone.

1. Introduction

Advancement of science and technology leads to a revolution in the procurement of weather related observations, especially through the sensors onboard varied satellite platforms. Conventional observations with poor spatial and temporal resolution and uneven distribution over the globe have made satellite observations crucial for Numerical Weather Prediction (NWP). Various instruments and sensors onboard the Geostationary and Low Earth orbiting (LEO) spacecraft provide new meteorological information, most of which are received and processed at the respective satellite operating centers. Some of the satellites can directly broadcast the information to various ground receiving stations while passing over that area. Most of the global NWP centers have special arrangements with satellite data providers to receive the satellite data on a near real time basis for its use in the NWP systems.

In the recent past, India has made special efforts to increase the volume of its meteorological and

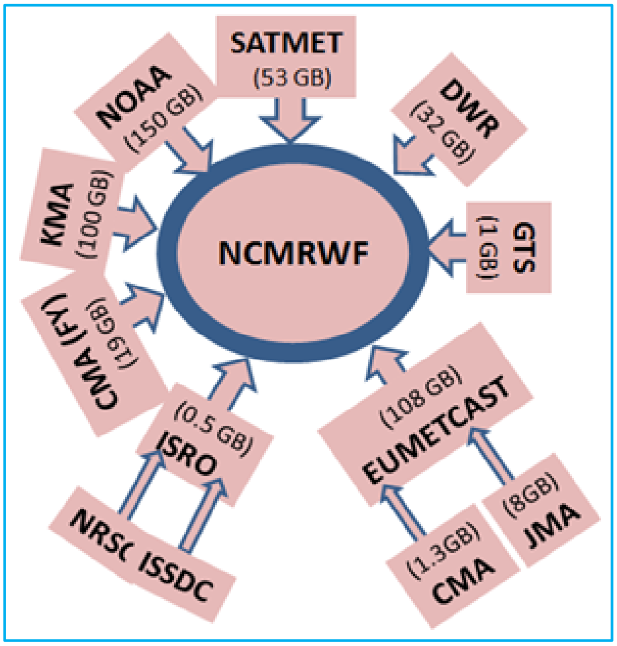


Fig. 1. Meteorological Observation Reception System at NCMRWF

oceanographic satellite data reception by making arrangements to receive these data directly from the satellite data providers. These arrangements complement the conventional reception of data through GTS (Global Telecommunication System) from RTH (Regional Telecommunication Hub) in New Delhi. The data from NOAA (National Oceanographic and Atmospheric Administration), CMA (China Meteorological Administration) and KMA (Korea Meteorological Administration) are being received from their respective data access servers PDA, FY4 and GK5, respectively, using internet protocols. Data from the EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) is being received from its terrestrial broadcast using the connectivity between NKN of India and NERN of Europe. The establishment of EUMETCast reception system, primary data dissemination mechanism of EUMETSAT, at NCMRWF (National Centre for Medium Range Weather Forecasting) became possible due to the signing of an MoU between India Meteorological Department (IMD) and EUMETSAT. Further, to enhance the timely availability of various LEO satellite data, India has joined the WMO's (World Meteorological Organization) DBNET, which uses GTS connectivity for data transfer. With these arrangements, satellite data reception for NWP in India has increased manifold. The data reception system at NCMRWF is depicted in Fig. 1.

Observations are required to be monitored both for their quantity and quality. A robust data monitoring mechanism is in place at NCMRWF and various reports generated by this system is hosted at https://www.ncmrwf.gov.in/t574-model/obs_monitor at six hourly intervals (0000, 0600, 1200 and 1800 UTC). Whenever NCMRWF receives new types observations such as scatteometer winds, INSAT AMV's, etc., new monitoring and validation mechanism for that dataset has been developed and implemented without delay (for example, Das Gupta and Rani, 2013). The impact of various satellite observations on the forecast skill needs to be studied with respect to the NWP model before its operational use. Traditionally the impact of observations on the forecast skill has been estimated through Observing System Experiments (OSEs). But in the recent past, a new adjoint-based observation sensitivity technique, called Forecast Sensitivity to Observation Impact (FSOI), has been developed and employed (Zhu and Gelaro, 2008; Cardinali and Buizza, 2004; Langland and Baker, 2004; Baker and Daley, 2000; Kumat *et al*., 2018). OSE is the common technique used to evaluate the newly available dataset (Peng *et al*., 1996; Barbieri *et al*., 2017; James *et al*., 2017; Ballarotta *et al*., 2020; Chen *et al*., 2020; Lupu *et al*., 2012; Randriamampianina *et al*., 2019). OSE involves a minimum of two sets of simulations using the assimilation-forecast system. The first, known as the 'control' run, use the baseline set of observations. The second one, called the 'experiment' run, is conducted by adding or denying a specific observation or set of observations. The presence or absence of a dataset is the only difference between the two simulations. The corresponding impact due to this addition or denial of observation is measured by comparing various statistical scores. The positive or negative impact obtained due to the addition or denial of a particular dataset can be attributed to the improvement or deterioration of initial conditions, respectively, so obtained from the assimilation system. Lupu *et al*. (2012) reported that the denial of certain observation types from the assimilation system influenced the effective weight of the remaining observations assimilated into the system. These results were illustrated through OSE using DFS (degree of freedom for signal) based methodology.

In FSOI, the observation's contribution to the forecast is measured by evaluating the observation impact with respect to a scalar function that represents the short-range forecast error. In general, it can be used to estimate the sensitivity measure with respect to any parameter of importance in the assimilation system. There are specific basic differences between the FSOI approach and the OSE. Unlike the OSE where the initial conditions get modified, the adjoint-based FSOI technique does not involve the comparison of two sets of simulation, one of which has data added or denied. It measures the observation impact on a specific forecast metric,

