NMRF/RR/06/2020

सत्यमेव जयते

RESEARCH REPORT

Validation and Assimilation of INSAT Atmospheric Motion Vectors

Priti Sharma, S. Indira Rani and M. Das Gupta

December 2020

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, Noida-201 309, INDIA

Validation and Assimilation of INSAT Atmospheric Motion Vectors

Priti Sharma, S. Indira Rani and M. Das Gupta

December 2020

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences
A-50, Sector-62, Noida-201309, INDIA

Ministry of Earth Sciences
National Centre for Medium Range Weather Forecasting
Document Control Data Sheet

1	Name of the Institute	National Centre for Medium Range Weather Forecasting
2	Document Number	NMRF/RR/06/2020
3	Date of Publication	December 2020
4	Title of the document	Validation and Assimilation of INSAT Atmospheric Motion Vectors
5	Type of Document	Research Report
6	No. of Pages, Figures and Tables	32 Pages, 22 Figures, 4 Tables
7	Number of References	16
8	Author (S)	Priti Sharma, S. Indira Rani and M. Das Gupta
9	Originating Unit	NCMRWF
10	Abstract	Due to enhanced spatial and temporal resolution, Atmospheric Motion Vectors (AMVs) have become one of the important inputs for the Numerical Weather Prediction (NWP) system. In the extratropics, wind field can be derived using mass field, but is not good for the small-scale features in the Tropics. Therefore, the AMVs are one of the crucial observations mainly over the tropical oceans. Indian Space Research Organization (ISRO) launched its first dedicated meteorological satellite, Kalpana-1 positioned at 74^0 E in 2002, and subsequently INSAT-3D (at 82^0E) in 2013 and INSAT-3DR (at 74^0 E) in 2016. The quality of Kalpana-1 AMVs was not comparable to AMVs from other geostationary satellites over the Indian Ocean, however, due to the modification in height assignment and quality control methods, noticeable improvement has been seen in the quality of INSAT-3D AMVs. Recently INSAT-3DR AMVs became available to NCMRWF. In this report, an attempt has been made to validate the INSAT 3DR AMVs against first guess and in-situ observations for May 2020, and results are compared with that for INSAT-3D and Meteosat-8. Study shows that the quality of INSAT-3DR AMVs are similar as that of INSAT-3D and comparable with Meteosat-8. An observing sytem experiment is carried out to see the impact of assimilating INSAT (both 3D and 3DR) AMVs in NCMRWF GFS global data assimilation and forecast system for the prediction of super cyclone "Amphan" formed over the Bay of Bengal(BOB) during 16^{th} – 21^{st} May 2020. Results show positive impact of INSAT AMVs on model analysis and forecast during Amphan.
11	Security classification	Unrestricted
12	Distribution	General
13	Key Words	Atmospheric Motion Vectors, INSAT, Meteosat

Table of Contents

Abstract

Due to enhanced spatial and temporal resolution, Atmospheric Motion Vectors (AMVs) have become one of the important inputs for the Numerical Weather Prediction (NWP) system. In the extratropics, wind field can be derived using mass field, but is not good for the small-scale features in the Tropics. Therefore, the AMVs are one of the crucial observations mainly over the tropical oceans. Indian Space Research Organization (ISRO) launched its first dedicated meteorological satellite, Kalpana-1 positioned at 74^0 E in 2002, and subsequently INSAT-3D (at 82^0E) in 2013 and INSAT-3DR (at 74^0 E) in 2016. The quality of Kalpana-1 AMVs was not comparable to AMVs from other geostationary satellites over the Indian Ocean, however, due to the modification in height assignment and quality control methods, noticeable improvement has been seen in the quality of INSAT-3D AMVs. Recently INSAT-3DR AMVs became available to NCMRWF. In this report, an attempt has been made to validate the INSAT 3DR AMVs against first guess and in-situ observations for May 2020, and results are compared with that for INSAT-3D and Meteosat-8. Study shows that the quality of INSAT-3DR AMVs are similar as that of INSAT-3D and comparable with Meteosat-8. An observing sytem experiment is carried out to see the impact of assimilating INSAT (both 3D and 3DR) AMVs in NCMRWF GFS global data assimilation and forecast system for the prediction of super cyclone "Amphan" formed over the Bay of Bengal(BOB) during 16^{th} – 21^{st} May 2020. Results show positive impact of INSAT AMVs on model analysis and forecast during Amphan.

1. Introduction :

For accurate forecasting of rapidly evolving weather systems, AMVs with enhanced temporal and spatial coverage has become one of the important inputs for the Numerical Weather Prediction (NWP) system. The mass field can be used to derive wind field in the extratropics, however, the same is not good for the small-scale features in the Tropics (Horayani et al., 2014). The AMVs are one of the sources for tropospheric wind data available mainly over the tropical oceans. Indian Space Research Organization (ISRO) launched its first dedicated meteorological satellite, Kalpana-1 positioned at 74^0 E, on 12 September 2002. After Kalpana-1, INSAT-3D exclusively designed for enhanced meteorological observations, positioned at 82^0 E was launched in July 2013. INSAT-3D generates images of the earth in six wavelength bands significant for meteorological observations viz., visible (0.52 - 0.72 μm), shortwave infrared (1.55 - 1.70 μm), middle infrared (3.80 - 4.00 μm), water vapour (6.50 - 7.00 μm) and two bands in thermal infrared regions - TIR1 (10.2 - 11.2 μm) and TIR2 (11.5 - 12.5 μm). The spatial resolution of visible (VIS) and shortwave infrared (SWIR) is 1 km, 4 km for middle infrared (MIR), TIR-1 and TIR-2, and 8 km for water vapour (WV) channels.

NCMRWF started receiving AMV observations from the Indian geostationary satellite through the Global Telecommunication System (GTS) since 2011 and regularly validate the same against NWP model first guess as well as in-situ observations (Das Gupta and Rani, 2013). A comaprison of the Kalpana-1 AMVs with those from other satellites over the same geographical area also has been reported (Rani and Das Gupta, 2013). These validation studies found that the quality of Kalpana-1 AMVs was not comparable to Meteosat-7 and hence were not used in the data assimilation systems operational at NCMRWF. However, subsequent modification in height assignment method and quality control scheme for deriving AMVs considerably improved the quality of INSAT-3D AMVs (Deb et al., 2014, 2016; Das Gupta et al., 2015). For deriving INSAT AMVs three consecutive images of 30-minute intervals are used, which consists of the following steps: 1) Image registration, thresholding, filtering, 2) Features/tracer selection and tracking, 3) Quality control and 4) Height assignment. Following the implementation of new height assignment scheme (Deb et al. 2014), quality of INSAT-3D AMVs was found comparable or better than that of Meteosat-7 over the Indian Ocean region (Das Gupta et al., 2015, Sharma et al., 2016), and NCMRWF has started assimilating the INSAT-3D AMVs operationally. ECMWF also monitor INSAT-3D AMVs regularly and reported that the quality of INSAT-3D AMVs is comparable with that of other satellite AMVs over the Indian Ocean (Salonen and Bormann, 2015). Assimilation experiments conducted using INSAT-3D AMVs in the ECMWF system (Lean and Bormann, 2018) showed INSAT-3D have consistent and closer agreement with the model background, however, the clear sky water vapour winds from INSAT-3D produced negative impacts when assimilated.

To provide service continuity to the earlier Indian meteorological satellite missions, INSAT-3DR (at 74^0 E), the repeat mission of INSAT-3D with similar configuration, was launched by ISRO on 08 September 2016. Recently, NCMRWF has started receiving INSAT-3DR AMVs through GTS along with INSAT-3D AMVs. In this report, an attempt has been made to validate the INSAT-3DR AMVs with in-situ winds and NCMRWF NWP first guess and compare them with that of INSAT-3D and METEOSAT-8. In a separate experiment, INSAT (both 3D and 3DR) winds are used in NCMRWF Global Data Assimilation and Forecast System to assess their impact on Super Cyclone "Amphan".

2. Data and Methodology

In this study AMVs from INSAT-3DR are validated against six-hourly first guess produced from the Global Data Assimilation Forecasting System (GDAFS) at NCMRWF (NGFS) (Prasad et al., 2011) and in-situ winds from the Pilot balloon, Radio-sonde and Aircraft for the month of May 2020. There are both advantages and disadvantages of collocating AMVs against in-situ observations. The main advantage is that it represents an evaluation against independent, unbiased observations; while the disadvantage is the limited geographical coverage, which shows an uneven distribution over land and very few observations over the Ocean. Short-term NWP forecast or analysis products can also be collocated with satellite winds in the same way as in-situ observations. The main advantage of this is the complete geographical coverage and the better temporal sampling of the forecast profiles. This enables a comparison for every AMV, eventhough the forecast model is not free from biases and errors and these in general have an impact on the collocation results as well. To assess the quality of INSAT-3DR AMVs a comparison of the validation statistics with that of INSAT-3D and Meteosat-8 has also been carried out.

2.1 Data

Global meteorological observations including INSAT and Meteosat-8 AMVs are being received at India Meteorological Department (IMD) via GTS and the same are transferred to NCMRWF in real-time. All AMV observations and the in-situ observations (Radio-sonde, Pilot balloon and Aircraft winds) used for validation are extracted from the NCMRWF observation data archive.

AMVs from each INSAT (3D and 3DR) are available at every 30 minutes interval; INSAT-3D and INSAT-3DR starting at 0000 and 0015 UTCs respectively. Combined INSAT (3D and 3DR) satellites provide AMVs at every 15 minutes with better temporal coverage (Deb et al., 2018). However the reception of INSAT AMVs are a bit irregular. It is to be noted that during this study period the reception of INSAT-3DR AMVs was very irregular after 16th May 2020. INSAT AMV bulletins received via GTS didn't append properly. A patch is developed to rectify the issue and decode AMVs using NCMRWF operational GFS decoders.

Meteosat-8, one of the Meteosat Second Generation (MSG-1) satellites, was launched on 28th August 2002 and relocated to 41.5°E on 1st February 2017 for the continuation of the Indian Ocean Data Coverage (IODC) replacing Meteosat-7. MSG satellites has a Spinning Enhanced Visible and Infrared Imager (SEVIRI) imaging radiometer onboard. SEVIRI is a twelve channel imager (four Visible and Near Infrared (VNIR) and eight InfraRed (IR) channels) observing the earth-atmosphere system. Eleven channels observe the earth's full disk with a 15-min repeat cycle.

A high-resolution visible (HRV) channel covers half of the full disk in the east-west direction and a full disk in the north-south direction. Out of twelve channels, eight IR channels and three visible (VIS) channels provide measurements with 3 km resolution whereas the high resolution VIS channel provides measurements with a resolution of 1 km at the subsatellite point. Meteosat-8 AMVs are available at every 45 minutes interval, starting from 00:45 UTC and thus receive AMVs from IR and WV channels 24 times a day, whereas winds from VIS channel are available only during daylight time ~18 times/day, between 01:45 and 18:45 UTC, with maximum winds reception at ~10:45 UTC. Average reception of INSAT-3D, 3DR and Meteosat-8 AMVs, for three different channels namely IR, VIS and WV, for various hours in a day for May 2020 are shown in Figures 1, 2 and 3 respectively. Figures 1(a), (b) and (c) show the half-hourly reception of INSAT-3D and 3DR and the hourly reception of Meteosat-8 AMVs for IR channels at NCMRWF during May 2020.

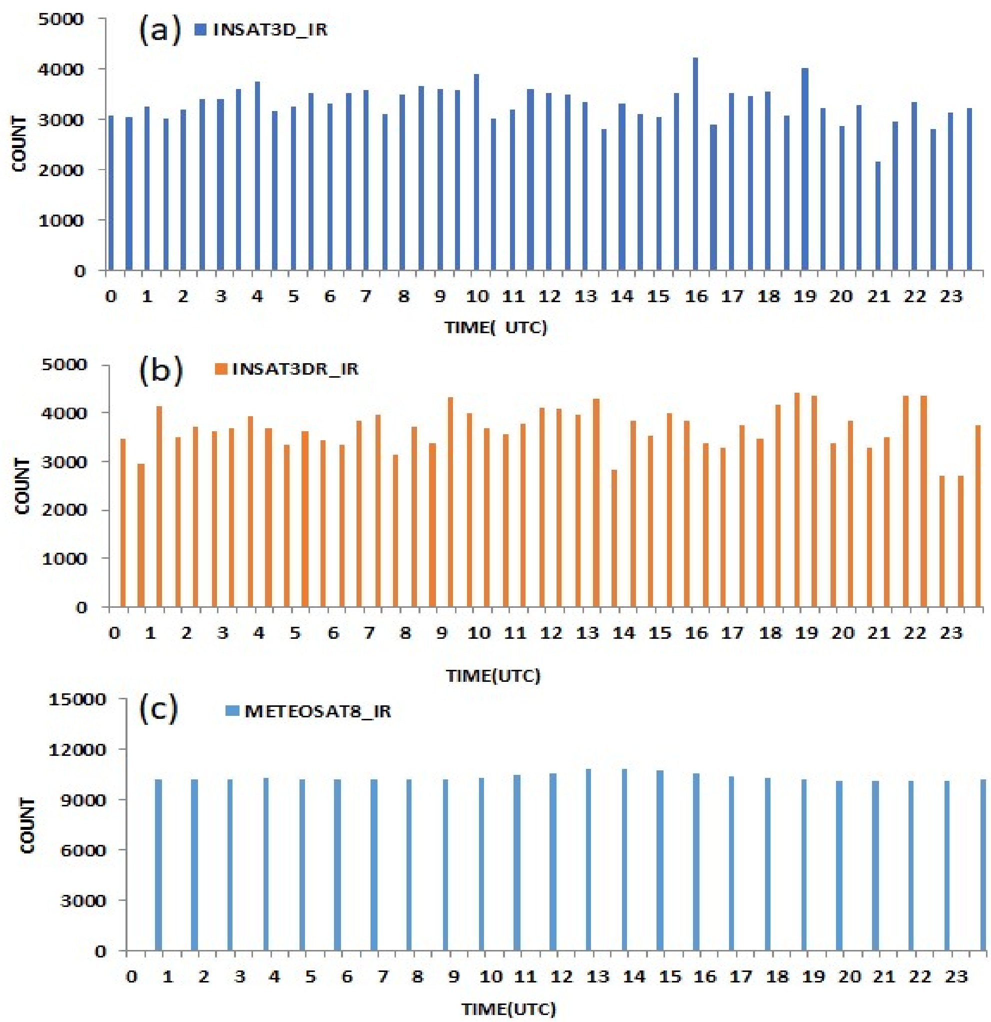

Figure1: Monthly average reception AMVs from IR channels of (a) INSAT-3D, (b) INSAT-3DR and (c) Meteosat-8 at NCMRWF for May 2020.

