Retrieval of Atmospheric Motion Vector using INSAT-3D and INSAT-3DR Imager Data in Staggering Mode

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ABSTRACT

At present two advanced Indian geostationary meteorological satellites INSAT-3D (launched on 26 July 2013) and INSAT-3DR (launched on 06 September 2016) with similar sensor characteristics are orbiting over Indian Ocean region and are placed at 82^oE and 74^oE respectively. Together these two satellites are providing images at every 15-minutes interval. Although atmospheric motion vectors (AMVs) are deriving operationally using data of different channels from individual satellite at 30-minutes interval, however in this study, first time an attempt has been to use 15-minute images from both the satellites in staggering mode for the retrieval of AMVs. This study is undertaken for doing a feasibility study, for exploiting the availability of higher temporal sampling of data from INSAT-3D and INSAT-3DR channels for the retrieval AMVs in staggering mode. It is found that the improvement in accuracy is noticed when AMVs are retrieved by combining data from both satellites when compared with individual INSAT-3D or INSAT-3DR AMVs. This study demonstrates the possibility of use of two satellites data together in staggering mode for the retrieval of good quality AMVs. This algorithm is made operational at Space Applications Centre, Ahmedabad for larger use-ability after successful testing and evaluation.

Key words*: Atmospheric Motion Vectors (AMV), INSAT-3D, INSAT-3DR and Staggering.*

1. Introduction

The geostationary satellite derived winds, also known as Atmospheric Motion Vectors (AMVs) are considered as one of the most reliable sources of wind information over oceanic region where normal ground based observations are very rare. Presently in India operationally AMVs are available from two advanced meteorological satellites *INSAT-3D* (Deb et al., 2016, Kishtawal et al., 2009) and *INSAT-3DR* using consecutive 30-minutes images (www.mosdac.gov.in). It is also well established that assimilation of AMVs in the numerical weather prediction (NWP) model leads to significant improvement in the weather forecast (Deb et al, 2010; Kaur et al., 2015; Kumar et al. 2016) over the Indian Ocean region. The availability of data from both *INSAT-3D* and *INSAT-3DR* with similar spectral characteristic and region of interest, at every 15-minutes has motivated us to re-look further for the improvement in retrieval algorithm to get better quality AMVs over the Indian Ocean region. The specific reason for this motivation is that instead of using 30-minute images for winds retrieval, the accuracy of winds will improve if shorter spatio-temporal images are used during the retrieval. For example, if *INSAT-3D* captured image at 0000 UTC, then *INSAT-3DR* does at 0015 UTC and similar nomenclature follows for other time of the day. The operational meteorological parameters derived using *INSAT-3DR* are same as that of *INSAT-3D*, with 15 minute time gap. In both the satellites, spectrum of the atmosphere is covered by six imager channels i.e. the Visible (VIS), Short-wave infrared (SWIR), Mid-wave infrared (MIR), Water vapor (WV) and two split window thermal infrared (TIR1 and TIR2) channels. The image registration accuracy significantly improved because of start sensors are present on both the satellites. The individual *INSAT-3D* and *INSAT-3DR* AMVs are derived every 30-minute intervals. As an example, the *INSAT-3D* AMVs are retrieved at 0000, 0030, 0100 UTC, while *INSAT-3DR* AMVs are derived at 0015, 0045, 0115 UTC respectively. The AMV derived from these satellites are widely accepted by different national and international operational agencies. In the present study, the algorithm for deriving AMVs using infrared and water vapor images from *INSAT-3D* and *INSAT-3DR* data in staggering mode is demonstrated. Subsequently, these new AMVs generated using staggering mode are inter-compared

with individually retrieved *INSAT-3D* and *INSAT-3DR* AMVs for a period of one month. The study demonstrated the improved accuracy of staggering mode AMVs with respect to individual *INSAT-3D* and *INSAT-3DR* AMVs, and possibility to explore further in this direction. The following Section 2 very briefly summarizes the information about *INSAT-3D* and *INSAT-3DR* data and AMVs derived using these satellites, followed by two other contemporary wind observations for validation. In the section-3, the methodology adopted for deriving staggering mode AMVs using *INSAT-3D* and *INSAT-3DR* data and procedure followed for validating the retrieved AMVs are discussed. The verification results are discussed in Section 4. Finally, section 5 summarizes the conclusions from this study.