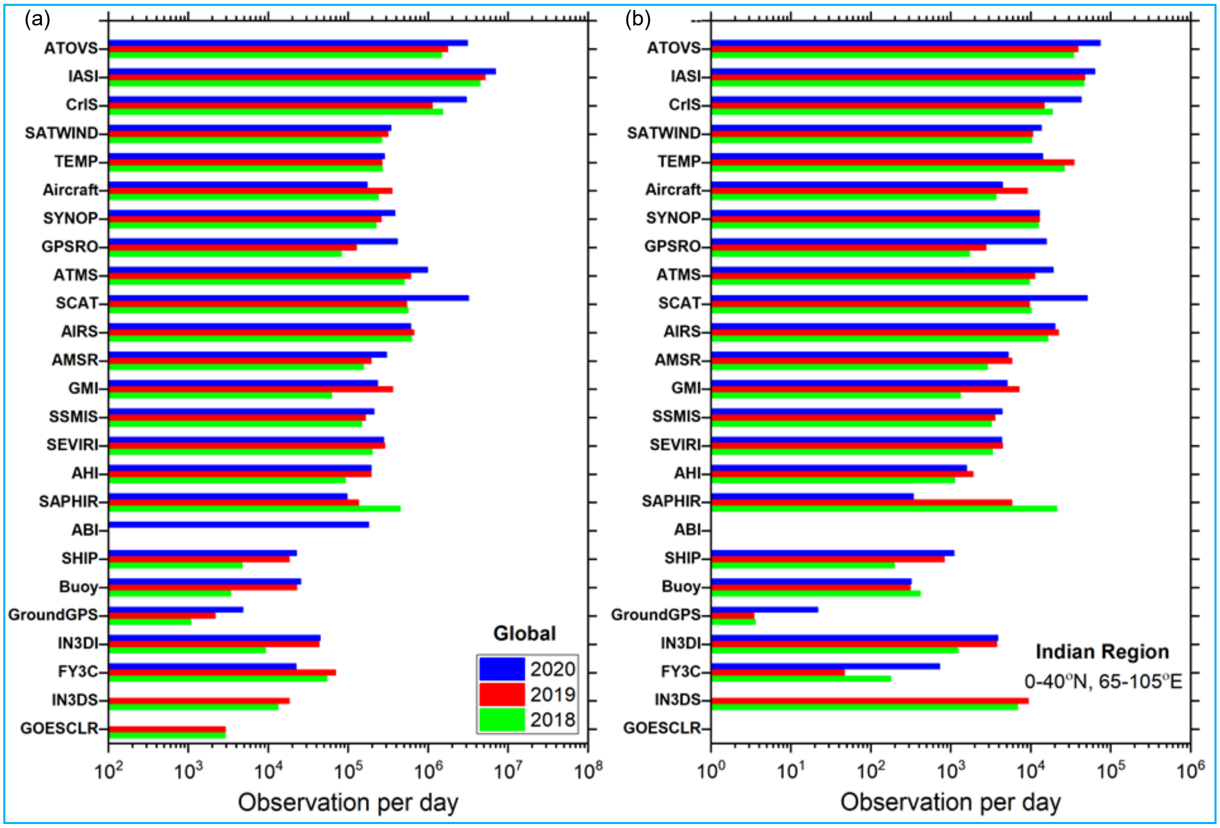
TABLE 1

Observations operationally used in the Data Assimilation systems at NCMRWF

Conventional Observations	Satellite Observations						
	Satellite Winds (AMV)		Scatterometer Winds	Satellite Radiances			GPSRO
	GEO	LEO		GEO	LEO		LEO
				IR	IR (HyS)	MW	Bending Angle
Surface: Land SYNOP (TAC & BUFR)	INSAT-3D	NOAA-15	ASCAT (MetOp-A)	INSAT-3D Imager	IASI (MetOp-A)	AMSU-A (MetOp-A)	COSMIC-1
	Meteosat-8	NOAA-18	ASCAT (MetOp-B)	SEVIRI (Meteosat-8)	IASI (MetOp-B)	AMSU-A (MetOp-B)	GRAS-A
SHIP (TAC & BUFR)	Meteosat-11	NOAA-19	Scatsat	SEVIRI (Meteosat-11)	AIRS (AQUA)	AMSU-A (NOAA-18)	GRAS-B
BUOY, TC BOGUS	HIMAWARI	MetOp-A	Windsat (Coriolis)	AHI (HIMAWARI-8)	CrIS (SNPP)	AMSU-A (NOAA-19)	TanDEM-X
	GOES-16	MetOp-B		INSAT-3D/3DR Sounder	CrIS (NOAA-20)	MHS (MetOp-A)	TerraSAR-X
Profiles: PILOT, TEMP (RS/RW-Both TAC & BUFR)	GOES-17	AQUA				MHS (MetOp-B)	FY-3C
		TERRA				MHS (NOAA-19)	COSMIC-2
Wind Profiler, Drop Sonde		SNPP				MT-SAPHIR	
		NOAA-20				ATMS (SNPP)	
DWR VAD Winds						SSMIS (DMSP-F17)	
Aircraft: AMDAR, AIREP						AMSR-2 (GCOM-W1)	
						FY-3C	
						GMI (GPM)	
						ATMS (NOAA-20)	

considering a full set of observations assimilated into the system. It quantifies the impact by computing the contribution to the reduction in forecast error by each of the observations present in the system. OSE instead quantifies the impact due to change in the observation set on various forecast metrics. FSOI technique can have either an adjoint or ensemble based approach. At NCMRWF, an adjoint-based FSOI approach is operational, which requires adjoint operators for both the tangent linear model. Use of tangent linear assumption and the adjoint model for backward propagation of forecast error information limits the validity of the impact diagnostic for 24 hours of forecast. On the contrary, OSE's can qualitatively and quantitatively measure even long-range forecast impact.

In India, NCMRWF is the leading modelling and Data Assimilation Centre. It routinely uses two different Global Data Assimilation and Forecasting (GDAF) systems; based on NCEP GFS and "Unified Model (UM) Partnership" (hereafter referred to as NCMRWF Unified Model, NCUM) frameworks. As described above, with the reception of new satellite data, many OSE (Prasad *et al.*, 2013; Rani *et al.*, 2014; Routray *et al.*, 2016; Johny *et al.*, 2019) and FSOI (Kumar *et al.*, 2018) experiments were conducted to study the impact of observations on the skill of the model forecasts. Based on OSE, the observations showing a neutral or beneficial impact on forecast quality have been included in the assimilation system. Once the new observation is validated and tested through OSE, their impact is monitored through FSOI on a routine basis.



Figs. 2(a&b). Observations assimilated per day in (a) global and (b) regional domains at NCMRWF in 2018, 2019 and 2020

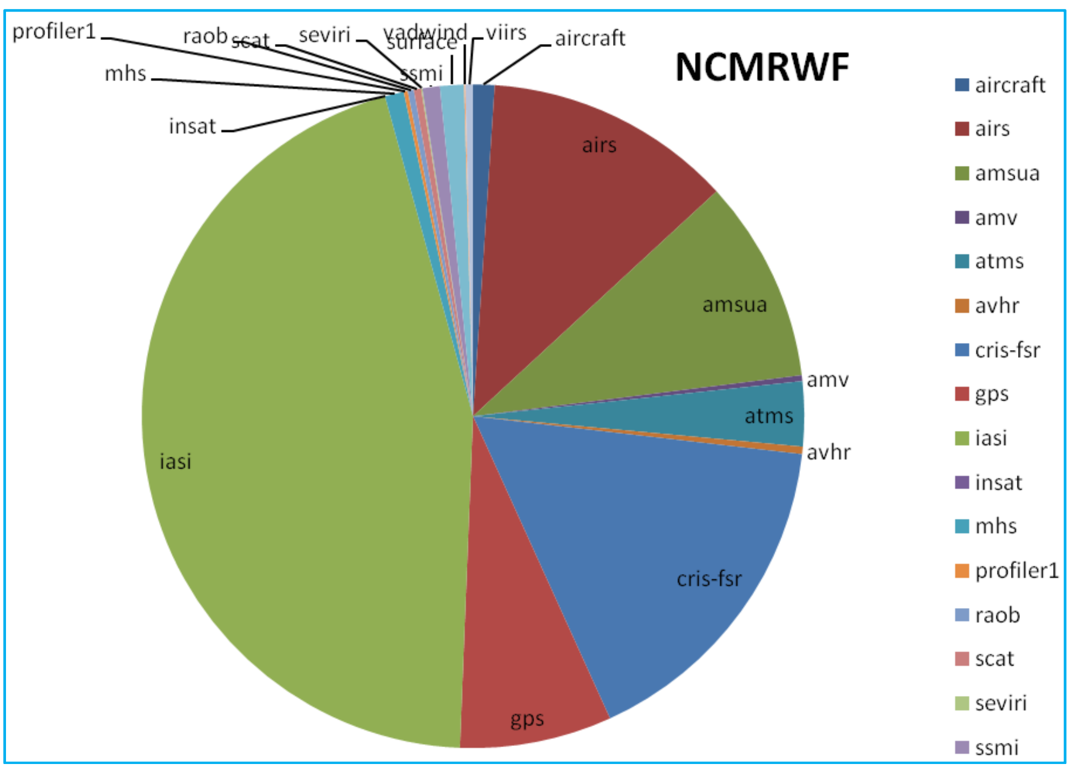


Fig. 3. Pie-Chart of the data volume and type of observations assimilated in the NCMRWF assimilation systems