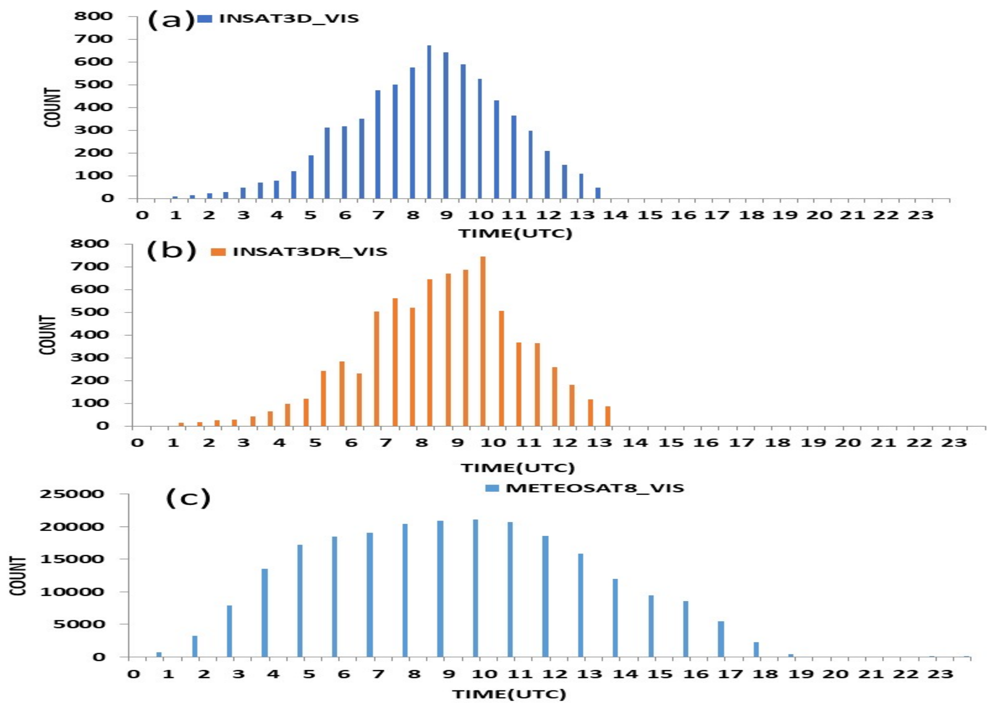

Figure 2: Monthly average reception AMVs from VIS channels of (a) INSAT-3D (b) INSAT-3DR and (c) Meteosat-8 at NCMRWF for May 2020.

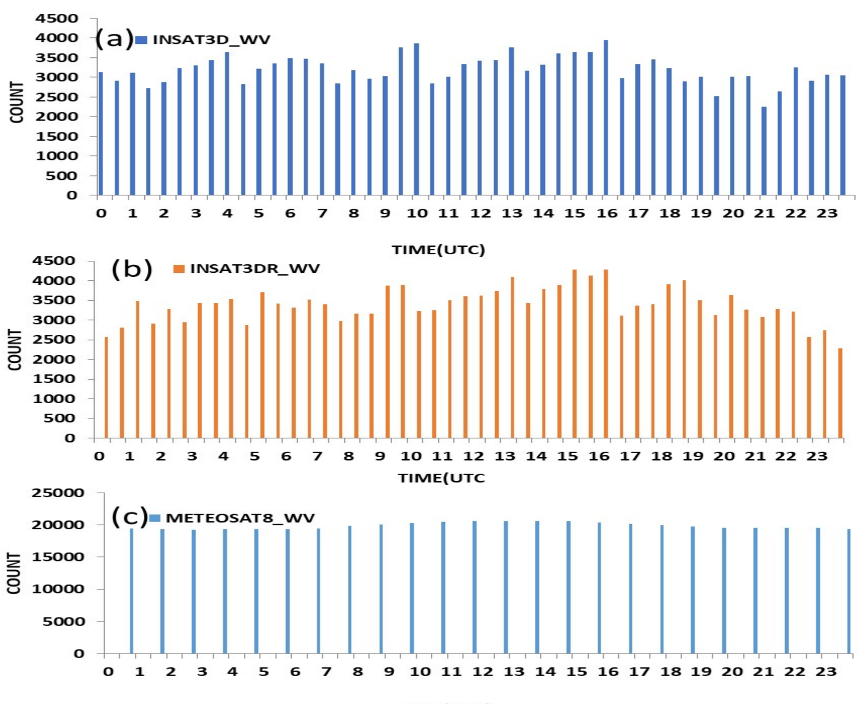

Figure 3: Monthly average reception of AMV from WV channels of (a) INSAT-3D, (b) INSAT-3DR and (c) Meteosat-8 at NCMRWF for May 2020.

It is seen from Figures 1, 2, and 3, the number of Meteosat-8 AMVs are more (~10,000/hour for IR, ~20,000/hour for WV and VIS) as compared to INSAT (3D and 3DR) (~7,000/hour for IR, ~8000/hour for WV and ~800/hour for VIS). This is due to the differences in the (i) image generation frequency of INSAT (3D and 3DR) and Meteosat-8 and (ii) resolution. For both INSATs, imageries are generated at every 30 minutes whereas Meteosat-8 imageries are generated at every 15 minutes (Schmetz et al., 2002). Meteosat-8 images are of higher resolution as compared to INSAT(3D and 3DR) (described in sections 1 and 2.1). Due to navigational problems, INSAT derived winds are sector generated products (SGPs) instead of the full disc (Deb et al., 2018). This is also one the reasons for the less number of INSAT AMVs compared to the Meteosat-8.

2.2 Methodology for validation

Validation of AMVs against in-situ winds from Radio-sonde, Pilot balloon and Aircraft is done as per the criteria set by the Coordination Group for Meteorological Satellites (CGMS). In this criteria collocation of in-situ winds and AMVs are considered only if following conditions are satisfied: (1) they are horizontally within 150 km, vertically within 25 hPa and temporally within 30 minutes (2) collocated winds are within a speed difference of 30 m/s and within a direction difference of 60°. AMVs are validated against NCMRWF NWP first guess following the NWP Satellite Application Facility (SAF) (Forsythe, 2007) criteria. AMVs from all three satellites derived using IR, VIS and WV channels are collocated with the first guess (grid box of 0.5° x 0.5°). Winds derived using IR window channels are available from low to upper level of the atmosphere. WV winds are determined by computing the gradient in water vapour present at the higher level using water vapour absorption band and VIS winds are determined by tracking the low level cloud movement using VIS channel (Rani and Das Gupta, 2013). Thus IR winds are classified as the low level (1000hPa - 700hPa), middle level (700hPa - 400hPa) and high level winds (400hPa - 100hPa), WV winds are considered as high level winds (above 400hpa) and VIS winds as low level winds (below 700hpa).

For validation, statistical parameters are computed for different latitudinal regions viz., Northern Hemisphere (20^0 N-90^0 N), Tropics (20^0 N-20^0 S) and Southern Hemisphere (20^0 S-90^0 S). Statistical parameters viz., mean observation speed, wind speed bias, vector difference (VD), root mean square vector difference (RMSVD) and normalized root mean square vector difference (NRMSVD) are computed as follows

$$Observation\ speed(OS) = \sqrt{obsu^2 + obsv^2}$$

$$Background\ speed(BS) = \sqrt{bgu^2 + bgv^2}$$

$$Speedbias = OS - BS$$

$$Vector\ difference(VD) = \sqrt{(obsu - bgu)^2 + (obsv - bgv)^2}$$

$$Root\ mean\ square\ vector\ difference(RMSVD) = \sqrt{\frac{\sum VD^2}{N}}$$

$$Normalized\ RMSVD(NRMSVD) = \frac{RMSVD}{Mean\ BS}$$

In the above equations, N is the number of collocated points, 'obsu' and 'obsv' are zonal and meridional component of AMVs (ms^{-1}), 'bgu' and 'bgv' are zonal and meridional component of winds (ms^{-1}) from model background.

2.3 Impact Assessment Experiments

AMVs play an important role in defining the initial position as well as the steering flow of tropical cyclones over the Ocean. Tropical cyclone "Amphan" emerged over the BOB on 15th May 2020, intensified rapidly to a Very Severe Cyclonic Storm (VSCS) and made landfall at the West Bengal coast on 20th May 2020. An attempt has been made to assess the impact of assimilating INSAT AMVs on the simulation of super-cyclone Amphan through Observing System Experiment (OSE). Two sets of run have been made using six-hourly intermittent NGFS 4D-VAR data assimilation system at T574L64(~25 km) resolution. In the first set of run (CNTL) all the observations listed in Table 1 from NCMRWF's operational data archive, except INSAT (3D and 3DR) winds, have been used. In the second set of run (EXP), similar to CNTL, but Meteosat-8 AMVs are denied and INSAT (3D and 3DR) winds are included in the assimilation system. Meteosat-8 AMVs have been assimilated. Both the runs (CNTL and EXP), have been carried out for 1st-20th May 2020 and 10-day forecasts is generated using the NGFS model at T1534L64 resolution (~12.5 km) (Shao, et al., 2016, GSI User's Guide Version 3.5), based on 00UTC initial condition of each day.

Table 1: Meteorological observations used for assimilation

Conventional Observations					
Surface observations over land (SYNOP), SHIP, BUOY, Pilot balloon, Radio-sonde, Wind Profiler, DWR VAD Winds, Aircraft observations					
Satellite Observations					
Satellite AMVs		Scatterometer Winds	Radiances		GPSRO
Geostationary	Polar		Geostationary	Polar	
INSAT-3D/3DR, Meteosat-8,11, HIMAWARI, GOES-16,17	NOAA-18,19, METOP-A,B,C	ASCAT, Windsat and SCATSAT	INSAT-3D (Imager & Sounder) SEVIRI (Meteosat-8/11), GOES-16/17 (Imager&Sounder), AHI (HIMAWARI-8)	AMSU-A (METOP-A/B, NOAA-18/19) MHS (METOP-A/B, NOAA-19), MT-SAPHIR, ATMS(SNPP), IASI (METOP A/B/C), AIRS(AQUA), CrIS (SNPP, NOAA-20)	COSMIC-2E1/ 2E2/2E3/2E4/2E5/2E6, COSMIC-6, FY-3C/3D, TerraSAR-X, TenDEM, PAZ KOMPSAT-5, METOP-A/B/C

3. Results and Discussions:

This section describes the validation statistics of INSAT-3DR AMVs and their comparison with those of INSAT-3D and Meteosat-8 AMVs. Impact of the assimilation of INSAT AMVs on the analysis and forecast of tropical cyclone Amphan is also discussed here.

3.1 Validation of AMVs against NWP First Guess

Validation of AMVs against NCMRWF NWP first guess has been carried out by generating monthly mean vector plots representing bias in the wind direction and speed bias density plots to assess the bias in the wind speed. Zonal plots, showing the average of the normalised root mean square vector difference (NRMSVD) is also produced. These plots are generated for IR (high level, middle level and low level), low-level VIS and high-level WV winds for INSAT (3D and 3DR) and Meteosat-8 over three latitudinal regions viz., Northern Hemisphere, Tropics and Southern Hemisphere for May 2020.

3.1.1 Vector plots

Figure 4 depicts the monthly mean vector plots of high level IR winds for INSAT-3DR for May 2020. In Figure 4 panels (a), (b), (c) and (d) respectively represent mean observation, mean background, mean vector difference between observation and background and the mean number of winds in each box of 0.5° x 0.5° size. Similarly Figures 5 and 6 depict the monthly mean vector plots for high level IR winds for INSAT-3D and Meteosat-8 respectively.