2. Data Used

2.1. INSAT-3D and INSAT-3DR

The advanced Indian meteorological geostationary satellites *INSAT-3D* and *INSAT-3DR* are placed at 82°E and 74°E over the Indian Ocean region (Fig-1a-b) and covering similar region of interest. The specifications of imager channels of both satellites are exactly same. The main reasons of two similar instruments are placed on the geostationary platform for acquiring images at 15-minute interval, for the purpose of enhanced meteorological research and operational needs over the Indian Ocean region. The details about the *INSAT-3D* spectral channels and data resolutions are not described as these are already presented in earlier work (Deb et. al 2016). In the staggering mode, retrieval of AMVs are done using data, re-sampled at 4 km spatial resolution with a common coverage area [30°-130°E, 50°S-50°N] over the Indian Ocean region (Fig.1c-d). This is done to avoid inaccuracies arises due to two different zenith angles for two satellites and area coverage of both the satellites in full-disc mode are not exactly one-to-one. The re-sampled images are generated using the data from both the satellites by using a mapping established between the output space i.e. sector of interest in the map projection plane and the input space i.e. full acquisition in the geodetic plane. During the mapping the re-sampling process generate: i) the intended sector product, ii) the

sun azimuth/elevation and iii) the satellite azimuth/elevation at regular grid intervals. The retrieval process in case of staggering mode is done at every 15-minute with same coverage area. For the present study, data from thermal infrared channel 1 (TIR1) and water vapor (WV) channel for both the satellites from 01 January 2017 to 31 January 2017 are used to retrieve the AMVs. Three sets of two types of AMVs using infrared and water vapor channel data are generated: i) *INSAT-3D*, ii) *INSAT-3DR* and iii) staggering AMVs with *INSAT-3D/3DR*.

2.2 Validation of data

The retrieved three sets of two types of AMVs are validated using: i) Radiosonde winds (http://www.esrl.noaa.gov/raobs/) and ii) Multi-angle Imaging Spectro-Radiometer (MISR) Stereo Motion Vectors (SMVs) [https://www-misr.jpl.nasa.gov/getData/] for the month of January 2017. The radiosonde data are generally used for validation of AMVs as per the Co-ordination Group of Meteorological Satellites (CGMS) guidelines. The Stereo Motion Vectors (SMVs), retrieved by tracking clouds from the MISR data is another sources of wind is used here for validating AMVs. The SMVs are retrieved by matching of cloud reflectivity patterns from three different view angles (Horvath and Davies, 2001).