Satellite observations from multiple sensors and varied forms have increased as seen from Figs. 2(a&b) except for few satellite platforms. The figure depicts the variations in the type and number of observations for the last three consecutive years assimilated in global [Fig. 2(a)] and regional [Fig. 2(b)] models. Compared to the conventional, satellite observation leads, in type and number, in the observations assimilated per day. Observations, especially from different satellite platforms, are increasing in number with time, as shown in Figs. 2(a&b). Contrary to most, there is a noticeable decrease in TEMP & AIRCRAFT observations in 2020 over the Indian region [Fig. 2(b)].

Table 1 lists the various observations that are being presently assimilated operationally at NCMRWF. GSI 4D-EnVar system at NCMRWF uses nearly the same set of observations used in the Hybrid 4D-Var data assimilation system of NCUM except for the INSAT-3D imager and microwave radiances from sensors onboard FY-3C. With the inclusion of new data sets, the volume of satellite data that are assimilated has increased many folds. It constitutes more than 90% of the total observations that are assimilated (Fig. 3). The impact of a few new observations on tropical cyclone forecasting over the north Indian Ocean (NIO) is discussed in this paper.

Section 2 provides a brief account of the national and international status of OSEs with satellite data, where few of the works on tropical cyclones over the NIO are highlighted. Section 3 explains the cyclogenesis in GDAS (Global Data Assimilation System) and section 4 provides a short note on FSOI based on NCUM.

2. National and international status on OSE with satellite data

2.1. *Satellite radiances*

The majority of satellite observations assimilated in the NWP models are in the form of radiances (or brightness temperature). Initially, satellite derived geophysical parameters (like temperature, humidity, precipitation rate, etc.) were only assimilated in the data assimilation systems. With advancements in data assimilation techniques, direct assimilation of satellite radiances is now operational in all leading NWP centers. One of the first OSEs conducted by Hayden (1973), assimilated temperature measurements derived from radiance data from Satellite Infrared Spectrometer (SIRS) onboard NIMBUS-4 using 4-dimensional assimilation technique. His experiment confirmed the possibility of real data getting assimilated into the NWP model and subsequent improvement of the analysis. Atkins and Jones (1975) evaluated the temperature profile from Satellite Infrared Spectrometer (SIRS) and found a modest improvement in the forecast. Manobianco *et al*. (1994) tested the impact of satellite derived precipitation rates on extratropical cyclone simulation and reported a profound impact on the low-level vertical motions, in addition to the frontal positions and mean sea level pressure minima. Dutta *et al*. (2013) examined the precipitation rate from SSM/I sensor onboard the DMSP satellites through OSE and found improvement in the forecast over the Tropics and Indian regions. Barbieri *et al.* (2017) reported lowering of geopotential anomaly correlation and increases in wind root mean square error (RMSE) when denied satellite radiances, GPSRO and radiosonde data in the Global 3DVar assimilation system. Dutta *et al*. (2016) assimilated surface sensitive infrared radiances from AIRS and IASI over land and using OSE showed significant positive impact beyond day-2 forecast over the Northern Hemisphere extra-tropics. Reale, *et al*. (2018) used a combination of OSE and adjoint methodologies to evaluate adaptive thinning methodology through AIRS radiance assimilation and showed improvement in the global skill of NWP model forecast and tropical cyclone representation. Bohra *et al*. (1998) and Prasad *et al*. (1999) studied the impact of NOAA-TOVS temperature profile data on the GDAF system. They showed the requirement for the direct radiance assimilation for enhancing the positive impact of satellite profile data. Further, Prasad *et al*. (2003) showed the impact of INSAT CMV (Cloud Motion Vector Wind) when reassigning their height using NWP first guess. Impact of IASI, CrIS and AIRS hyperspectral radiances in the NCMRWF NWP systems were reported by Sharma *et al*. (2016); Srinivas *et al*. (2016) and Mallick *et al*. (2016) through OSEs. The impact of the radiances from microwave humidity and temperature channels through OSEs and FSOI were reported by Rani *et al*. (2016 a&b) and Kumar *et al*. (2018). Similarly, the impact of the infrared radiances from Indian geostationary satellites in the NCUM 4D-VAR assimilation and forecast system were reported by Rani *et al*. (2016c and 2019). James *et al*. (2017), using GSI Hybrid Ensemble-Variational Data Assimilation with Hourly Update Rapid Refresh Model, did OSE’s during three seasons and found GOES cloud observations have a major positive impact. In addition to the operational agencies' daily weather forecasts, forecasting of severe weather events like cyclones, thunderstorms, western disturbance, etc., are of utmost importance and priority. These severe weather events responsible for the mass destruction of life and property require accurate forecasts. Data used for the assimilation are also tested on their ability to improve the forecast of severe weather events. Peng *et al*. (1996) assimilated the rainfall rates retrieved from SSM/I and showed a reduction in the 48-hr forecast position error of cyclones. Deb *et al*. (2010) showed improvement in initial position errors and track forecasts of tropical cyclones due to the assimilation of Kalpana-1 derived water vapor winds. Routray *et al*. (2016 a) reported improvements in cyclone track along with intensity and landfall position over the Bay of Bengal on assimilating the satellite radiances in the Weather Research and Forecasting (WRF) - 3DVar system. Simulation of NIO cyclones, *viz*., Phailin, Helen, Lehar and Madi formed during 2013, using radiative transfer models and their comparison with observations was reported in Rani and Prasad (2014). Rani *et al*. (2016) analyzed the structure of warm-core of the cyclone Phailin (8-14 October, 2013) formed over the NIO using the brightness temperatures from various channels of INSAT-3D sounder and reported multiple maxima with a strong primary maximum in the middle level (600-500 hPa) and the secondary maximum in the upper level (300-250 hPa), unlike the conventional belief suggested warm core existence at 250 hPa. Routray *et al*. (2016b) demonstrated the impact of hyperspectral radiances on the simulation of Tropical cyclones using regional models. Impact of ASCAT scatterometer winds from MetOp - A and B satellites on the simulation of cyclones in the 4D-VAR frameworks was reported by Srinivas *et al*. (2016).