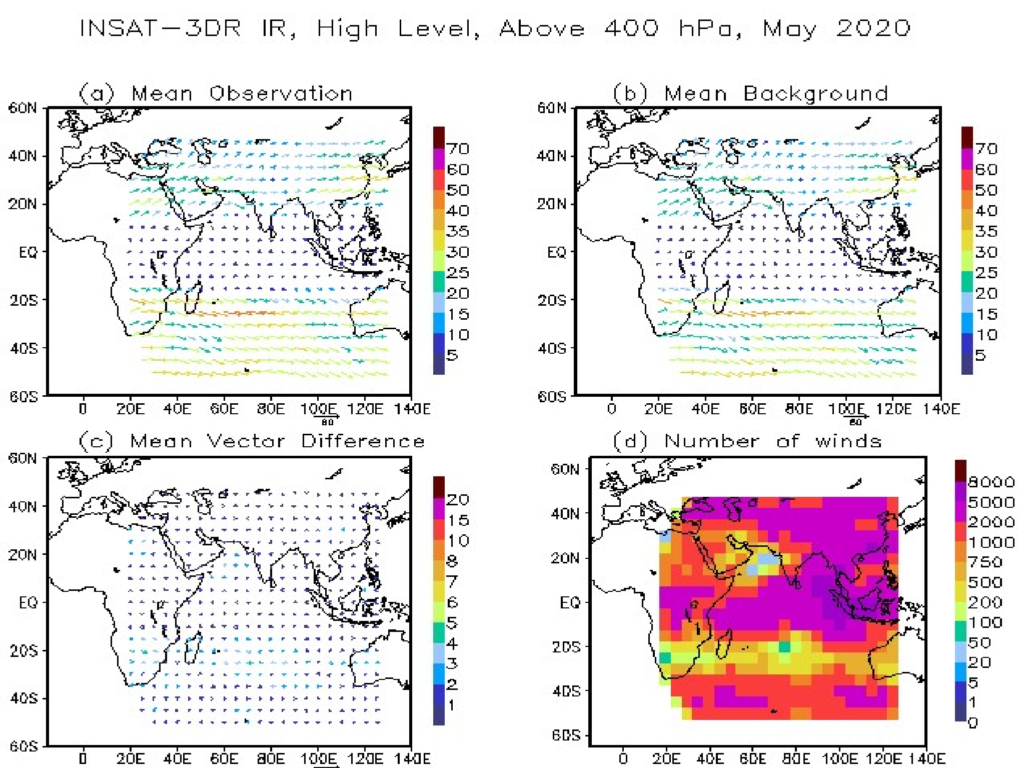

Figure 4: Monthly mean vector plot of INSAT-3DR high level IR (a) mean observation, (b) mean background, (c) mean vector differences and (d) number of winds for May 2020.

INSAT-3D IR, High Level, Above 400 hPa, May 2020

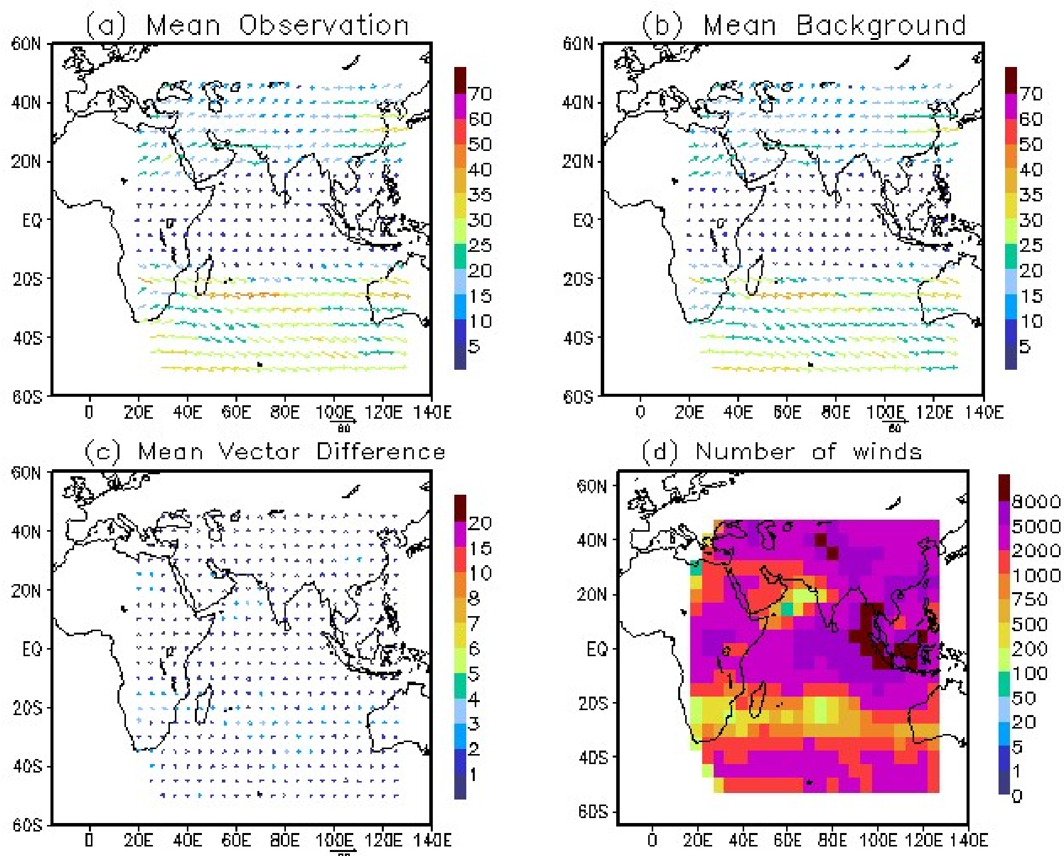

Figure 5: Similar to Figure 4, but for INSAT-3D high level IR winds

For all three satellites mean observed wind direction of higher level IR winds matches with that of mean background, however, at higher level INSAT-3DR and INSAT-3D IR AMVs are stronger than the mean background near 25^0 S and between 40^0 E to 80^0 E (Figures 4 and 5) whereas Meteosat-8 IR observed winds are weaker compared to the background over the same region (Figure 6).

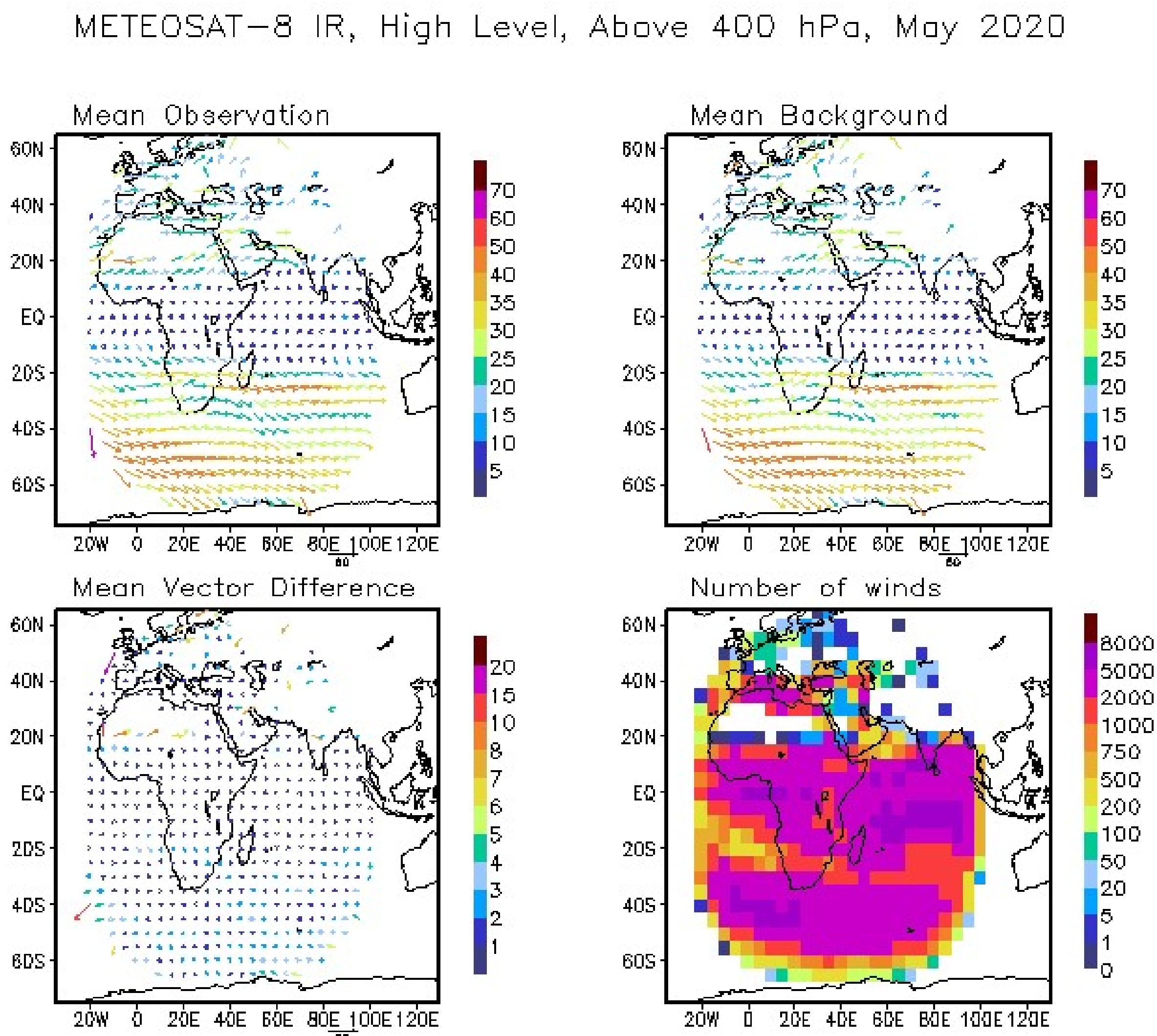

Figure 6: Similar to Figure 4, but for Meteosat-8 high level IR winds.

Figures 7, 8 and 9 show the wind vector plots for higher level WV winds for INSAT-3DR, INSAT-3D and Meteosat-8 respectively. In the case of WV channels, INSAT winds near 40^0 S are slightly stronger than the first guess as compared to Meteosat-8 WV winds. The mean vector difference for WV winds against the first guess is similar for both the INSAT satellites whereas slightly higher for Meteosat-8 over the Indian region. Similar results are obtained in the case of VIS winds (plots are not shown here).

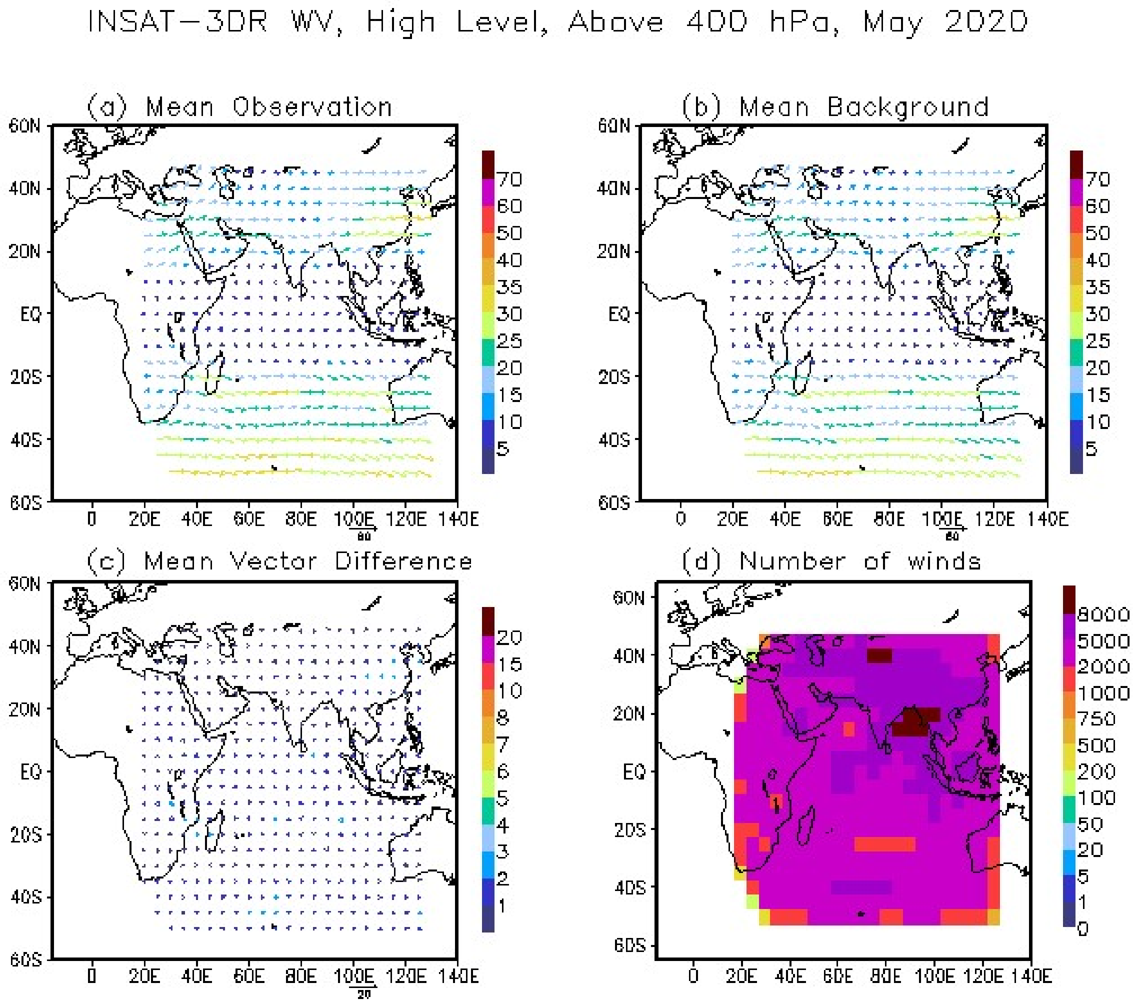

Figure 7: Monthly mean vector plot for high level WV winds from INSAT-3DR (a) mean observation, (b) mean background, (c) mean vector differences and (d) number of winds for May 2020.