3. Methodology

3.1 Retrieval algorithm

The operationally four different spectral channels of *INSAT-3D* and *INSAT-3DR* are used to derive AMVs over the Indian Ocean region and operational retrieval algorithm is described in Deb et al. 2016. However, in the present study, a new staggering algorithm is developed where data from infrared (i.e. TIR1) and water vapor (i.e. WV) channels of both the satellites are used simultaneously for higher temporal scale retrieval. In this section a very brief summary of AMV retrieval algorithm is discussed (Fig. 2). At first, the satellite ID from which first input image is coming is checked, if it is from *INSAT-3DR*, then second image from *INSAT-3D* is read. In the first image possible cloud tracers are identified and each selected tracer is represented by a box of 32 x 32 pixel. The tracer box in the first image (i.e. *INSAT-3DR*) is calibrated with respect to
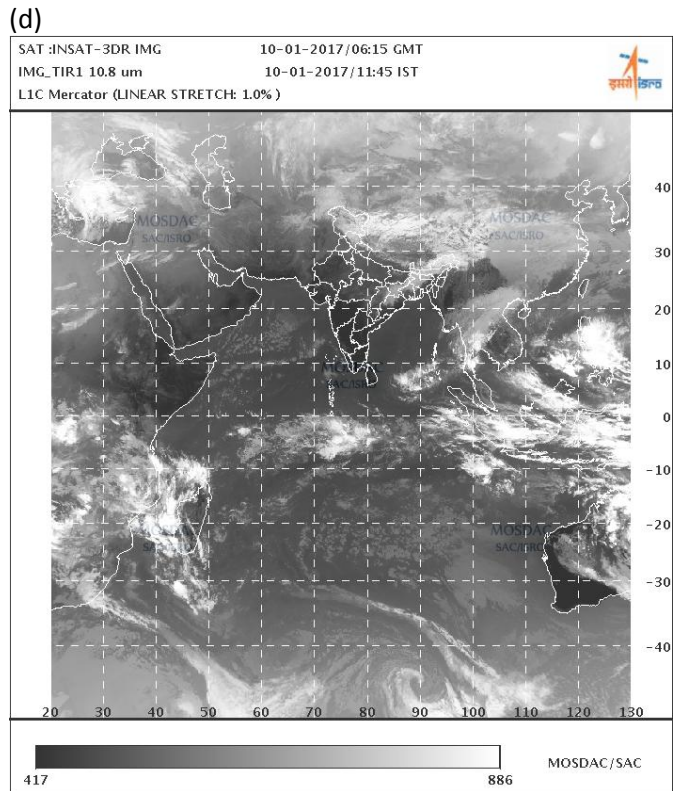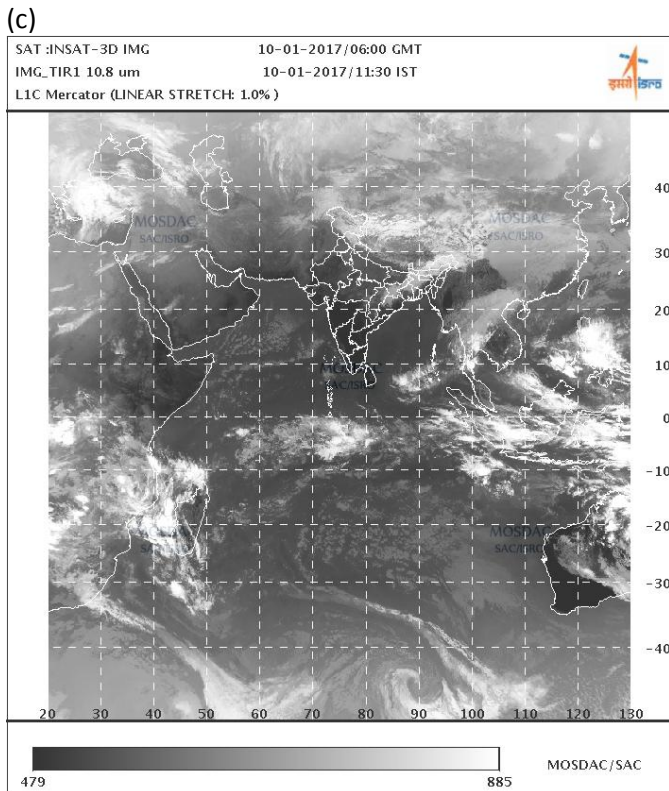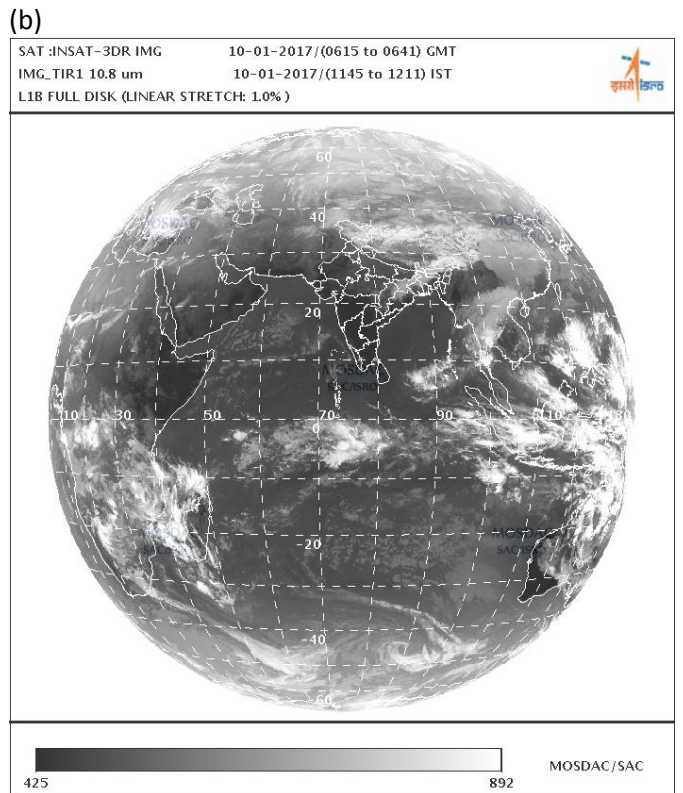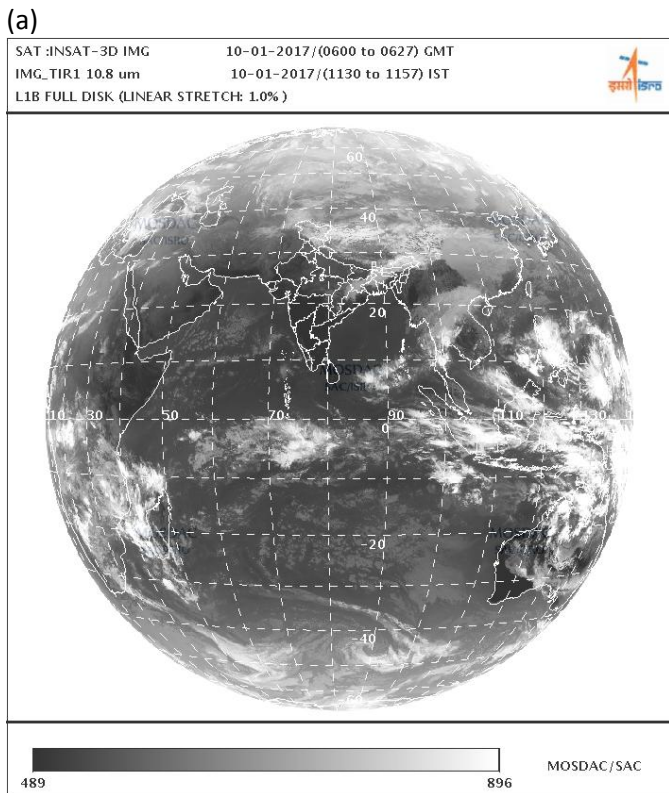