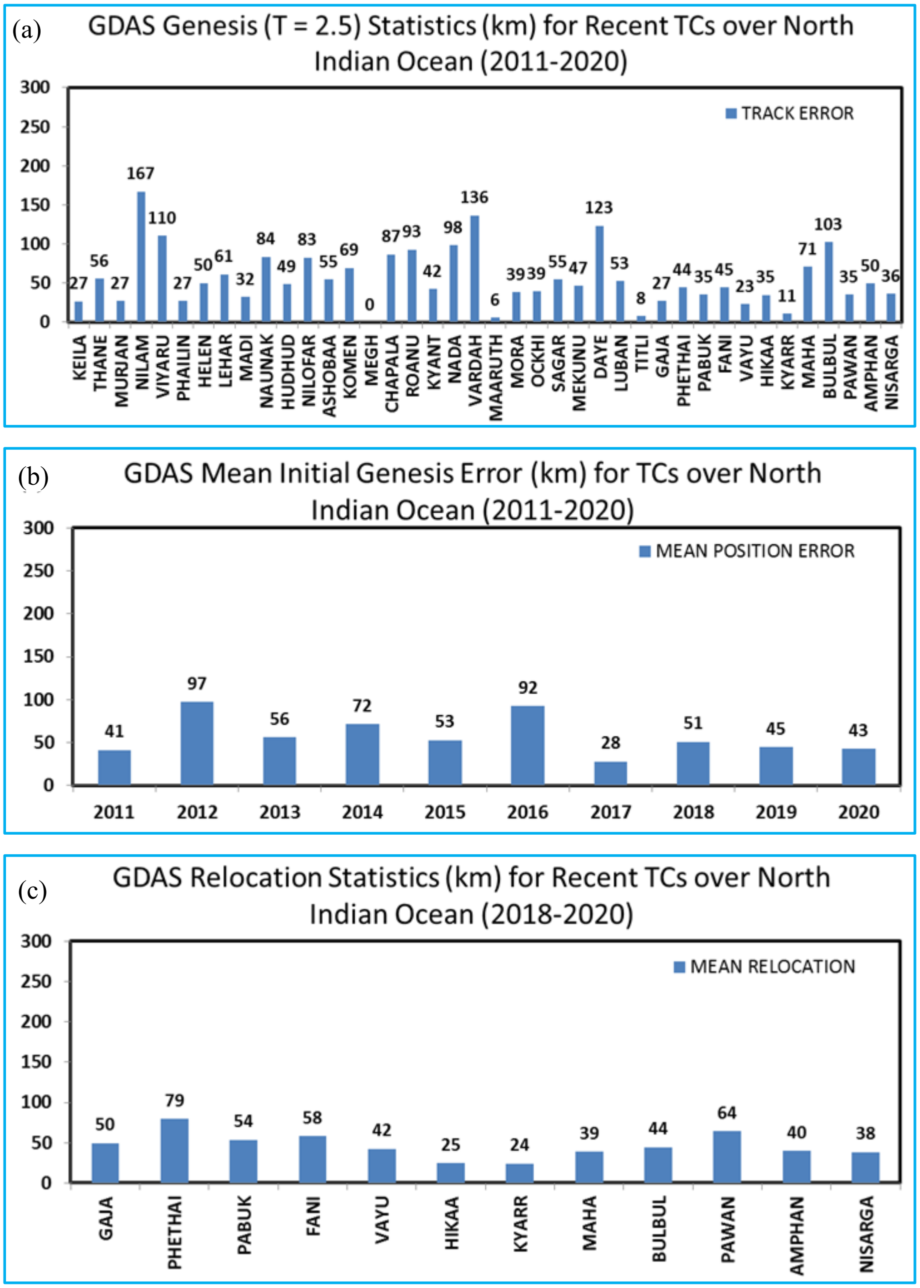
2.2. *Scatterometer wind and AMVs*

Satellite wind measurements are obtained from scatterometer instruments onboard the satellite and AMV (Atmospheric Motion Vector). AMV's enrich the wind information with good aerial coverage in troposphere, especially over the Oceans and higher latitudes. Kumar *et al*. (2017) assimilated INSAT-3D derived AMV's using WRF models and reported improvements in temperature, wind speed and moisture analyses and forecasts over South Africa, Australia and Indian Ocean region. Deb *et al*. (2011) also reported improvements in initial position errors and track forecasts of tropical cyclone, Aila, due to Kalpana-1 derived AMVs' assimilation. Scatterometer measures ocean surface winds and this information is very crucial for the estimation of surface fluxes. The benefits of scatterometer winds are mostly highlighted over the Southern Hemisphere (Yu *et al*., 1984). Improvement in forecast skill (de Haan *et al.*, 2013) and reduction in the RMSE of background winds (Laloyaux *et al*., 2016) were observed on assimilating scatterometer winds from various instruments. Assimilation of wind vectors from Indian scatterometers near the cyclone position at the analysis time has been found to improve the track forecast (Prasad *et al*., 2013; Johny *et al*., 2019 and Bushair *et al*., 2019).

3. Genesis of tropical cyclone

Prasad *et al*. (2013) demonstrated the performance of NWP with GDAS in the prediction of TCs formed over the NIO. They highlighted the tropical cyclone relocation technique's requirement to correct the initial errors in the model first guess. Even a 1% error at the initial model integration time may lead to error growth by 10% in 72 hours and growth thereafter is linear. So, it is very important to provide the best estimate of the storm position (latitude, longitude) at the initial time prior to the data assimilation. This information is provided in the form of an ASCII file called - "TC-VITALS," which contains records of the cyclones occurring all over the globe during that particular assimilation window. These records contain information related to tropical cyclones in a particular format that includes the cyclone centre position (latitude, longitude), intensity (maximum wind, minimum central sea level pressure), structure (radius of maximum wind of four quadrants at 34, 50, 64 knots) and speed and movement of cyclone system (storm speed and direction) in a single line valid for one particular hour. These files for all global cyclones are generated in house at NCMRWF using the tropical cyclone bulletins received through GTS from various global RSMC/cyclone centers (Srinivas *et al.*, 2020). Further, the information in the file regarding cyclones over the NIO region is updated with IMD's information. A detailed evaluation of track and intensity prediction of NCUM for a large number of Tropical Cyclones formed over the NIO is presented in Routray *et al*. (2019).