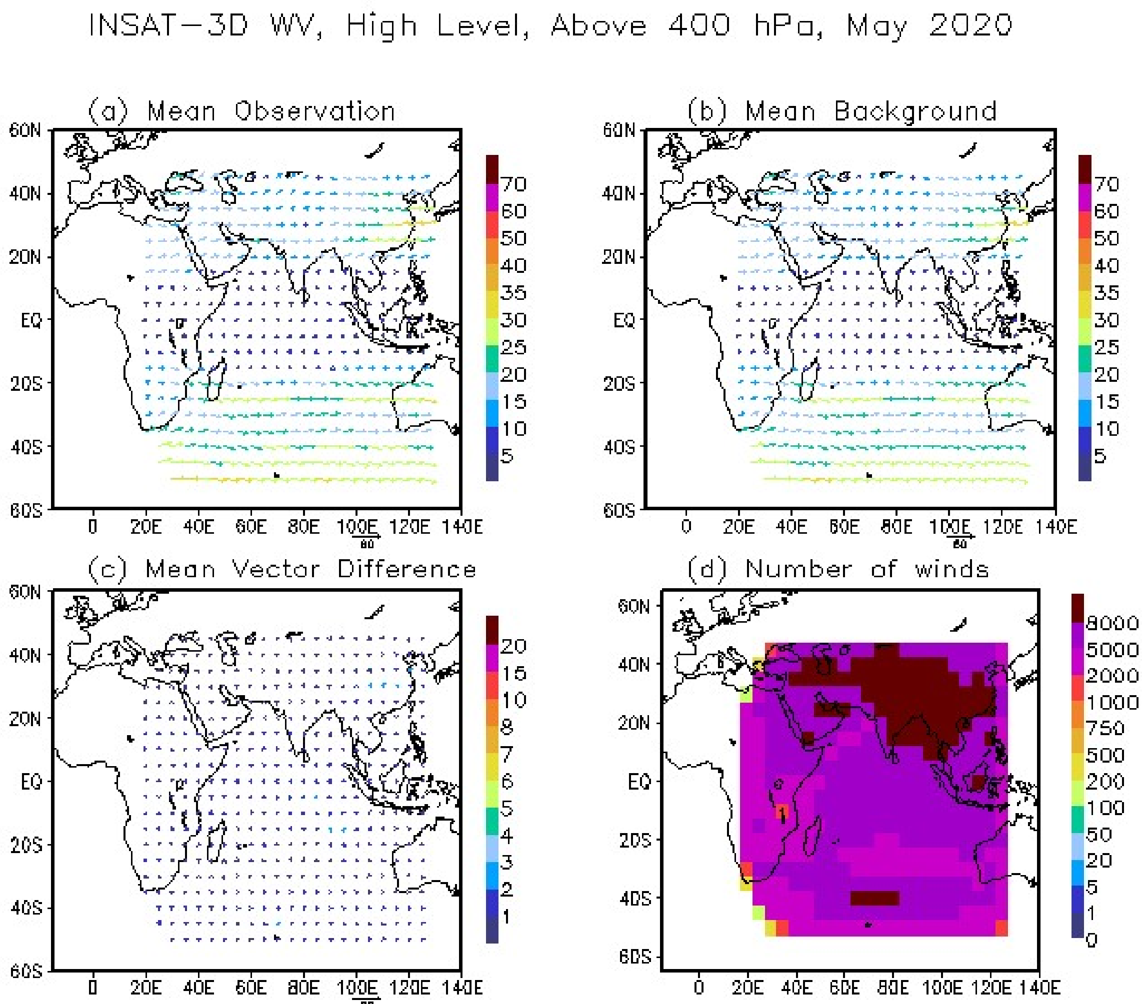

Figure 8: Similar to Figure 7, but for INSAT-3D

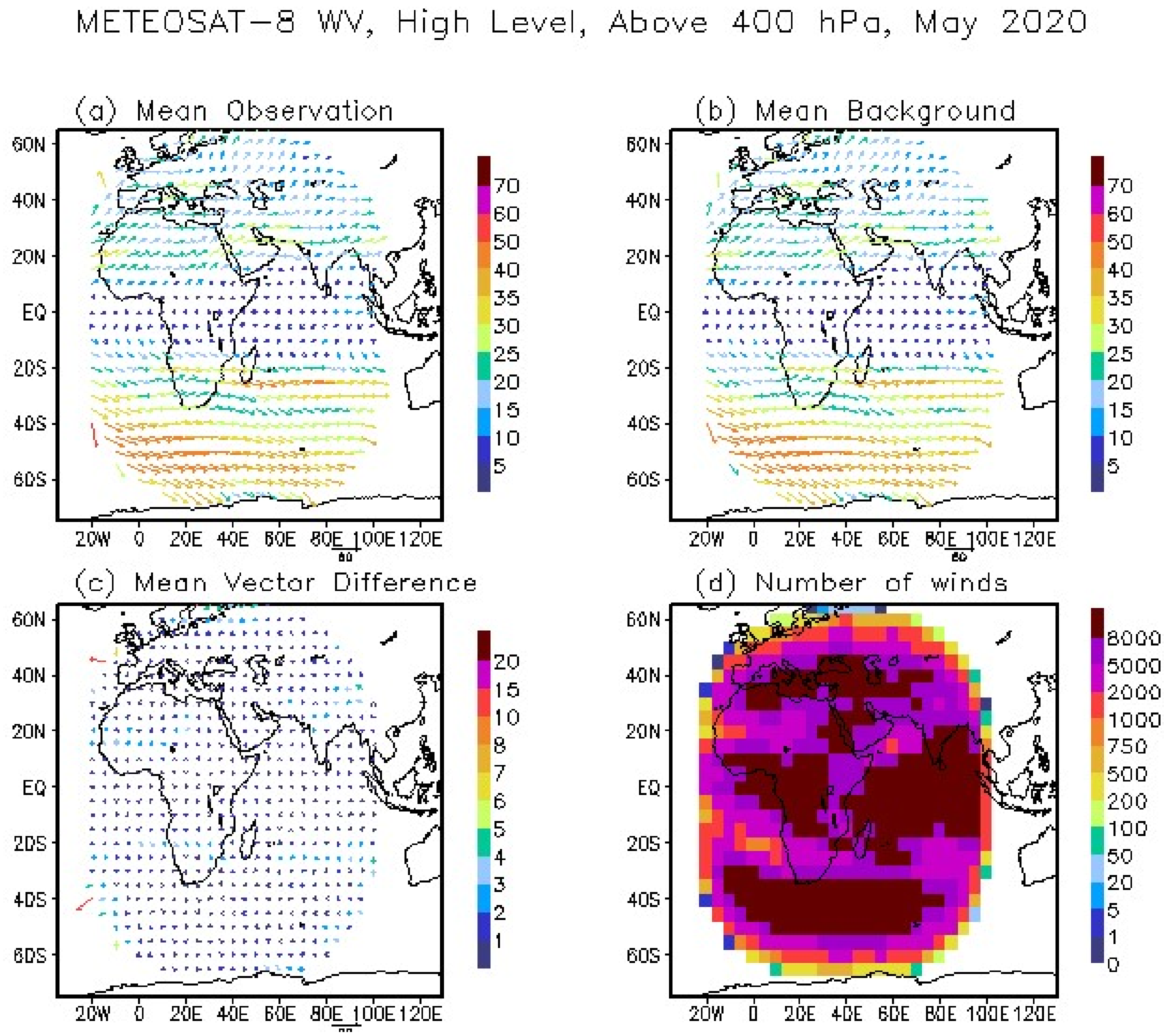

Figure 9: Similar to Figure 7, but for Meteosat-8

3.1.2 Speed bias density plots

Speed bias density plots for INSAT and Meteosat-8 AMVs against the NCMRWF NWP background are generated by plotting the number of observed wind speed corresponding to different background wind speeds. These plots are used to identify the errors associated with AMVs of different speeds. Speed bias density plots are generated separately for three regions viz. Northern Hemisphere (20°N-90°N), Tropics (20°S-20°N) and Southern Hemisphere (20°S-90°S).

Figure 10 shows the speed bias density plots for INSAT-3DR (top panel), INSAT-3D (middle) and Meteosat-8 (lower panel) high level IR winds over the three latitudinal regions. Stastics computed over different latitudinal regions are also included in the plots. As seen from the plots, the observed wind speed (AMV) at high level matches well with that of the background wind speed for INSAT-3DR and INSAT-3D, however, over the Tropics INSAT AMVs have slightly higher bias compared to Meteosat-8. Over the Southern Hemisphere Jet region, Meteosat-8 AMVs are not agreeing well with background winds, while INSAT AMVs being SGP, are not available over this region.

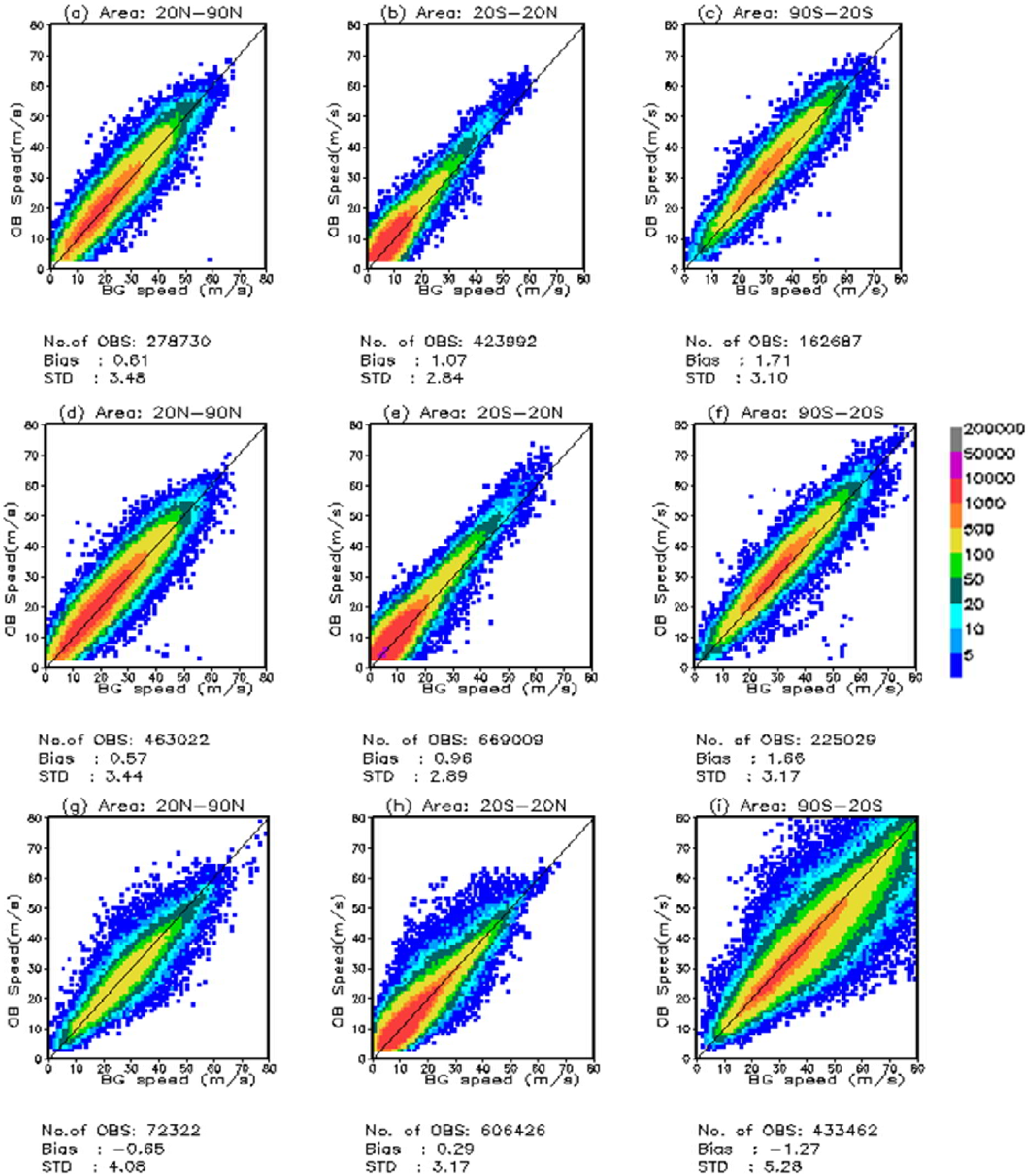

Figure10: Speed bias density plots for high level winds from INSAT-3DR (upper pannel, a, b, c), INSAT-3D (middle pannel, c, d, e) and Meteosat-8 (lower pannel, f, g, h) over Northern Hemisphere (20^0N-90^0N), Tropics (20^0S-20^0N) and Southern Hemisphere (20^0S-90^0S) during May 2020.