Figure 1: A typical example of full disc thermal infrared channel 1 images from: a) *INSAT-3D* **valid for 0600 UTC of 10 January 2017, b)** *INSAT-3DR* **valid for 0615 UTC of 10 January 2017. c-d) same as a-b but re-sampled at common area [30°-130°E, 50°S-50°N]**
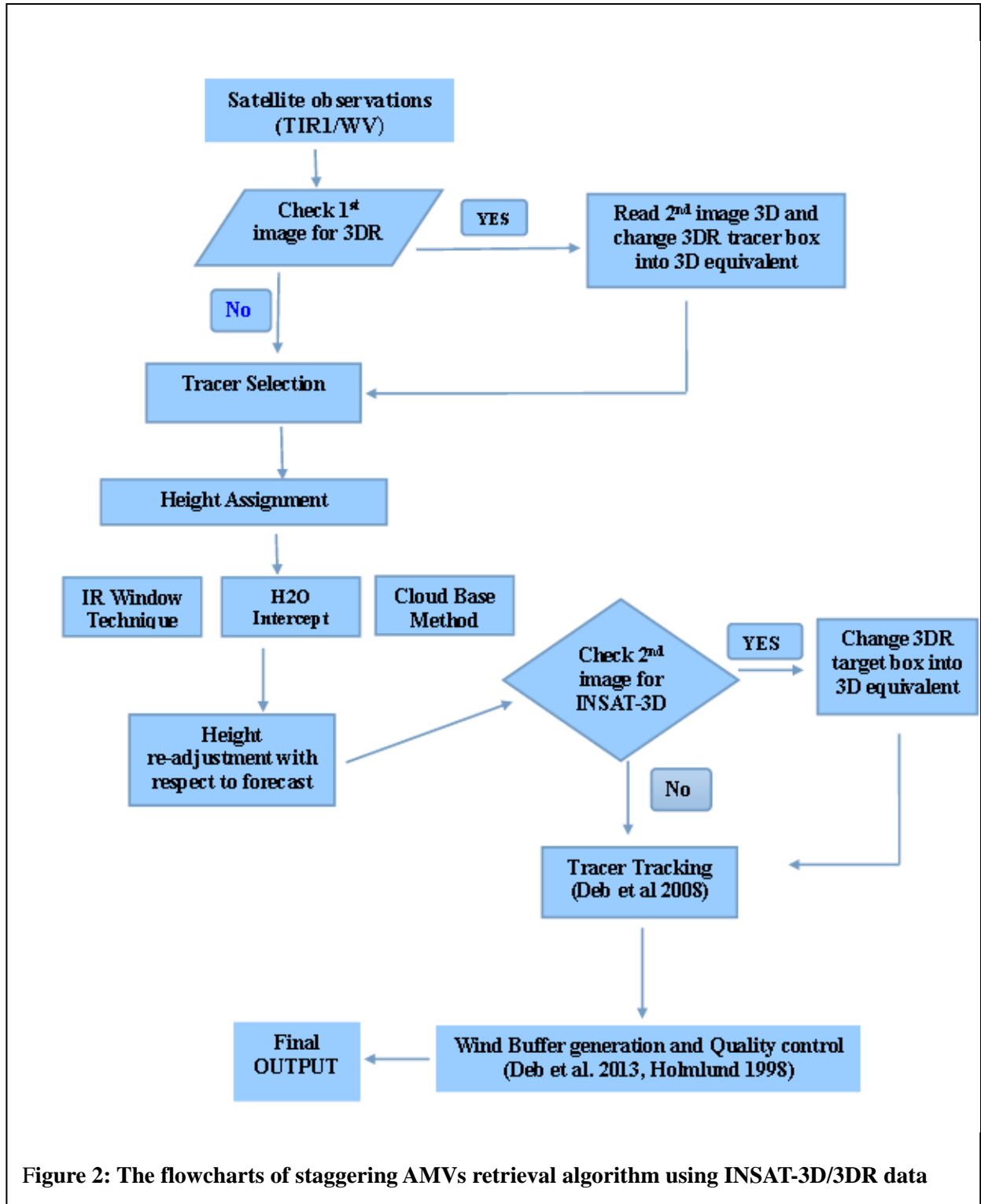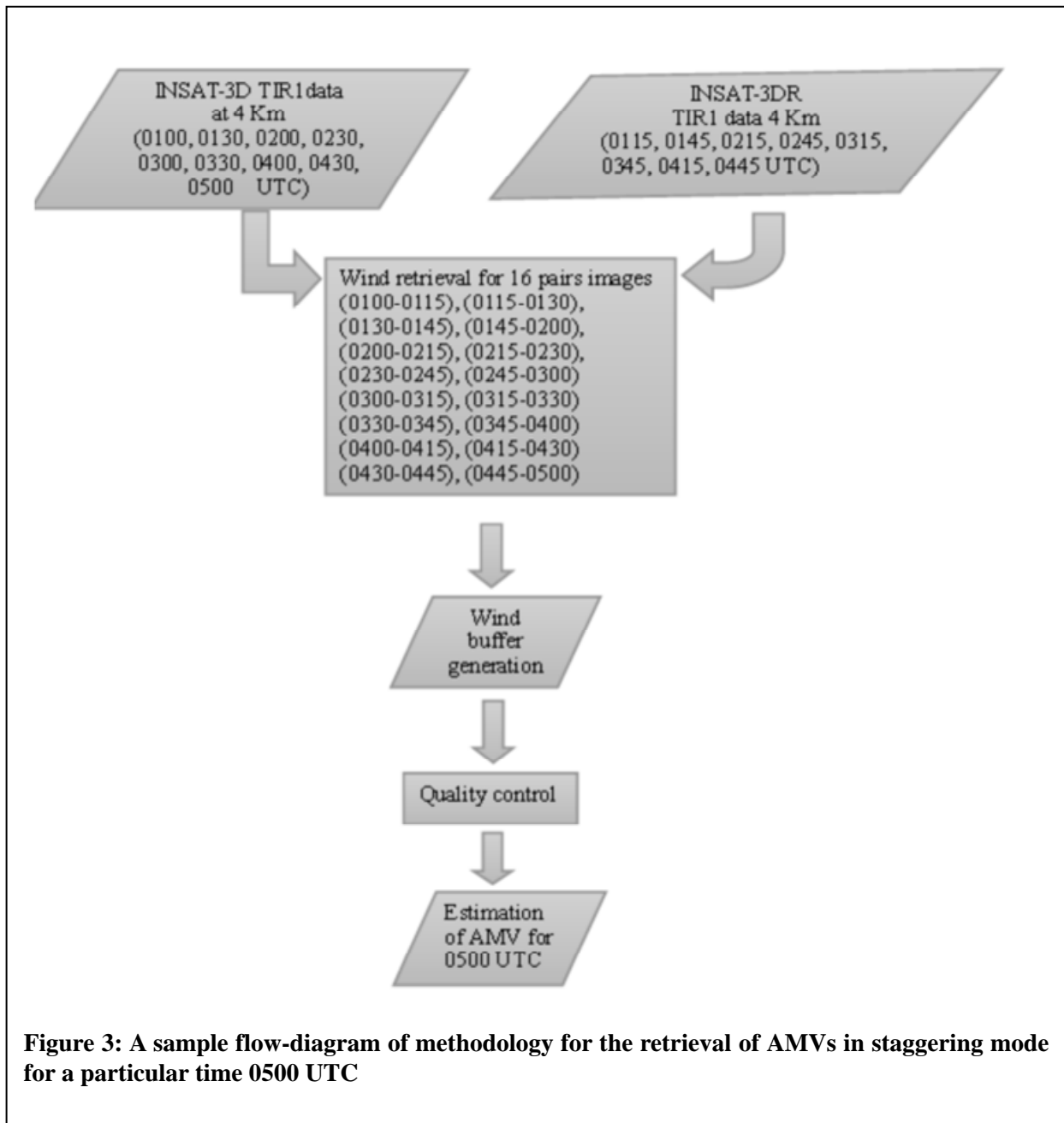
Figure 2: The flowcharts of staggering AMVs retrieval algorithm using INSAT-3D/3DR data