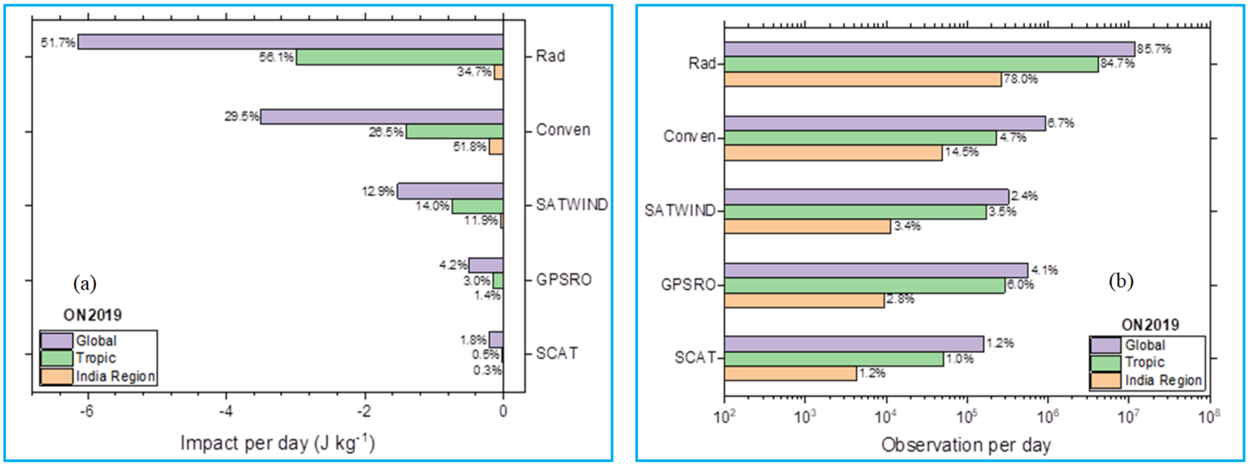
The present study is focused on the TCs of the recent decade (2011-2020). During this period, 40 cyclones formed over the NIO basin. To evaluate the initial position of the TCs, five parameters, u- and v- components of wind, mean sea level pressure, vorticity and geopotential height, are considered. The direct position error (DPE) is evaluated with respect to the best-fit track observation of IMD and is presented in Fig. 4(a). The initial position error for TCs during 2011-2020 is found to be within 50 km for 21 cases and less than 100 km for all other cases except 5 Bay of Bengal (BoB) TCs (NILAM, VIYARU, VARDAH, DAYE and BULBUL). The mean initial genesis error for TCs during the same period is shown in Fig. 4(b). The mean Direct Positional Error (DPE) for the individual years is less than 100 km. In recent years, significant improvement in GDAS analysis has lowered the DPE to consistently less than 50 km. TC relocation procedures were introduced in GDAS in 2018. Fig. 4(c) demonstrates the mean relocation statistics for the recent 12 cyclonic storms during 2018-2020. It includes the mean relocation of the position of individual TCs throughout their life period. Except for few cyclones (Pethai, an Pawan, etc.) where the track error remains higher even after TC relocation, in majority of cases, not only the initial position of the cyclones but also its position in the first guess got improved, with an accuracy of mean error of around 46 km.



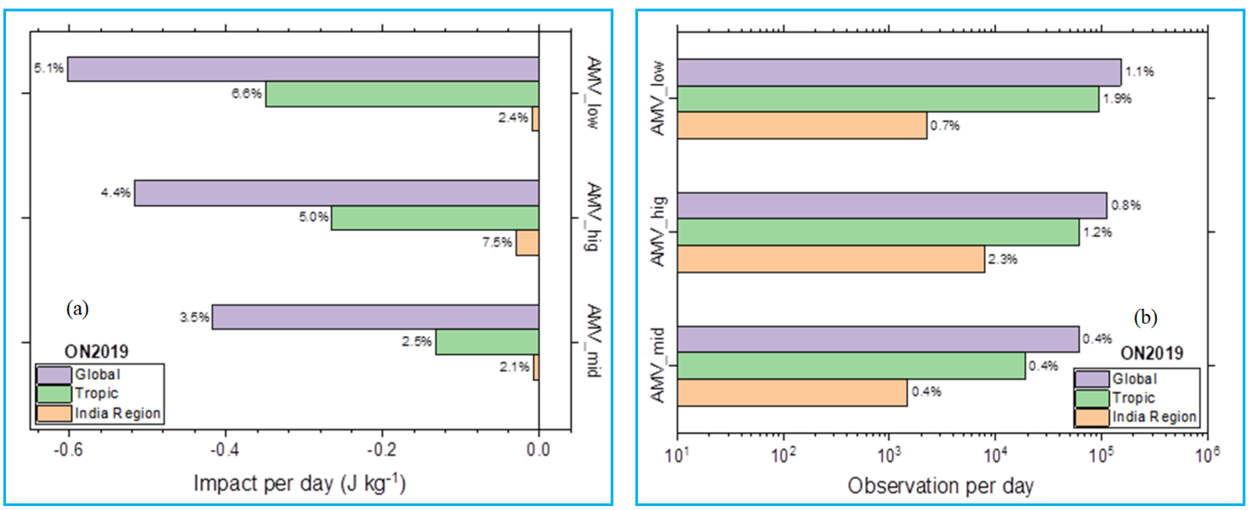
Figs. 4(a-c). GDAS cyclogensis showing (a) Track error (km) for TC's during (2011-2020), (b) Mean position error (km) for TC's during (2011-2020) and (c) Mean relocation ststistics (km) for TC's during (2018-2020)

4. Forecast Sensitivity to Observation Impact (FSOI)

An adjoint-based FSOI method is used to study each observation's forecast impact in the NCUM system for the last few years. A detailed account of the observation impact on NCUM 24 hr forecast, with special focus on satellite microwave humidity observations, during October-November, 2016 and June-August, 2017, was reported in Kumar *et al*. (2018). Considering the cyclonic season of NIO, this FSOI study focuses on the post-monsoon months of October and November 2019. As the study was carried out for a reasonably longer period, the results are applicable to the cyclonic disturbances during that period. The impact of the observation on the forecast per day is expressed in energy norms (in units J/kg) and the observations assimilated per day are discussed here. Observations from different platforms over the Global,



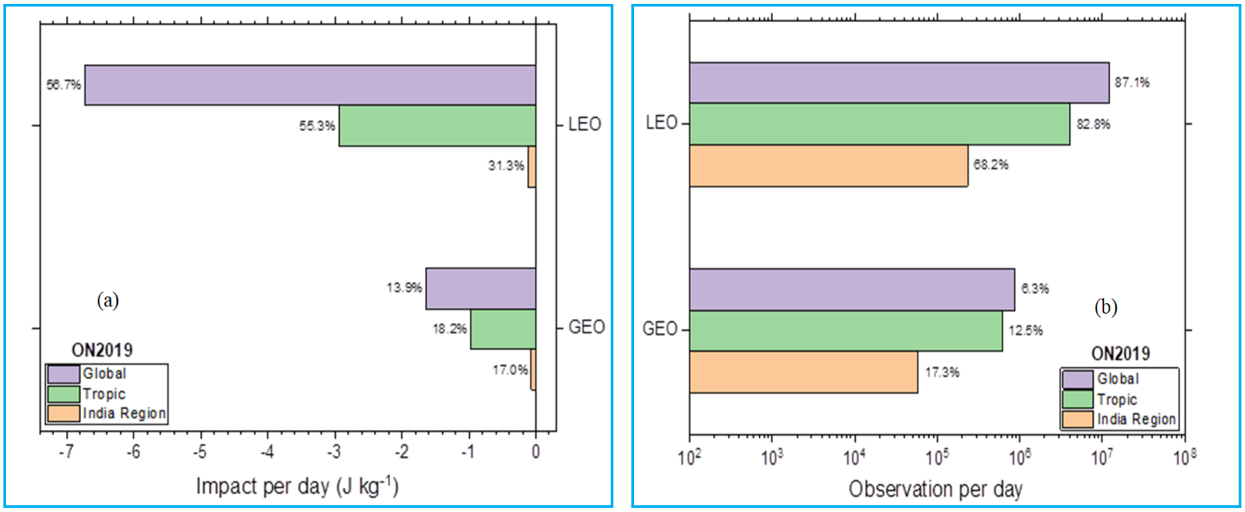
Figs. 5(a&b). (a) Observation impact per day (J/kg) and (b) number of observation per day over Global, Tropics and Indian Region for Satellite Radiance, Conventional data, satellite derived Wind (SATWIND), GPSRO and Scatterometer. Percentages are representative of respective regions. ON2019 indicate the months of October and November of 2019



Figs. 6(a&b). (a) Impact of observation per day (J/kg) and (b) Number of observation per day over Global, Tropics and India Region for AMV's at low, middle and high atmospheric levels. Percentages are representative of respective regions. ON2019 indicate the months of October & November of 2019

Tropics (30° S-30° N) and Indian region (0°-40° N & 65°-105° E) are presented in Figs. (5-7). Percentage values given in the figure against the histograms are representative of the respective region. Large negative "impact" values (impact per observation) indicate a more beneficial impact of the observation on the 24 hr forecast. It should be noted that the impact per day shown in Figs. 5-7 are representative of October and November 2019. The values might change during other months or seasons of the year.