Table 2 provides the mean bias and standard deviation (STD) of INSAT (3D and 3DR) and Meteosat-8 AMVs computed against NCMRWF NWP first guess for May 2020. Standard deviation in Meteosat-8 AMVs derived from IR and WV channels is slightly higher compared to that of INSAT-3D and INSAT-3DR. However Visible winds from Meteosat-8 have less standard deviation over the Northern Hemisphere and the Tropics compared to both INSAT Visible winds but higher over the Southern Hemisphere. In general, the AMVs from all the three satellites are faster over the Tropics compared to the background. When compared against the NWP background, the AMVs from INSAT(3D and 3DR) and Meteosat-8 are found to be stastistically significant ($p < 0.01$) for all the three channels (IR, VIS and WV).

Table 2: Validation statistics INSAT-3D, INSAT-3DR and Meteosat-8 AMVs against NWP first guess for May 2020.

Satellite	**Northern Hemisphere**		**Tropics**		**Southern Hemisphere**	
	Bias	STD	Bias	STD	Bias	STD
	High Level IR Winds					
INSAT-3D	0.57	3.44	0.96	2.89	1.86	3.17
INSAT-3DR	0.61	3.48	1.07	2.84	1.71	3.10
Meteosat-8	-0.65	4.08	0.29	3.17	-1.27	5.28
	Mid Level IR Winds					
INSAT-3D	-0.24	2.56	0.37	2.24	-0.55	2.66
INSAT-3DR	-0.29	2.53	0.36	2.21	-0.64	2.66
Meteosat-8	0.70	4.67	0.74	3.25	-0.24	5.52
	Low Level IR Winds					
INSAT-3D	0.37	2.41	0.89	2.00	1.93	1.82
INSAT-3DR	0.12	2.34	0.89	1.90	1.87	1.82
Meteosat-8	-0.19	2.73	0.22	1.77	0.02	1.92
	WV Winds					
INSAT-3D	0.74	3.48	1.03	2.98	1.23	3.20
INSAT-3DR	0.72	3.48	1.15	2.92	1.41	3.19
Meteosat-8	-0.34	4.74	0.82	3.38	0.05	5.61
	VIS Winds					
INSAT-3D	-0.33	2.81	-0.04	1.89	0.16	1.76
INSAT-3DR	-0.49	2.72	0.07	1.84	0.20	1.74
Meteosat-8	-0.02	2.36	0.13	1.68	0.07	1.81

3.1.3 Zonal average plots

Zonal average of the NRMSVD of INSAT-3D, INSAT-3DR and Meteosat-8 AMVs are computed at various level of the atmosphere. For computing, zonal averages, AMVs are binned in to pressure-latitude boxes of 10 hPa by 2° for IR, VIS and WV channels. Figures 11 (a), (b) and (c) depict the zonal average plots of the NRMSVD over each latitude in different atmospheric levels for INSAT-3D, INSAT-3DR and Meteosat-8 for IR winds. The zonal average of NRMSVD for IR channel is found to be higher over the Tropics for both INSAT and Meteosat-8 satellites. Similarly, NRMSVD for WV channel as shown in Figure 12 is found to be higher over the Tropics for all the three sateliites. For Meteosat-8, this high value covers larger latitudinal extent compared to INSAT-3D and 3DR. Cotton, J. 2014, and Warrick, F. (2018) also reported similar results for Meteosat-8. Similar results are obtained for VIS channel for all the three satellites (plots are not shown here).

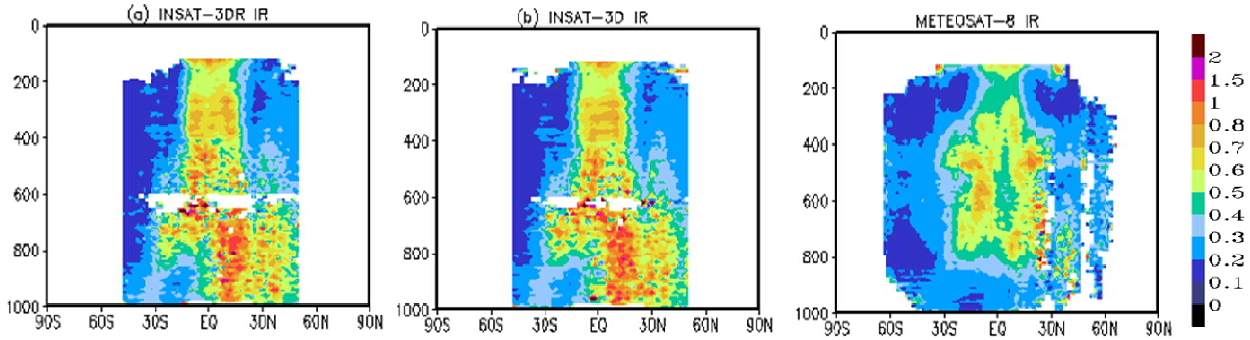

Figure11: Zonal average plot for IR winds (a) INSAT-3DR (b) INSAT-3D and (c) Meteosat-8

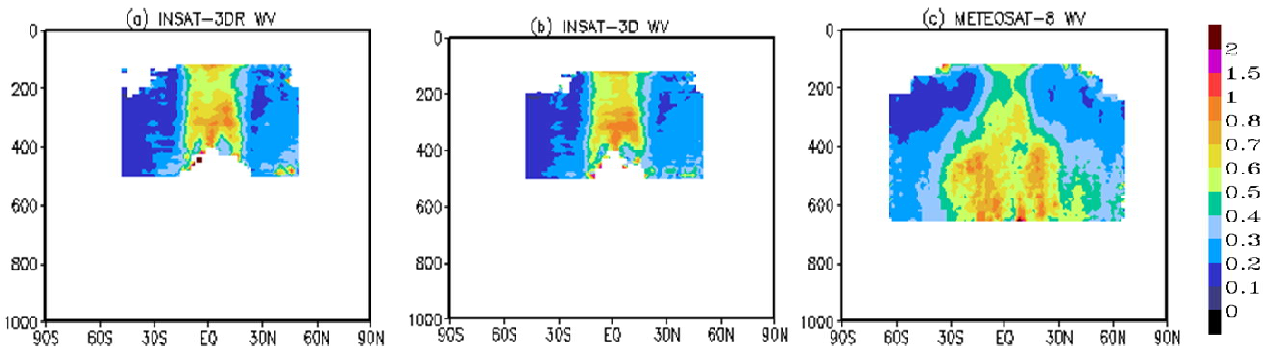

Figure12: Zonal average plot for WV winds (a) INSAT-3DR (b) INSAT-3D and (c) Meteosat-8

3.2 Validation against In-situ Winds

Statistical parameters such as speed bias and Root Mean Square Vector Difference (RMSVD) and number of AMVs collocated with in-situ winds for INSAT-3D, INSAT-3DR and Meteosat-8 IR and WV winds are computed for May 2020. Validation of AMVs from INSAT and Meteosat-8 against in-situ winds over the Northern Hemisphere, the Tropics and the Southern Hemisphere from IR and WV channels are summarized in Table 3.

The number of collocated winds is more for both INSAT-3D and 3DR IR winds compared to that of Meteosat-8 except over the Southern Hemispheric high level and middle level over the Tropics. In the case of WV channels, the number of collocated winds are more for Meteosat-8 as compared to INSAT except over the Tropics. The availability of two water vapour channels for Meteosat-8 instead of one as in the case of INSAT-3D and 3DR could be the reason for more WV AMVs from Meteosat-8. INSAT AMVs are faster at high level (both IR and WV) and slower at the mid and low level compared to the in-situ observations. Meteosat-8 winds are mostly slower than the in-situ observations. The RMSVD for Meteosat-8 AMVs against in-situ observations is higher compared to both INSAT-3D and 3DR over the different latitudinal regions, except for low level IR winds over the Tropics.

Table 3: INSAT-3D, INSAT-3DR (INS-3DR) and Meteosat-8 AMV collocation statistics computed against in-situ winds for May 2020

Satellite	Northern Hemisphere			Tropics			Southern Hemisphere		
	Bias	RMSVD	No. of collocations	Bias	RMSVD	No.of collocations	Bias	RMSVD	No. of Collocations
High Level IR Winds									
INSAT-3D	0.36	6.57	9535	0.42	4.73	15447	1.83	5.99	395
INSAT-3DR	0.52	6.57	5314	0.39	4.72	11488	1.61	5.90	374
Meteosat-8	-1.97	7.76	2593	-1.33	6.53	10716	0.62	8.51	1087
Mid Level IR Winds									
INSAT-3D	-0.75	5.16	2989	-0.57	3.93	656	-0.55	4.98	283
INSAT-3DR	-0.97	5.06	1268	0.39	4.72	260	-1.91	5.25	184
Meteosat-8	0.28	7.35	968	-0.17	5.25	944	2.73	9.82	183
Low Level IR Winds									
INSAT-3D	0.19	4.73	1994	1.15	4.18	2111	-0.68	4.83	918
INSAT-3DR	0.07	4.20	1476	1.09	4.29	1147	-0.10	4.81	484
Meteosat-8	1.41	8.88	331	-0.16	3.93	530	-1.01	6.6	318
WV Winds									
INSAT-3D	0.61	6.89	19633	0.76	5.28	18583	0.80	6.43	1699
INSAT-3DR	0.60	6.73	10457	0.90	5.19	11620	1.30	6.80	699
Meteosat-8	-2.36	8.92	32747	-0.02	6.54	6823	0.64	9.15	2748

3.3 Impact of INSAT AMVs in the simulation of cyclone "Amphan"

To assess the impact of INSAT (3D and 3DR) AMVs on analysis and subsequent prediction of tropical cyclone Amphan an OSE has been carried out as discussed in section 2. Results of the OSEs are discussed this section. Coverage of INSAT (3D and 3DR) and Meteosat-8 low level AMVs (VIS and IR) for 06 UTC assimilation cycle on 15th May 2020 received at NCMRWF are shown in Figure 13 (a) and (b) respectively. Though very high density AMVs are seen over BOB, especially for Meteosat-8, all of these are not assimilated. Before assimilation, proper thining was applied for both INSAT and Meteosat-8 AMVs following http://nwpsaf.eu/monitoring/amv/amvusage/ncepmodel.html, horizontal: 200 km, vertical: 100 hPa and temporal: 3 hrs. The coverage of INSAT and Meteosat-8 AMVs assimilated in the system after thinning and quality control are shown in Figure 13 (c) and (d) respectively. As seen from Figure 13, the density of observed AMVs over the BOB was quite higher for Meteosat-8; however, after thinning and quality checks, number of AMVs assimilated for INSAT (3D +3DR) and Meteosat-8 are almost similar. The broad cyclonic circulation over south BOB associated with the genesis of low pressure system has been captured by both INSAT and Meteosat-8. Figure 14 depicts the coverage of high-level INSAT and Meteosat-8 winds received and assimilated for 06 UTC of 15th May 2020. At high level, both INSAT and Meteosat-8 AMVs could capture the upper level anticyclonic steering flow. However the number of INSAT (3D + 3DR) AMVs assimilated over the BOB are more than that of Meteosat-8.