INSAT-3D). This is performed to reduce the uncertainty in inter-calibration of two different satellites, all-though their sensor specifications are exactly same. Then cloud tracers are selected by local image anomaly technique in a particular image and subsequently height of the selected tracers is calculated. The height assignment component of operational AMV retrieval algorithm uses widely used traditional methods viz. the infrared window (WIN) technique, the H_2O intercept method (Nieman et al., 1993) and the cloud base method (LeMarshall et. al., 1993). Then selected tracers are tracked in larger window in the subsequent image by using the Nash-Sutcliffe model efficiency (Nash and Sutcliffe, 1970)

Figure 3: A sample flow-diagram of methodology for the retrieval of AMVs in staggering mode for a particular time 0500 UTC

coefficient. If the selected first image is from *INSAT-3D*, the tracers are selected and height assignment is done, then before tracking the selected tracers in the second *INSAT-3DR* image, collocated tracer box in *INSAT-3DR* is calibrated to *INSAT-3D* equivalent. The process of tracer selection, height assignment and tracking is repeated for sixteen pair of images to generate sixteen pairs of raw winds which is called as wind buffer. Later, this wind buffer is used for quality control of AMVs. During the quality control, temporal, spatial consistency checks are performed with neighbouring vectors extracted from the wind buffer. A sample flow-diagram of methodology for the retrieval of staggering AMVs at 0500

UTC is shown in Figure 3. To derive winds valid at 0500 UTC requires total seventeen images of 15-minute interval viz. nine images from *INSAT-3D* starting from 0100 UTC and eight images from *INSAT-3DR* starting from 0115 UTC. In the next steps wind buffer is calculated using sixteen wind pairs. In the following step quality control technique is applied to wind buffer to estimate the final output valid at 0500 UTC. A typical example of derived TIR1 AMVs using *INSAT-3D* (Fig.4a) valid at 0000 UTC, *INSAT-3DR* (Fig.4b) valid at 0015 UTC and staggering AMVs using *INSAT-3D/3DR* data (Fig.4c) valid at 0000 UTC of 31 January 2017 are shown in Fig.4. It is visible from the figure
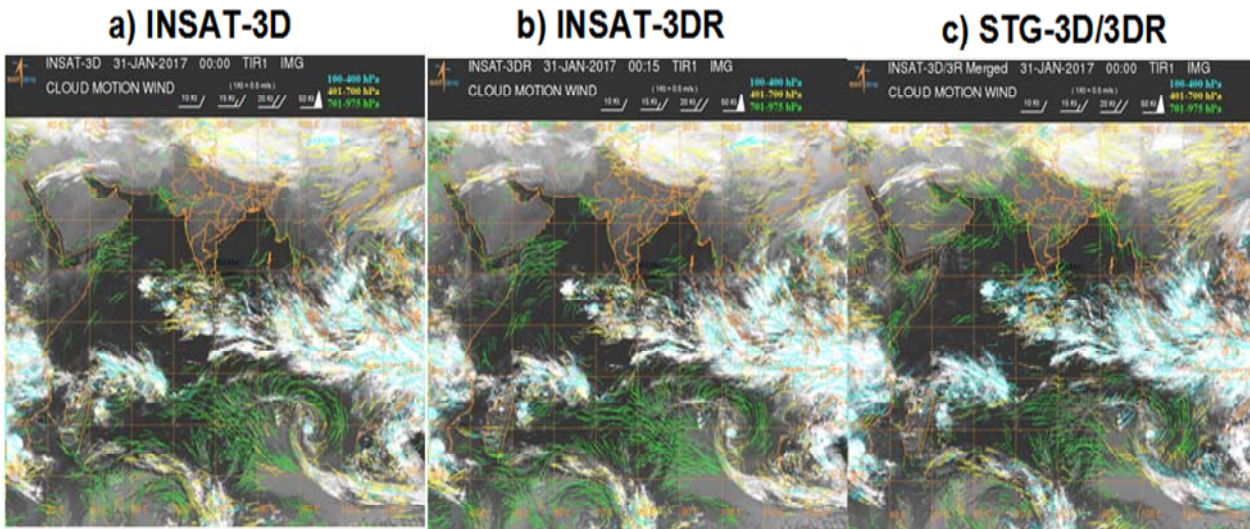
Figure 4: A typical example of operationally derived infrared AMVs using a) INSAT-3D valid at 0000 UTC, b) INSAT-3DR valid at 0015 UTC and c) staggering AMVs using INSAT-3D/3DR data valid at 0000 UTC of 31 January 2017

that staggering version retrieved around 10-15% more wind compared to other two versions.