Satellite radiances with the highest observation count [Fig. 5(b)] show major impact [Fig. 5(a)] in Global (51.7%) domain and over the Tropics (56.1%) compared to other observations. Contrary to other two regions, Indian region with lesser conventional observation per day (14.5%) compared to radiance (78.0%), interestingly show higher impact per day (51.8%) for conventional observations. The scatterometer winds with least observation count show lowest impact over all the three regions. Satellite-derived winds (SATWIND) though lower than radio occultation (GPSRO) observations over the Tropics, have higher impact. OSE's have shown that scatterometer winds are crucial and plays a vital role in simulating the early stage of cyclogenesis (Johny *et al.*, 2019). During the stage of depression and deep depression, the assimilation of scatterometer wind improves the system's intensity and location.



Figs. 7(a&b). (a) Impact of observation per day (J/kg) and (b) Number of observation per day over Global, Tropics and India Region for satellites over Low Earth Orbit (LEO) and Geosynchronous Equatorial Orbit (GEO). Percentages are representative of respective regions. ON2019 indicate the months of October & November of 2019

FSOI of AMVs at various tropospheric levels, [lower (1000-700 hPa), middle (700-400 hPa) and high (> 400 hPa)] are presented in Figs. 6(a&b). AMVs in all three levels show highest impact globally [Fig. 6(a)] with the highest observation count per day [Fig. 6(b)]. Over global domain, tropical and Indian regions, highest impact of AMV is seen on the upper tropospheric level. AMV's show least impact over the middle level for all three regions.

FSOI for LEO and GEO satellite observations are presented in Figs. 7(a&b). Many instruments in LEO satellites provide higher observation count than single or two instruments onboard GEO satellites [Fig. 7(b)]. This is observed over all the three regions, which can be inferred from the observation assimilated per day.

5. Summary

This article provides a summarized review of the importance of satellite data in NWP. With the up-gradation of computing resources and advancement of NWP models and data assimilation techniques, assimilation of satellite data has increased over time, in both number and type. NCMRWF made impetus effort and succeeded in receiving global satellite observations directly from the satellite data providers. Satellite observations like radiances, satellite derived winds (*viz.*, AMV, HLOS), scatterometer winds and radio occultation (RO) measurement are the high impact data used in the NWP systems. Various assimilation techniques are being used to exploit and make the best use of available data. Forecasts with very high temporal and spatial precision are needed for severe weather events (like cyclones, thunderstorms, etc.) impacting life and property. The genesis of tropical cyclone is also discussed along with the importance of tropical cyclone relocation technique. With the assimilation of satellite data, the cyclone forecasting has improved in terms of intensity, track and landfall position.

Any observation, conventional or non-conventional, needs critical validation and evaluation before its inclusion in the operational assimilation and forecasting system. Apart from the routine validation of satellite observations against *in situ* observations, OSE and FSOI are the two techniques currently employed in India to evaluate the impact of observation on the forecast for any observation type. This paper highlights the evaluation of observation impact on forecast studies, especially on the tropical cyclone forecast, through OSE and FSOI techniques since both complement each other.

Acknowledgements

The authors express their sincere gratitude and thanks to DG-IMD and Head, NCMRWF for providing the opportunity of writing this article.

References

Atkins, M. J. and Jones, M. V., 1975, "Experiment to determine the value of satellite infrared spectrometer (SIRS) data in numerical forecasting", *Meteorological Magazine*, **104**, 125-142.

Baker, Nancy, L. and Daley, Roger, 2000, "Observation and background adjoint sensitivity in the adaptive observation-targeting problem", *Quarterly Journal of Royal Meteorological Society*, **126**, 1431-1454. doi:10.1002/qj.49712656511.

Ballarotta, Maxime, Clément Ubelmann, Marine Rogé, Florent Fournier, Yannice Faugère, Gérald Dibarboure, Rosemary Morrow and Nicolat Picot, 2020, "Dynamic Mapping of Along-Track Ocean Altimetry: Performance from Real Observations", *Journal of Atmospheric & Oceanic Technology*, **37**, 9, 1593-1601.

Barbieri de Azevedo, Helena, Luis Gustavo Gonçalves de Gonçalves, Carlos Frederico Bastarz, Bruna Barbosa Silveira, 2017, "Observing System Experiments in a 3DVAR Data Assimilation System at CPTEC/INPE", *Weather and Forecasting*, **32**, 3, 873-880.

Bohra, A. K., Ramesh, K. J., Prasad, V. S. and Iyengar, G. R., 1998, "Impact of Satellite derived temperature profile data in Global Data Assimilation and Forecasting System : A Case Study", *The global Atmosphereand Ocean System*, **5**, 345-365.

Bormann, Niels, Lawrence, Heather and Farnan, Jacky, 2019, "Global observing system experiments in the ECMWF assimilation system", ECMWF Technical Memorandum, 839.

Bushair, M. T., Rani, S. I., George, G. and George, J., 2019, "Use of multi-platform satellite derived Ocean surface winds in the NCMRWF assimilation and forecast system", Pro. Ocean Soc. India Conf. (OSICON-19), CMLRE (MoES), Kochi, 12-14 December 2019, 90-91.

Cardinali, C. and Buizza, R., 2004, "Observation sensitivity to the analysis and the forecast : a case study during ATreC targeting campaign", Proceedings of the First THORPEX International Science Symposium, 6-10 December 2004, Montreal, Canada, WMO TD 1237 WWRP/THORPEX N. 6.

Chen, Tse-Chun and Kalnay, Eugenia, 2020, "Proactive Quality Control: Observing System Experiments Using the NCEP Global Forecast System", *Monthly Weather Review*, **148**, 9, 3911-3931.

Das Gupta, M. and Rani, S. I., 2013, "Validation of Kalpana-1 atmospheric motion vectors against upper air observations and numerical model derived winds", International Journal of Remote Sensing, **34**, 7, 2350-2367. doi : 10.1080/01431161.2012.744489.

de Haan, S., Marseille, G., de Valk, P. and Vries, J. de, 2013, "Impact of ASCAT Scatterometer Wind Observations on the High-Resolution Limited-Area Model (HIRLAM) within an Operational Context", *Weather & Forecasting*, **28**, 489-503. https://doi.org/10.1175/WAF-D-12-00056.1.

Deb, S. K., Kishtawal, C. M. and Pal, P. K., 2010, "Impact of Kalpana-1-Derived Water Vapor Winds on Indian Ocean Tropical Cyclone Forecasts", *Monthly Weather Review*, **138**, 3, 987-1003.