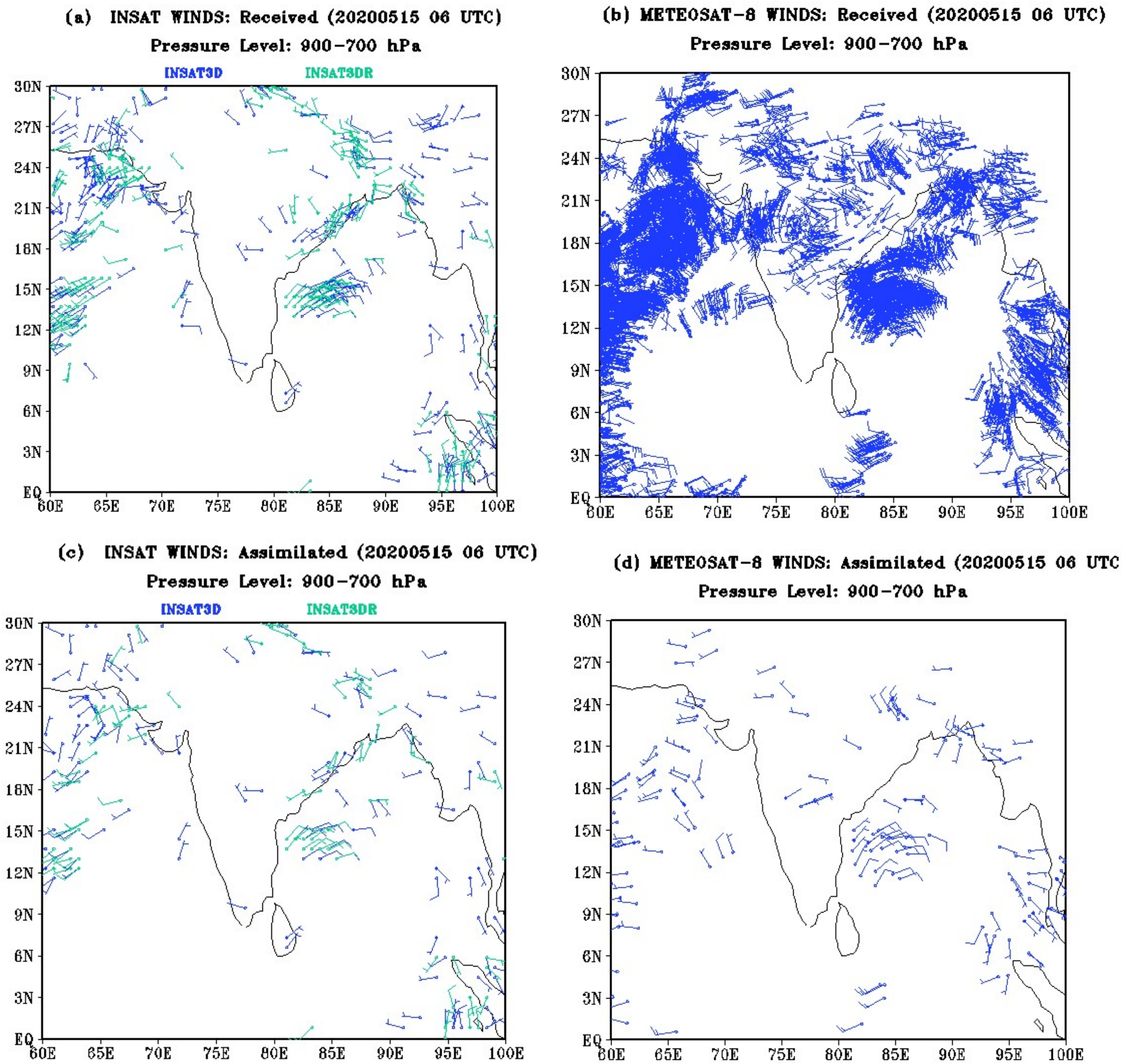

Figure 13: Coveragre of low level (900-700 hPa) AMVs received at NCMRWF from (a) INSAT (3D and 3DR) (b) Meteosat-8 and assimilated in the NGFS (c) INSAT (3D and 3DR) and (d) Meteosat-8 assimilated after thinning and QC valid for 06 UTC of 15th May 2020.

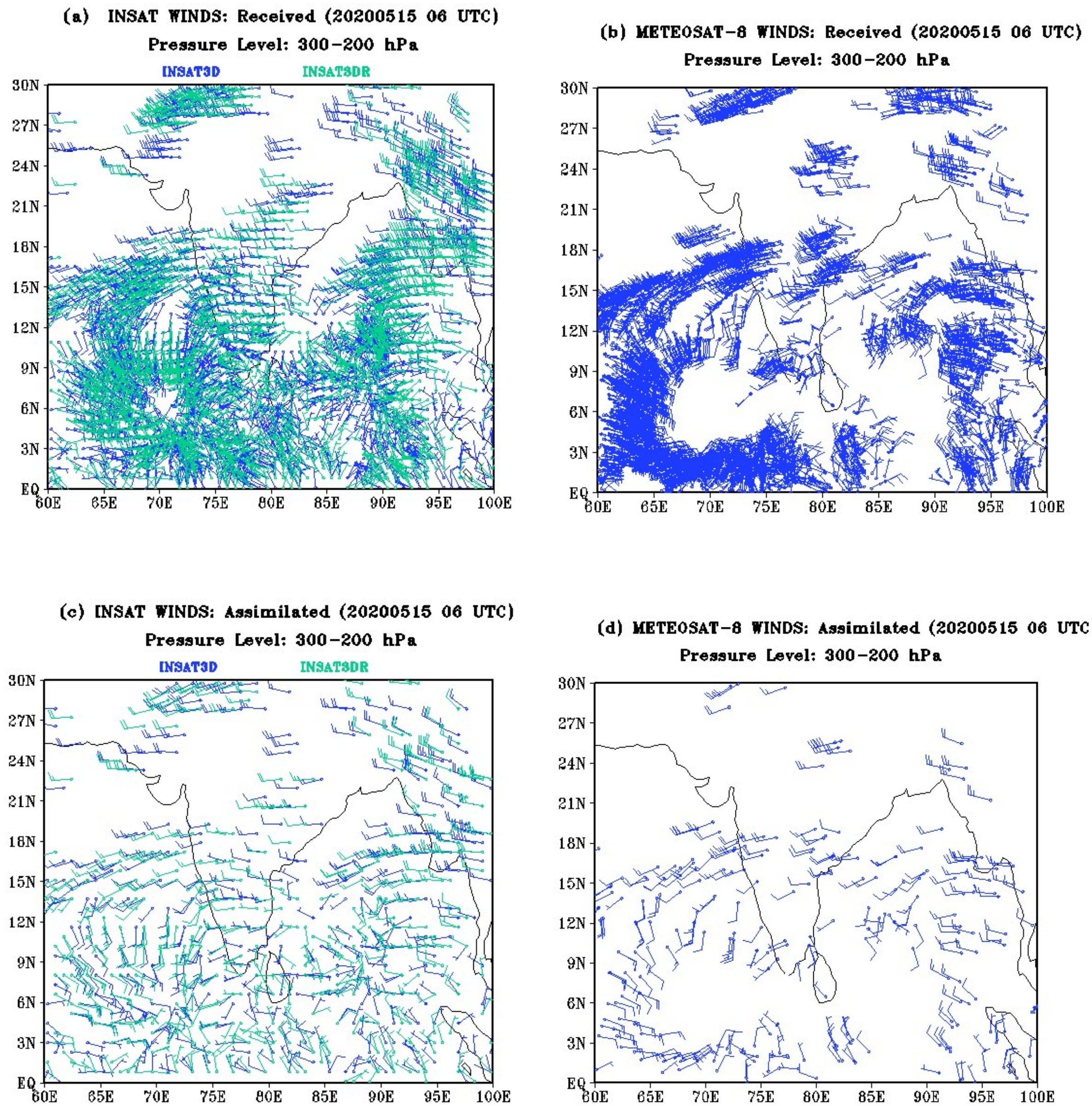

Figure 14: Coveragre of high level (300-200 hPa) AMVs received at NCMRWF from (a) INSAT (3D and 3DR) (b) Meteosat-8 and assimilated in the NGFS (c) INSAT (3D and 3DR) and (d) Meteosat-8 assimilated after thinning and QC valid for 06 UTC of 15th May 2020.

Figure 15 depicts the upper level (300 -200 hPa) AMVs as received and assimilated on 06 UTC of 17th May 2020. The position of the tropical cyclone Amphan is also plotted along with the AMVs (in red colour). INSAT-3DR AMVs were not received during this particular assimilation cycle. As seen from Figure 15, at high level, good number of INSAT AMVs (north-westerly winds) assimilated over south the BOB region; but not the Meteosat-8 AMVs.

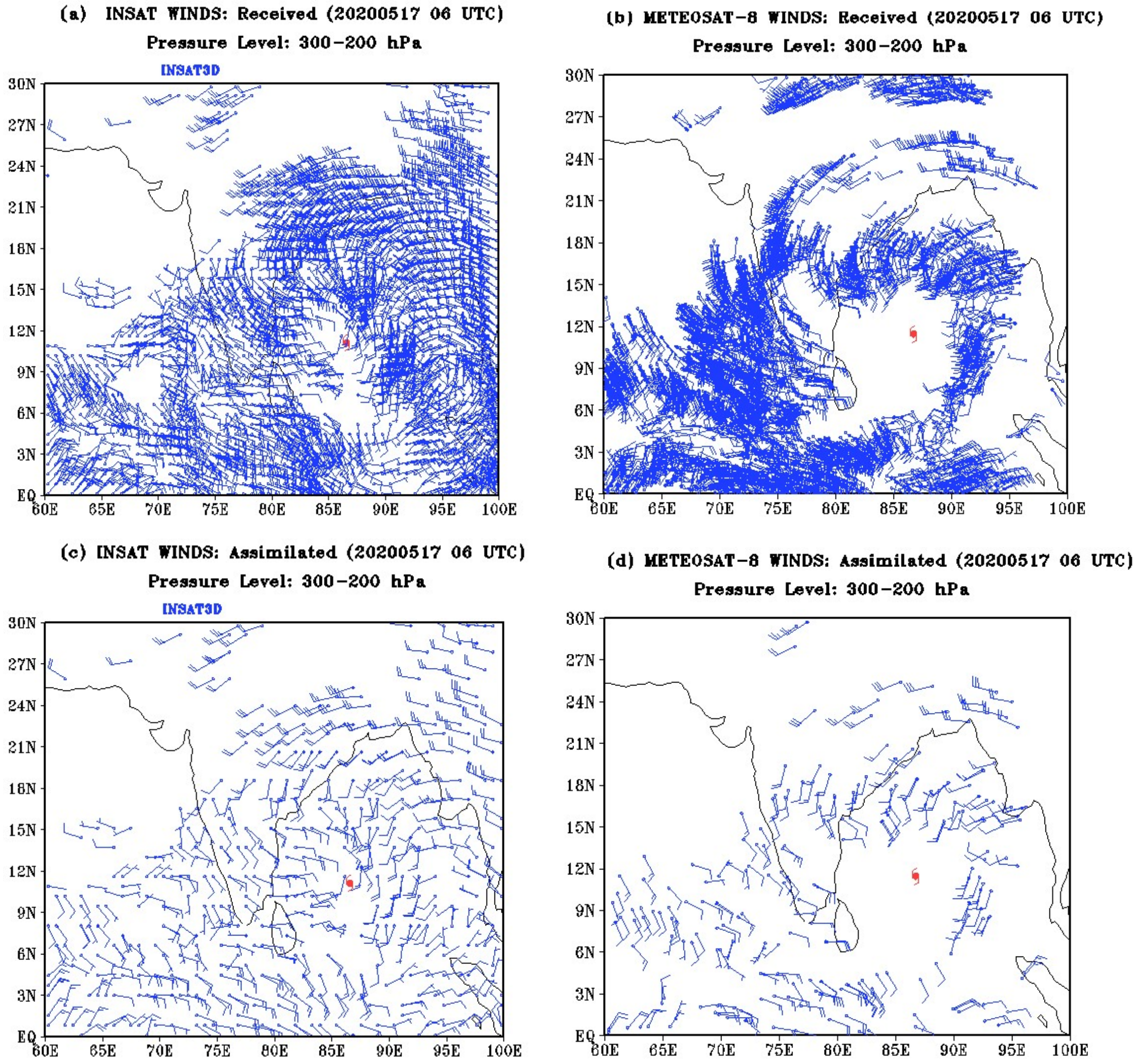

Figure 15: Coveragre of high level (300-200 hPa) AMVs received at NCMRWF from (a) INSAT (3D and 3DR) (b) Meteosat-8 and assimilated in the NGFS (c) INSAT (3D and 3DR) and (d) Meteosat-8 assimilated after thinning and QC valid for 06 UTC of 17th May 2020.

Both sets of analysed winds (EXP and CNTL) is compared with in-situ winds at various atmospheric levels. Figure 16 shows the Root Mean Square Error (RMSE) of the analysed winds for 00 UTC 1st-20th May 2020 over India and neighbouring region (-10° S to 40° N and 60°E to110° E) against Radio-sonde and Pilot balloon observations. A slight improvement is seen in the horizontal wind components due to the assimilation of INSAT AMVs (EXP). The improvement in the zonal wind is more pronounced between 800 to 300 hPa (Figure 16 a), whereas the improvement in the meridional wind can be seen up to 150 hPa (Figure 16 b).

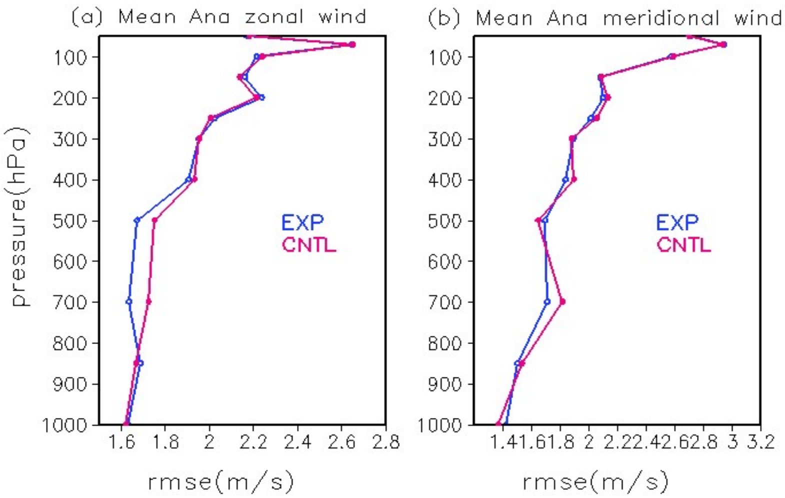

Figure 16: RMSE of analysed winds at various pressure level for EXP and CNTL run averaged for 00 UTC, 1st -20th May 2020 (a) Zonal wind (b) Meridional winds

Impact of INSAT AMVs is seen in the initial analysis and subsequent forecast of the tropical cyclone Amphan. Figure 17 depicts the analysed 850 hPa wind for EXP and CNTL run along with their differences (EXP-CNTL) for 00UTC of 10th May 2020. Both the runs have captured cross-equatorial easterly wave over the Indonesian region; however, the two analyses do not differ much over that region.