3.2 Verification strategy

The verification procedure used for the quantitative assessments of three sets of two types AMVs (viz. *INSAT-3D, INSAT-3DR* and staggering AMVs using *INSAT-3D/3DR*) retrieved using TIR1 and WV channels are discussed here. In the subsequent text, three sets of satellite winds: i) winds retrieved using *INSAT-3D* is represented as 3D, ii) winds retrieved using *INSAT-3DR* is represented as 3R, and iii) staggering modes winds retrieved using *INSAT-3D/3DR* as STG respectively. For validation, three sets (3D, 3R and STG) of TIR1 AMVs and three sets of WV AMVs are compared with collocated radiosonde winds. The AMVs retrieved at 0000 or 0015 UTC and 1200 or 1215 UTC are collocated with radiosonde winds available at 0000 and 1200 UTC. For collocations with MISR SMVs, the AMVs retrieved at 0000 or 0015 UTC, 0600 or 0615 UTC, 1200 or 1215 UTC and 1800 or 1815 UTC are used. The data collocation and quantitative assessment are done as per CGMS guidelines (Tokuno, 1998) by calculating the Root Mean Square Vector Difference (RMSVD) and speed bias in m/s. The AMVs

with Quality Indicator (QI) value greater than or equal to 0.8 are considered for all quantitative analysis. The root mean square differences (RMSD) and bias of zonal and meridional wind, wind speed, wind direction and height are calculated for comparison with MISR SMVs. During bias calculation difference with respect to truth is taken. In the present study radiosonde winds and MISR SMVs are considered as truth. During collocation a spatial difference of 0.5 degrees and temporal collocation of ±1.5 hour within the AMVs and MISR SMVs are considered (Velden and Holmlund, 1998). However, the AMVs close to MISR wind height is selected for collocations without considering any vertical collocation threshold. Since there is a possibility of large errors in AMV height assignment, a vertical collocation threshold value during collocation in this case may wrongly matched the wind, while actually they are not present around the same levels. As standard practice, the AMVs with a speed and direction differences greater than 30 m/s and 60 degrees with respect to observed winds are assumed as erroneous either due to wrong retrieval or due to errors in observations. This constitutes a very small percentage of total validation data sets. As per CGMS guideline, level wise error statistics are generated for

high- (i.e. 100-400 hPa), mid- (i.e. 401-700 hPa) and low-levels (i.e. 701-950 hPa) for TIR AMVs and only high level (100 - 400 hPa) for WV AMVs.

4. Results and Discussion

4.1 Assessment with Radiosonde data

The Table-1 shows the monthly average values of RMSVD and speed bias of *INSAT-3D (i.e. 3D), INSAT-3DR (i.e. 3R)* and staggering mode AMVs using *INSAT-3D/3DR* (i.e. STG) TIR1 and WV AMVs with respect to radiosonde observation for three different broad atmospheric levels i.e. low-, mid- and

high-levels for the month of January 2017.

The RMSVD values of TIR1 AMVs are matched well for both 3D and 3R versions in all levels, with few exceptions. In the STG version the accuracy has improved in mid- and low-levels compared to 3D and 3R versions, however at high-level the accuracy in STG version has not improved as expected. This might be due to the problem of the inter-calibration of two satellites in terms of brightness temperature at higher-levels, which in turn lead to slightly higher error in the height assignment. In the region-wise analysis like tropical regions ($20^oS – 20^oN$), northern hemisphere ($20^oN – 60^oN$) and southern

Table 1. Monthly mean comparison of *INSAT-3D, INSAT-3DR* and staggering AMVs (TIR1 and WV) using INSAT-3D/3DR data with radiosonde observations available over land for the months of January 2017 for different regions

		TIR1 (3D)			TIR1 (3R)			TIR1(STG-3D/3R)			WV (INSAT-3D, 3R and STG-3D/3R)		
		January 2017											
		INSAT-3D			INSAT-3R			STG-3D/3R			INSAT-3D	INSAT-3R	STG-3D/3R
		HIGH	MID	LOW	HIGH	MID	LOW	HIGH	MID	LOW	HIGH	HIGH	HIGH
		All regions (Retrieval domain)											
RMSVD		5.18	5.57	4.57	5.19	5.55	4.69	5.62	5.28	4.29	6.51	6.34	6.59
BIAS		0.07	0.16	0.64	0.22	0.33	0.73	-0.27	-0.68	-0.33	0.05	0.02	-0.02
NC		19098	11296	7420	19461	11499	8553	21605	16368	8170	38427	37516	39609
		Tropic (20oS-20oN)											
RMSVD		5.04	4.25	3.91	5.04	4.23	4	5.15	3.87	3.86	5.55	5.53	6.11
BIAS		0.02	0.64	0.9	0.16	0.8	1.07	0.33	0.49	0.95	0.48	0.39	0.45
NC		17843	1677	1111	18246	1210	1079	17289	646	1246	23534	24973	27655
		Northern Hemisphere (20oN – 60oN)											
RMSVD		6.37	5.8	4.59	6.82	5.7	4.74	7.42	5.39	4.32	7.19	7.08	7.56
BIAS		0.61	0.04	0.62	0.84	0.17	0.69	-2.97	-0.73	-0.45	-0.59	-0.65	-1.16
NC		952	9483	6263	915	10117	7442	3514	15637	6633	14077	11669	11279
		Southern Hemisphere (20oS – 60oS)											
RMSVD		5.59	4.73	6.01	4.82	4.04	5.47	4.15	3.44	4.11	5.87	5.43	5.7
BIAS		-0.27	0.97	-0.1	0.24	1.82	0.13	0.03	0.76	-0.66	0.92	0.74	0.64
NC		303	136	46	300	172	32	518	117	59	816	874	675
		The units of RMSD and Bias is m/s											