Deb, S. K., Kumar, Prashant, Pal, P. K. and Joshi, P. C., 2011, "Assimilation of INSAT data in the simulation of the recent tropical Cyclone Aila", *International Journal of Remote Sensing*, **32**, 18, 5135-5155.

Dutta, S. K., Garand, L. and Heilliette, S., 2016, "Assimilation of Infrared Radiance Observations with Sensitivity to Land Surfaces in the Canadian Ensemble–Variational System", *Journal of Applied Meteorology and Climatology*, **55**, 561-578.

Dutta, Surya K. and Prasad, V. S., 2013, "Impact of Precipitation Rate Assimilation over India and Surrounding Regions", *Earth Science Research*, **2**, 1, 74-92.

Hayden, C. M., 1973, "Experiments in the Four-Dimensional Assimilation of Nimbus 4 SIRS Data", *Journal of Applied Meteorology*, **12**, 425-436.

James, Eric P., Benjamin, Stanley G., 2017, "Observation System Experiments with the Hourly Updating Rapid Refresh Model Using GSI Hybrid Ensemble-Variational Data Assimilation", *Monthly Weather Review*, **145**, 8, 2897-2918.

Johny, C., Singh, S., Prasad, V. S., 2019, "Validation and Impact of SCATSAT-1 Scatterometer Winds", *Pure and Applied Geophysics*, **176**, 2659-2678.

Kumar, P., Deb, S. K., Kishtawal, C. M. and Pal, P. K., 2017, "Impact of assimilation of INSAT-3D retrieved atmospheric motion vectors on short-range forecast of summer monsoon 2014 over the South Asian region", *Theoretical and Applied Climatology*, **128**, 575-586.

Kumar, S., Rani, S. I., George, J. P. and Rajagopal, E. N., 2018, "Megha-tropiques SAPHIR radiances in a hybrid 4D-Var data assimilation system: Study of forecast impact", *Quarterly Journal of Royal Meteorological Society*, **144**, 792-805. https://doi.org/10.1002/qj.3251.

Laloyaux, Patrick, Jean-Noël Thépaut and Dick Dee, 2016, "Impact of Scatterometer Surface Wind Data in the ECMWF Coupled Assimilation System", *Monthly Weather Review*, **144**, 3, 1203-1217.

Langland, Rolf H. and Nancy L. Baker, 2004, "Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system", *Tellus*, **56A**, 189-201.

Lupu, Cristina, Pierre Gauthier, Stéphane Laroche, 2012, "Assessment of the Impact of Observations on Analyses Derived from Observing System Experiments", *Monthly Weather Review*, **140**, 1, 245-257.

Mallick, S., Rani, S. I., Srinivas, D. and George, J. P., 2016, "Assimilation of CrIS Hyperspectral Radiances in a 4D-Var Assimilation System", Proc. SPIE 9880, Multispectral, Hyperspectral and Ultraspectral Remote Sensing Technology, Techniques and Applications VI, 98800Q (April 30, 2016); doi : 10.1117/12.2222775, SPIE 2016, 4-7 April 2016, Delhi.

Manobianco, John, Steven Koch, Mohan Karyampudi V. and J. Negri, Andrew, 1994, "The impact of assimilating satellite derived precipitation rates on numerical simulations of the ERICA IOP 4 cyclone", *Monthly Weather Review*, **122**, 341-365.

Peng, M. S. and Chang, S. W., 1996, "Impacts of SSM/I retrieved rainfall rates on numerical prediction of a tropical cyclone", *Monthly Weather Review*, **124**, 1181-1198.

Prasad, V. S., Gupta, Anjari, Rajagopal, E. N. and Basu, Swati, 2013, "Impact of OScat surface wind data on T574L64 assimilation and forecasting system - A study involving tropical cyclone Thane", *Current Science*, **104**, 5, 627-631.

Prasad, V. S., Ramesh, K. J., Bohra, A. K. and Bhatia, R. C., 1999, "Assessment of quality and impact of full resolution TOVS temperatureprofile data on the operational Global Data Assimilation-Forecast Systemof India", *Meteorology and Atmospheric Physics*, **68**, 197-212.

Prasad, V.S & Ramesh, K. & Bohra, A. & Prasad, Sant. (2003). Impact of a consistent height reassignment method for INSAT derived cloud motion vectors. Meteorology and Atmospheric Physics. 83. 163-172.

Randriamampianina, R., Schyberg, H. and Mile, M., 2019, "Observing System Experiments with an Arctic Mesoscale Numerical Weather Prediction Model", *Remote Sensing*, **11**, 981.

Rani S. I. and Gupta, M. Das, 2013a, "An inter-comparison of Kalpana-1 and Meteosat-7 atmospheric motion vectors against radiosonde winds and NWP forecasts during monsoon 2011", *Meterological Applications*, doi : 10.1002/met.1411.

Rani, S. I. and Gupta, M. Das, 2013b, "Oceansat-2 and RAMA buoy winds: A comparison', *Journal of Earth System Science*, **122,** 1571-1582 (2013). https://doi.org/10.1007/s12040-013-0368-x.

Rani, S. I. and Prasad, V. S., 2014, "Simulation and Validation of INSAT-3D sounder data at NCMRWF", 19th International TOVS Study Conference (ITSC-19), Jeju Island, South Korea, https://cimss.ssec.wisc.edu/itwg/itsc/itsc19/program/papers/1_08_rani.pdf.

Rani, S. I., Doherty, M., Atkinson, N., Bell, W., Newman, S., Renshaw R., George, J. P. and Rajagopal, E. N. 2016a, "Assimilation of SAPHIR radiance : Impact on hyper-spectral radiances in 4D-VAR, Proc. SPIE 9880, Multispectral, Hyperspectral and Ultraspectral Remote Sensing Technology", Techniques and Applications VI, 98800M (April 30, 2016); doi : 10.1117/12.2222781, SPIE 2016, 4-7 April, 2016, Delhi (Invited Talk).

Rani, S. I., Gupta, M. Das, Sharma, Priti and Prasad, V. S., 2014, "Intercomparison of Oceansat-2 and ASCAT Winds with In Situ Buoy Observations and Short-Term Numerical Forecasts", *Atmosphere-Ocean*, **52**, 1, 92-102.

Rani, S. I., Prasad, V. S., Rajagopal, E. N. and Basu, S., 2016 a, "Height of warm core in very severe cyclonic storms Phailin: INSAT-3D perspective, Proc. SPIE 9882, Remote Sensing and Modeling of the Atmosphere, Oceans and Interactions VI, 98821J (3 May, 2016); doi: 10.1117/12.2223582.

Rani, S. I., Srinivas, D., Mallick, M. and George, J. P., 2016b, "Impact of Advanced Technology Microwave Sounder data in the NCMRWF 4D-VAR Data Assimilation System", Proc. SPIE 9882, Remote Sensing and Modeling of the Atmosphere, Oceans and Interactions VI, 98820F (May 3, 2016); doi : 10.1117/12.2223501, SPIE 2016, 4-7 April, 2016, Delhi.