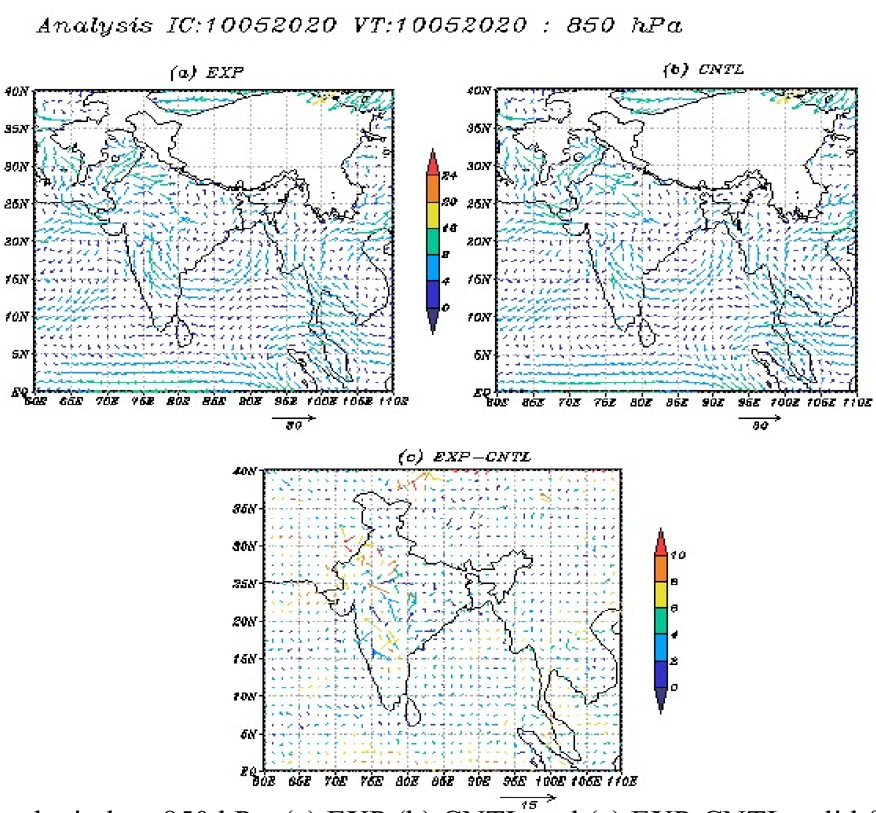

Figure 17: Analysed wind at 850 hPa (a) EXP (b) CNTL and (c) EXP-CNTL valid for 00 UTC of 10th May 2020 .

Based on the 00UTC of 10th May 2020 initial condition, subsequent 120hr (5day) forecast was able to predict the cyclogenesis over south the BOB by both EXP and CNTL runs; however intensity of the system differs in both EXP and CNTL. Figure 18 depicts the 120 hour predicted 850 hPa wind for EXP and CNTL run along with their differences (EXP-CNTL) based on 00UTC of 10th May 2020 initial condition, valid for 00UTC of 15th May 2020. 120 hr predicted low level circulation over BOB is slightly stronger in CNTL as compared to EXP.

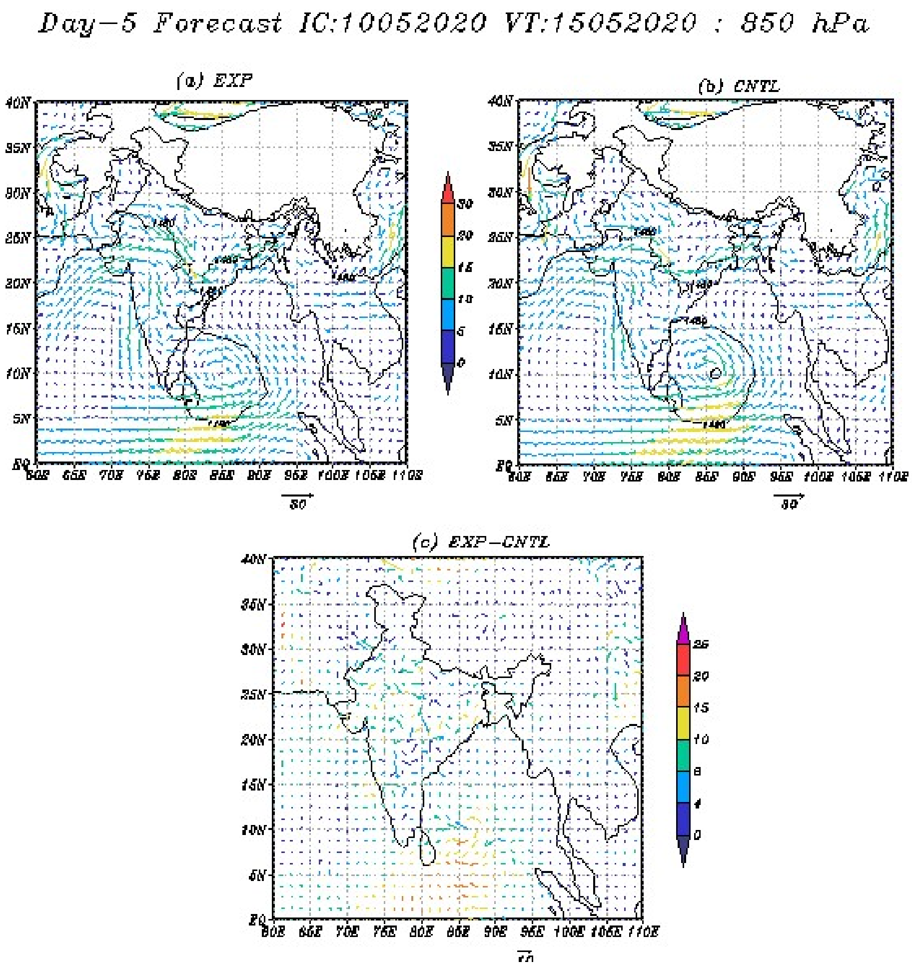

Figure 18: 120 hour 850 hPa predicted wind (a) EXP, (b) CNTL and (c) EXP-CNTL based on the initial condition of 00 UTC 10th May 2020 (valid for 00 UTC 15th May 2020).

Figure 19 depicts the 120 hour predicted upper level (200 hPa) wind for EXP and CNTL run along with their differences (EXP-CNTL) based on 00UTC of 10th May 2020 initial condition, valid for 00UTC of 15th May 2020. As seen from Figure 19, in the upper level the predicted divergent flow over BOB is also stronger in CNTL compared to EXP.

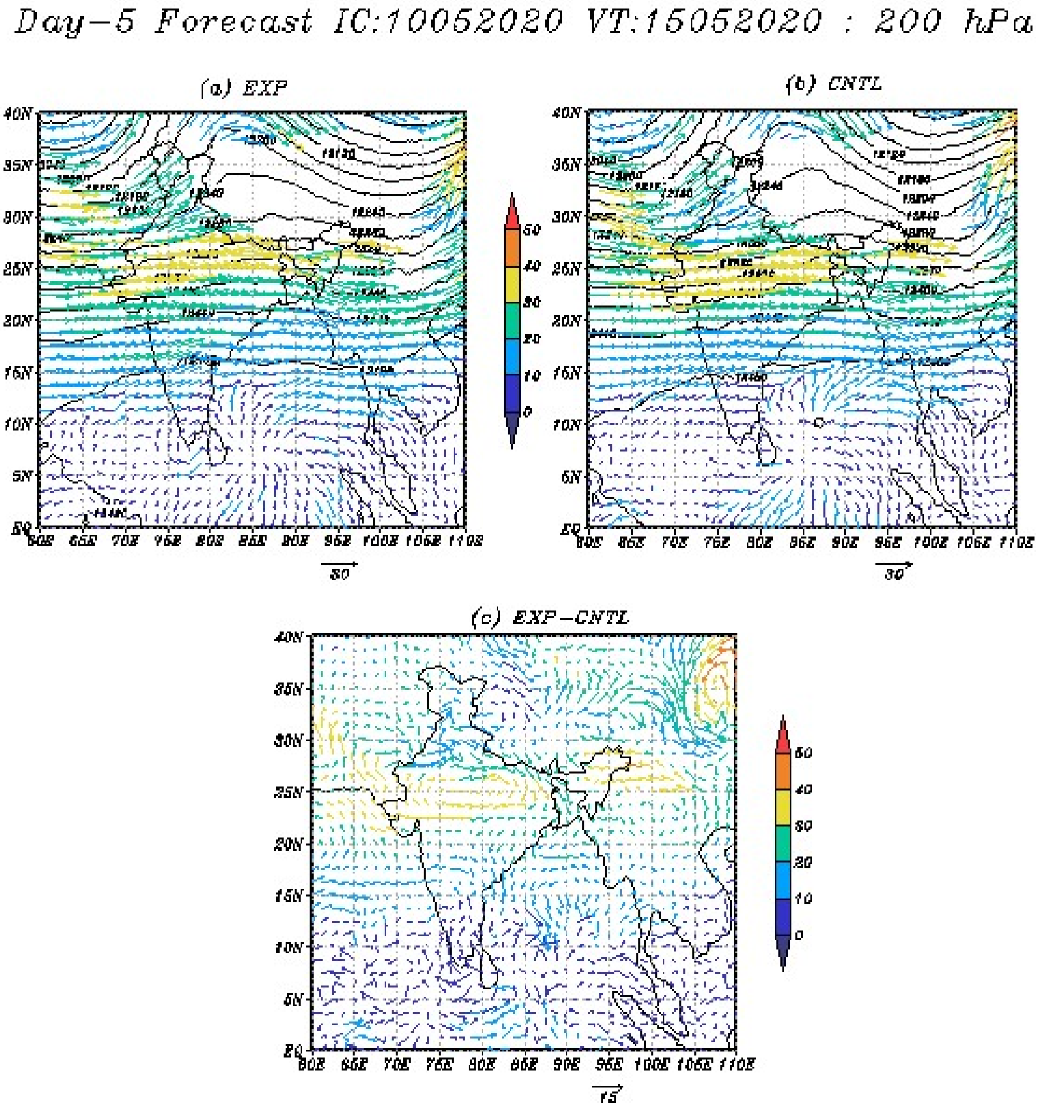

Figure 19 : 120 hour 200 hPa predicted wind (a) EXP, (b) CNTL and (c) EXP-CNTL based on the initial condition of 00 UTC 10th May 2020 (valid for 00 UTC 15th May 2020).

Day -10 predicted wind at 850 hPa based on 00UTC 10th May 2020 initial condition valid for 20th May 2020 shown in Figure 20. Both EXP and CNTL could predict the north-north-westerly movement of Amphan; however, the position is different in the day-10 forecasts. Assimilation of Meteosat-8 AMVs simulated a faster moving cyclone (CNTL) compared to the assimilation of INSAT AMVs (EXP). Landfall of Amphan occured between 10 and 12 UTC of 20th May 2020 over the West Bengal coast. Predicted centre of the cyclone on 00UTC of 20th May 2020 in EXP run was over the Head Bay, near West Bengal coast, whereas in the CNTL run the movement of the system is faster than the observed and Day-10 predicted position is over Bangladesh.