Rani, S. I., Taylor, R., George, J. P. and Rajagopal, E. N., 2016c, "Use of INSAT-3D sounder and Imager radiances in the 4D-VAR data assimilation system and its implications in the Analyses and Forecasts", Proc. SPIE 9876, Remote Sensing of the Atmosphere, Clouds and Precipitation VI, 98761G (May 5, 2016); doi : 10.1117/12.2223496, SPIE 2016, 4-7 April, 2016, Delhi.

Rani, S.I., Taylor, R., Sharma, P., Bushair, M.T., Jangid, B.P., George, J.P., Rajagopal, E.N., 2019,"Assimilation of INSAT-3D imager water vapour clear sky brightness temperature in the NCMRWF's assimilation and forecast system", *Journal of Earth System Science*, **128**, 7. https://www.ias.ac.in/article/fulltext/jess/128/07/0197.

Reale, Oreste, Erica L. McGrath-Spangler, Will McCarty, Daniel Holdaway, Ronald Gelaro, 2018, "Impact of adaptively thinned airs cloud-cleared radiances on tropical cyclone representation in a global data assimilation and forecast system", *Weather and Forecasting*, **33**, 4, 909-931.

Routray, A., George, J. P., Singh, V. and Rani, S. I., 2016b, "Impact of Hypersepectral Radiance in the Simulation of Tropical Cyclone using NCUM-Regional Model", Proc. SPIE 9882, Remote Sensing and Modeling of the Atmosphere, Oceans and Interactions VI, 98821C (May 3, 2016). doi : 10.1117/12.2223520, SPIE 2016, 4-7 April, 2016, Delhi.

Routray, Ashish, Dutta, Devajyoti and George, John, P., 2019, "Evaluation of Track and Intensity Prediction of Tropical Cyclones over North Indian Ocean using NCUM Global Model", *Pure and Applied Geophysics*, **176**, 1, 421-440.

Routray, Ashish, Mohanty, U. C., Osuri, Krishna K., Kar, S. C. and Dev, Niyogi, 2016a, "Impact of Satellite Radiance Data on Simulations of Bay of Bengal Tropical Cyclones Using the WRF-3DVAR Modeling System", *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 4, 2285-2303.

Sharma, P., Rani, S. I., Mallick, S., Srinivas, D., George, J. P. and Das Gupta, M., 2016, "IASI hyper-spectral radiances in the NCMRWF 4D-VAR assimilation system : OSE", Proc. SPIE 9880, Multispectral, Hyperspectral and Ultraspectral Remote Sensing Technology, Techniques and Applications VI, 98800P (April 30, 2016); doi : 10.1117/12.2225868, SPIE 2016, 4-7 April, 2016, Delhi.

Srinivas, D., Rani, S. I., Mallick, S. and George, J. P., 2016, "Assimilation of ASCAT Winds using 4DVAR : An Impact study", Proc. SPIE 9882, *Remote Sensing and Modeling of the Atmosphere, Oceans and Interactions VI*, 98821D (May 3, 2016). doi : 10.1117/12.2223523, SPIE 2016, 4-7 April, 2016, Delhi.

Srinivas, D., Rani, S. I., Mallick, S. and George, J. P., 2016, "Impact of AIRS Radiance in the NCUM 4D-Var Assimilation System", Proc. SPIE 9880, Multispectral, Hyperspectral and Ultraspectral Remote Sensing Technology, Techniques and Applications VI, 98800O (April 30, 2016). doi : 10.1117/12.2223516, SPIE 2016, 4-7 April, 2016, Delhi.

Srinivas, Desamsetti, Sanjeev Kumar, Singh, Johny C. J. and Prasad, V. S., 2020, "Generation of TC-Vitals at NCMRWF", *NCMRWF, Technical Report*, NMRF/TR/05/2020.

Yu, Tsann-Wang and Ronald D. Mcpherson, 1984, "Global Data Assimilation Experiments with Scatterometer Winds from SEASAT-A", *Monthly Weather Review*, **112**, 2, 368-376.

Zhu, Y. and R. Gelaro, 2008, "Observation Sensitivity Calculations Using the Adjoint of the Gridpoint Statistical Interpolation (GSI) Analysis System", *Monthly Weather Review*, **136**, 335-351.

Appendix

ABI	-	Advanced Baseline Imager
AHI	-	Advanced Himawari Imager
AIREP	-	Aircraft Report
AIRS	-	Atmospheric Infrared Sounder
AMDAR	-	Aircraft Meteorological Data Relay
AMSR	-	Advanced Microwave Scanning Radiometer
AMSU	-	Advanced Microwave Sounding Unit
ASCAT	-	Advanced Scatterometer

ATMS	-	Advanced Technology Microwave Sounder
ATOVS	-	Advanced TIROS Operational Vertical Sounder
BUFR	-	Binary Universal Form
CMA	-	China Meteorological Administration
COSMIC	-	Constellation Observing System for Meteorology, Ionosphere and Climate
CrIS	-	Cross-track Infrared Sounder
DWR	-	Doppler Weather Radar
EUMETSAT	-	European Organisation for the Exploitation of Meteorological Satellites
FSOI	-	Forecast Sensitivity Observation Impact
FY-3	-	FengYun-3
GEO	-	Geosynchronous Equatorial Orbit
GMI	-	GPM Microwave Imager
GNSS	-	Global Navigation Satellite System
GOES	-	Geostationary Operational Environmental Satellite
GPM	-	Global Precipitation Measurement
GPSRO	-	Global Positioning System Radio Occultation
GRAS	-	GNSS Receiver for Atmospheric Sounding
GTS	-	Global Telecommunication System
IASI	-	Infrared Atmospheric Sounding Interferometer
IMD	-	India Meteorological Department
IN3D	-	INSAT 3D
INSAT	-	Indian Satellite
ISSDC	-	Indian Space Science Data Center
ISRO	-	Indian Space Research Organisation
JMA	-	Japan Meteorological Agency
KMA	-	Korea Meteorological Administration
LEO	-	Low Earth Orbiting
METOP	-	Meteorological Operational Polar Satellite
MHS	-	Microwave Humidity Sounder
NCMRWF	-	National Centre for Medium Range Weather Forecasting
NIO	-	North Indian Ocean
NRSC	-	National Remote Sensing Centre
NOAA	-	National Oceanographic and Atmospheric Administration
NWP	-	Numerical Weather Prediction
OSE	-	Observing System Experiment
RTH	-	Regional Telecommunication Hub
SATMET	-	Satellite Meteorology
SATWIND	-	Satellite Derived Wind
SAPHIR	-	Sondeur Atmosphérique du Profild' Humidité Intertropicale par Radiométrie
SCAT	-	Scatterometer Winds
SEVIRI	-	Spinning Enhanced Visible and Infra-Red Imager
SNPP	-	Suomi National Polar-orbiting Partnership
SSMIS	-	Special Sensor Microwave Imager Sounder
SYNOP	-	Synoptic Observation
TANDEM-X	-	TerraSAR-X add-on for Digital Elevation Measurement
TEMP	-	Temperature Observation
TerraSAR-X	-	X-band Synthetic Aperture Radar onboard Terra satellite
TIROS	-	Television InfraRed Observation Satellite
TOVS	-	TIROS-N Operational Vertical Sounder
VAD	-	Velocity-Azimuth Display
WMO	-	World Meteorological Organization