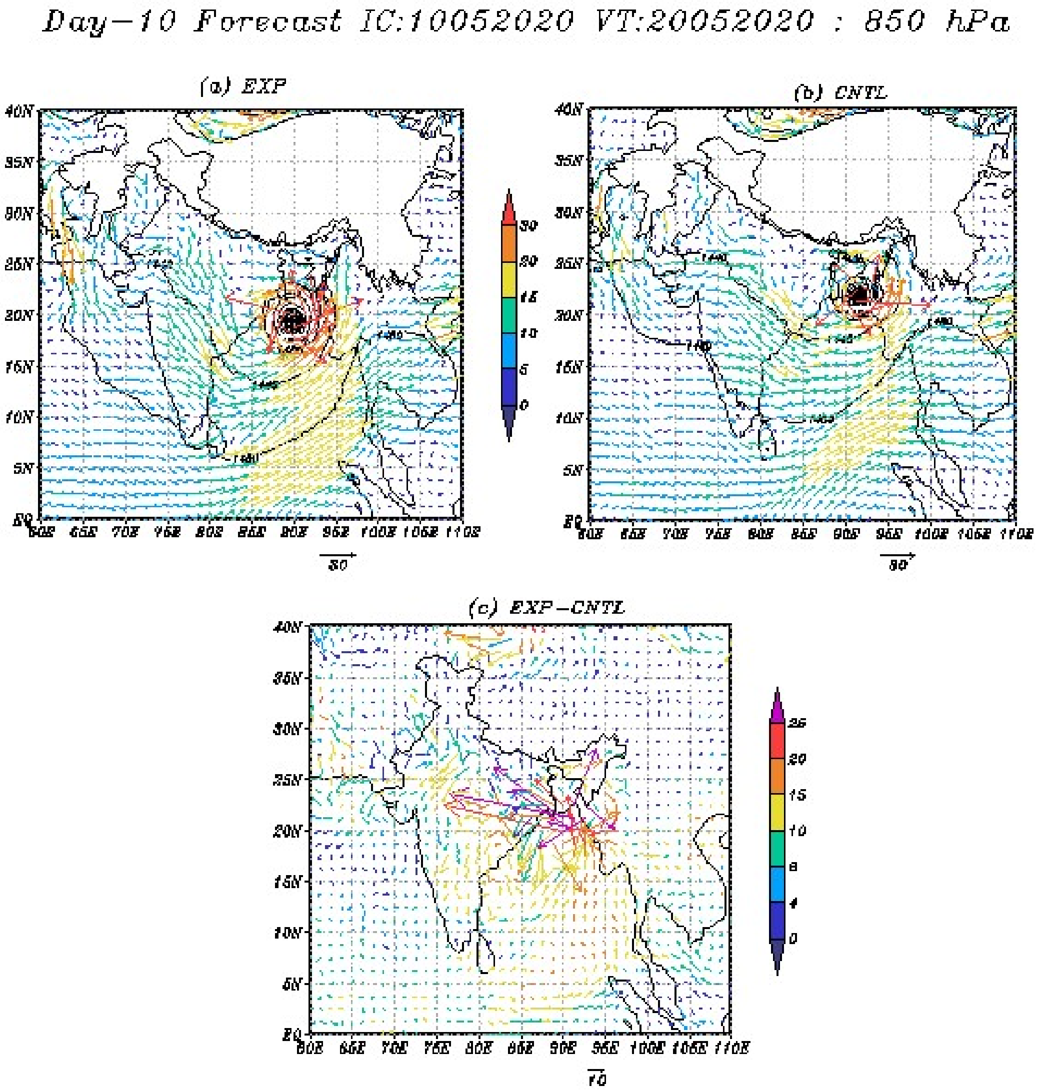

Figure 20: 240 hour 850 hPa predicted wind (a) EXP, (b) CNTL and (c) EXP-CNTL based on the initial condition of 00 UTC 10th May 2020 (valid for 00 UTC 20th May 2020).

120 hour predicted winds at 850 hPa valid for 00UTC of 20th May 2020, based on 00UTC of 15th May 2020 initial condition is shown in Figure 21. Here also CNTL is showing faster movement compared to that in EXP and a stronger storm can be seen in EXP compared to CNTL. Probably the stronger steering flow at the higher tropospheric level in CNTL resulted in faster movement of the cyclone, predicting an early landfall compared to EXP.

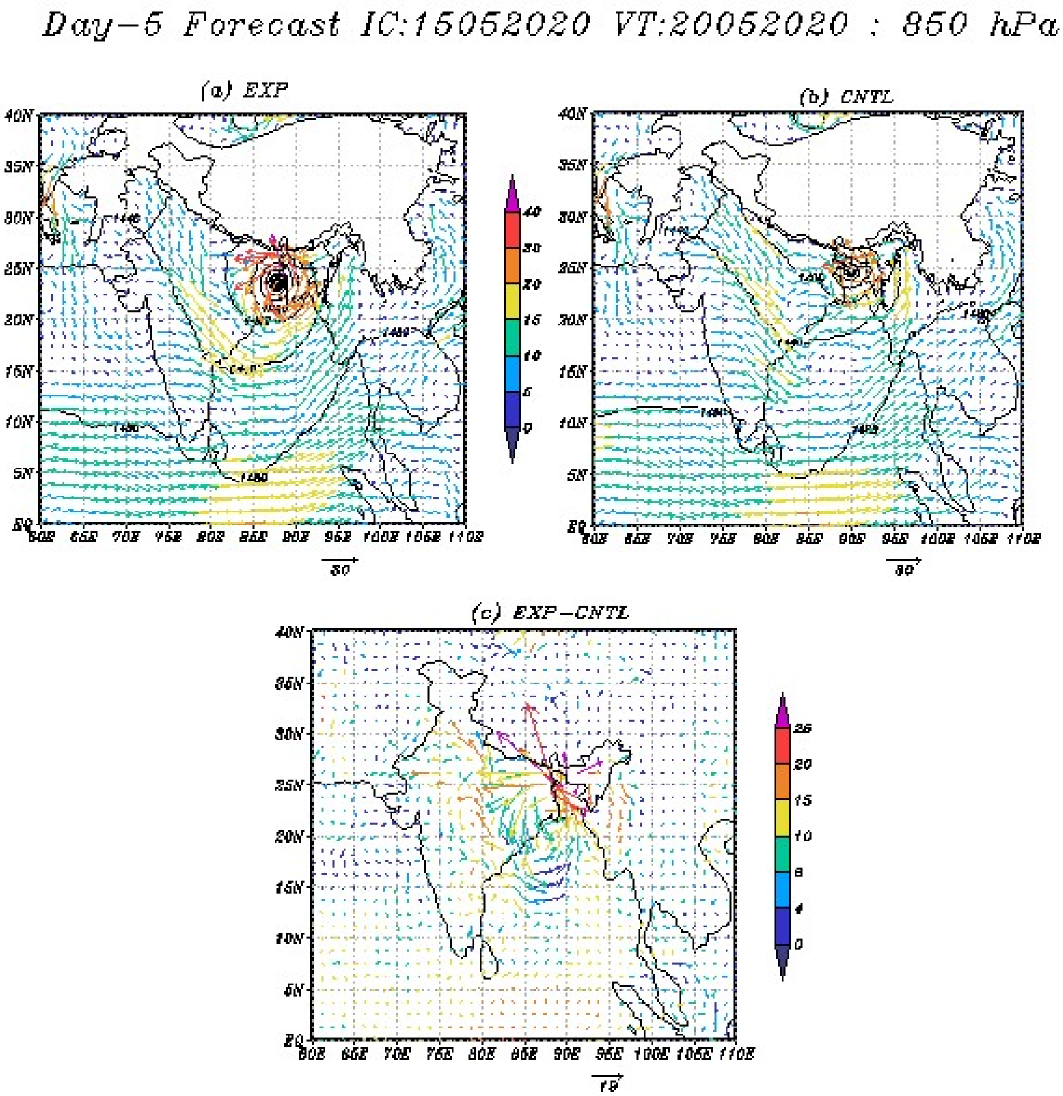

Figure 21: 120 hour 850 hPa predicted wind (a) EXP, (b) CNTL and (c) EXP-CNTL based on the initial condition of 00 UTC 15th May 2020 (valid for 00 UTC 20th May 2020).

Predicted tracks for cyclone Amphan, based on the IC 00UTC of 15th and 17th May 2020, along with the observed track are shown in Figures 22 (a) and (b) respectively. Predicted track by CNTL shows faster and more northeastward movement as compared to the observed track. Predicted track for EXP is closer to the observations compared to CNTL. The average forecast track errors using analysed and predicted position of the cyclone has been computed against IMD's best track observations (16th to 20th May 2020 - the life span of Amphan) and is shown in Table 4. Here the track errors are provided up to 120 hour forecast, as beyond that track errors on some days are very large and the number of cases are very few. As expected the track errors of both the runs increased with forecast hours. However, after 72 hours track error for EXP is relatively less than CNTL which shows a positive impact of assimilating INSAT AMVs on analysis and prediction of Amphan.

(a) (b)

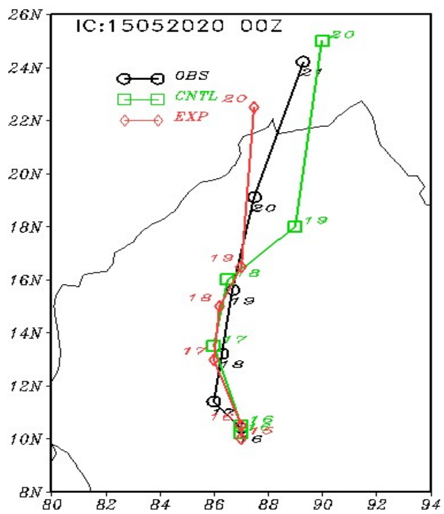

Figure 22:Predicted track for Amphan based on the initial conditions of 00 UTC of (a) 15th May 2020 and (b) 17th May 2020

Table 4: The average forecast track errors and no. of cases in EXP and CNTL computed against IMD best track for cyclone Amphan

Forecast hours / Track error in km	0	24	48	72	96	120
EXP	32	60	129	176	212	283
CNTL	36	59	130	187	262	342
No. of cases	4	5	6	6	6	6

4 Conclusions

INSAT-3DR AMVs are validated against NCMRWF NWP short forecast and in-situ observations and the statistics are compared against that of INSAT-3D and Meteosat-8 AMVs. Study showed that INSAT-3DR AMVs are of similar quality as that of INSAT-3D and Meteosat-8. INSAT (3D and 3DR) AMVs are found to be slightly better than Meteosat-8 AMVs at different atmospheric levels and latitudinal belts when validated against both NWP background and in-situ observations. Assimilation of INSAT (3D and 3DR) AMVs improved the mid-tropospheric wind analysis and produced improved track and intensity of the cyclone Amphan, particularly from day-3.

Acknowledgements

The authors extend their gratitude to Head, NCMRWF for his constant encouragement during the course of this work. Authors also extend their thanks to IMD and SAC for providing near-real time INSAT-AMV observations.

References

Cotton, J., 2014:. NWP SAF AMV monitoring: the 6th Analysis Report (AR6). *Document NWPSAF-MO-TR-029.*

Das Gupta M. and Rani S.I., 2013: "Validation of Kalpana-1 atmospheric motion vectors against upper air observations and numerical model derived winds". *Int. J. Remote Sensing 34(7):*2350-2367, DOI:101080/01431161.2012.744489

Das Gupta M., Sharma P. and Rani S.I., 2015: "Validation of INSAT-3D Atmospheric Motion Vectors", *NCMRWF Research Report, NMRF/RR/01/2015*

Deb, S.K., Wanzong, S., Velden, C.S., Kaur, I, Kishtawal, C.M., Pal, P.K., Menzel, W.P., 2014: "Height assignment improvement in Kalpana-1 atmospheric motion vectors". *J. Indian Soc. Remote Sens. 42 (4),* 679–687. http://dx.doi.org/10.1007/s12524-013-0278-z

Deb S.K, Kishtawal C M, Kumar P, Kumar A K, Pal P K, Kaushik N and Sangar G, 2016: "Atmospheric motion vectors from INSAT-3D: Initial quality assessment and its impact on track forecast of cyclonic storm Nanauk", *Atmos. Res. 169,* 1–16.

Deb S.K., kumar D., K. Sankhala and Kishtawal, C. M., 2018: "Retrieval of Atmospheric Motion Vector using INSAT-3D and INSAT-3DR Imager Data in Staggering Mode ",*Vayu Mandal 42(2),* pp 31-46

Forsythe M., 2007: "Atmospheric motion vectors: past, present and future". *ECMWF Annual Seminar,* September 2007. Met office: Exeter, UK

Horanyi A, Cardinali C, Rennie M, Isaksen L,. 2014: "The assimilation ´ of horizontal line-of-sight wind information into the ECMWF data assimilation and forecasting system. Part I: The assessment of wind impact". *Q. J. R. Meteorol. Soc.*, doi: 10.1002/qj.2430.

Shao Hu M. H., Stark D, Newman K,. Zhou C., and Zhang X., 2016: Gridpoint Statistical Interpolation (GSI) User's Guide Version 3.5. Developmental Testbed Center Rep.,141 pp.

Lean K. and Bormann N., 2018: "Indian Ocean AMVs: Moving to Meteosat-8 and assessing alternative options". *EUMETSAT/ECMWF Fellowship Programme Research Report No. 46*

Prasad V.S., Saji Mohandas, Munmun Das Gupta, E.N. Rajagopal and Surya Kanti Dutta, 2011: Implementation of Upgraded Global Forecasting Systems (T382L64 and T574L64) at NCMRWF", *NCMRWF Technical Report, NCMR/TR/5/2011*

Salonen, K., Bormann, N., 2015: "Atmospheric Motion Vector observations in the ECMWF system: Fourth year report". *EUMETSAT/ECMWF Fellowship Programme Research Report No.36.*

Schmetz J., Pili P, et al., 2002: "An Introduction to METEOSAT Second Generation (MSG)," *BAMS*, pp. 977-992

Rani S. I., and Das Gupta M, 2013: "An inter-comparison of Kalpana-1 and Meteosat-7 atmospheric motion vectors against radiosonde winds and NWP forecasts during monsoon 2011", *Meterol. Appl.* DOI: 1002/met.1411

Sharma P., Rani S.I and Das Gupta M., 2016: "Validation of INSAT-3D Atmospheric Motion Vectors for Monsoon 2015", *Proc. of SPIE Vol. 9881,* doi: 10.1117/12.2223564

Warrick, F., Cotton, J., 2018: NWP SAF AMV monitoring: the 8th Analysis Report (AR8). *Document NWPSAF-MO-TR-035*.