hemisphere (20^oS – 60^oS), except at high-level in the northern hemisphere the RMSVD and bias values for STG are either better or similar to the corresponding values of 3D or 3R. The mid-level bias is slightly higher compared to high and low-levels in all the three sets. The RMSVD and speed bias for WV AMVs for all three sets are similar in nature, however, among them the 3R version of WV AMVs are slightly better compared to other two sets for all regions.

The Figure 5 (a-d for infrared and f-i for water vapor AMVs) shows the mean vertical profiles of RMS differences in speed and direction along with respective biases with much finer scales for all the month of January 2017. As mentioned, in the figure, 3D, 3R and STG represents *INSAT-3D*, *INSAT-3DR* and staggering AMVs with *INSAT-3D/3DR* versions respectively. All the three sets have similar RMS difference and bias in speed and direction for both infrared and water vapor AMVs except the STG version (both TIR and WV) have slightly higher RMS differences in speed from 350 hPa to further higher levels (**Figure 5a, f**) respectively. The higher RMS differences in the STG version may be due to higher inaccuracies in the height assignment from mid to high-levels. The higher inaccuracies in the height assignment of STG version may be due to calibration issue of *INSAT-3D* and *INSAT-3DR* satellites. The RMS differences in direction for TIR1 and WV AMVs of all three sets are similar (Figure 5b, 5g). The bias in speed is positive or zero at the lower-levels, while negative at 200-400 hPa levels (Figure 5c), with slightly higher for the STG version of TIR1 AMVs. The range of bias in direction for all three sets are comparable (Figure 5d). The RMS differences in speed for WV AMVs (Figure 5f) are slightly better for 3D and 3R versions compared to the STG version from mid- to high-levels respectively. Consequently the speed bias is lower for 3D and 3R versions, compared to STG version. The RMS difference and bias in direction for all three sets are comparable (Figure 5g, i). The Figure 5(e, j) shows the total numbers of collocations for the month of January 2017 for both infrared and water vapor AMVs. The collocations for TIR1 AMVs is mostly dominated at the upper levels, which reflects higher retrieval of TIR1 AMVs at these levels (Figure 5e). Again, since

WV AMVs are retrieved around 100 – 500 hPa levels, as a results the collocations are mostly available at these levels (Figure 5j). The STG version has higher number of collocations in the high-levels, compared to other two sets.

The assessment till now are demonstrated using all AMVs irrespective of quality indicator values. However, for the operational use of new sets of *staggering AMVs,* it's essential to investigate the sensitivity of accuracies with respect to different quality indicator values. This is because, many operational centres use AMVs for the assimilation in the model after assessing the accuracy with respect to different quality indicator values. The RMSVD values (a, b, c and d, upper panel), speed bias (e, f, g and h, middle panel) and numbers of collocations (i, j, k and l, lower panel) of infrared AMVs for high-, mid- and low-levels and water vapor AMVs for high-level using various quality indicators values are shown in Figure 6. The infrared AMVs for high-level (Figure 6a), RMSVD values of 3D and 3R versions are lower compared to STG version for all quality indicator values, while for mid- and low-levels RMSVD values of STG version is better compared to 3D and 3R versions (**Figure 6b,c**). In case of water vapor AMVs the RMSVD values of 3D and STG versions are similar, while in 3R version it is better compared to other two (Figure 6d). In all versions the RMSVD value is not much sensitive to the different quality indicator values (Figure 6a-d). It is noticed that for any quality indicator value the RMSVD value ranges between 5.0 – 6.0 m/s for high-level, 5.0 - 5.5 m/s for mid-level and 4.2 - 4.7 m/s for low-level. As expected, for all quality indicators the RMSVD values are reducing very slowly from 0.0 quality indicator to 0.8 quality indicator for high-, mid- and low-levels, respectively. In case of speed bias (Figure 6e-h) for all three versions, the sensitivity with respect to quality indicator values is very small. However, if total number of collocations are considered (Figure 6i-l), collocation decreases drastically as one move to higher quality indicator values and collocations is higher in STG versions compared to other two versions.
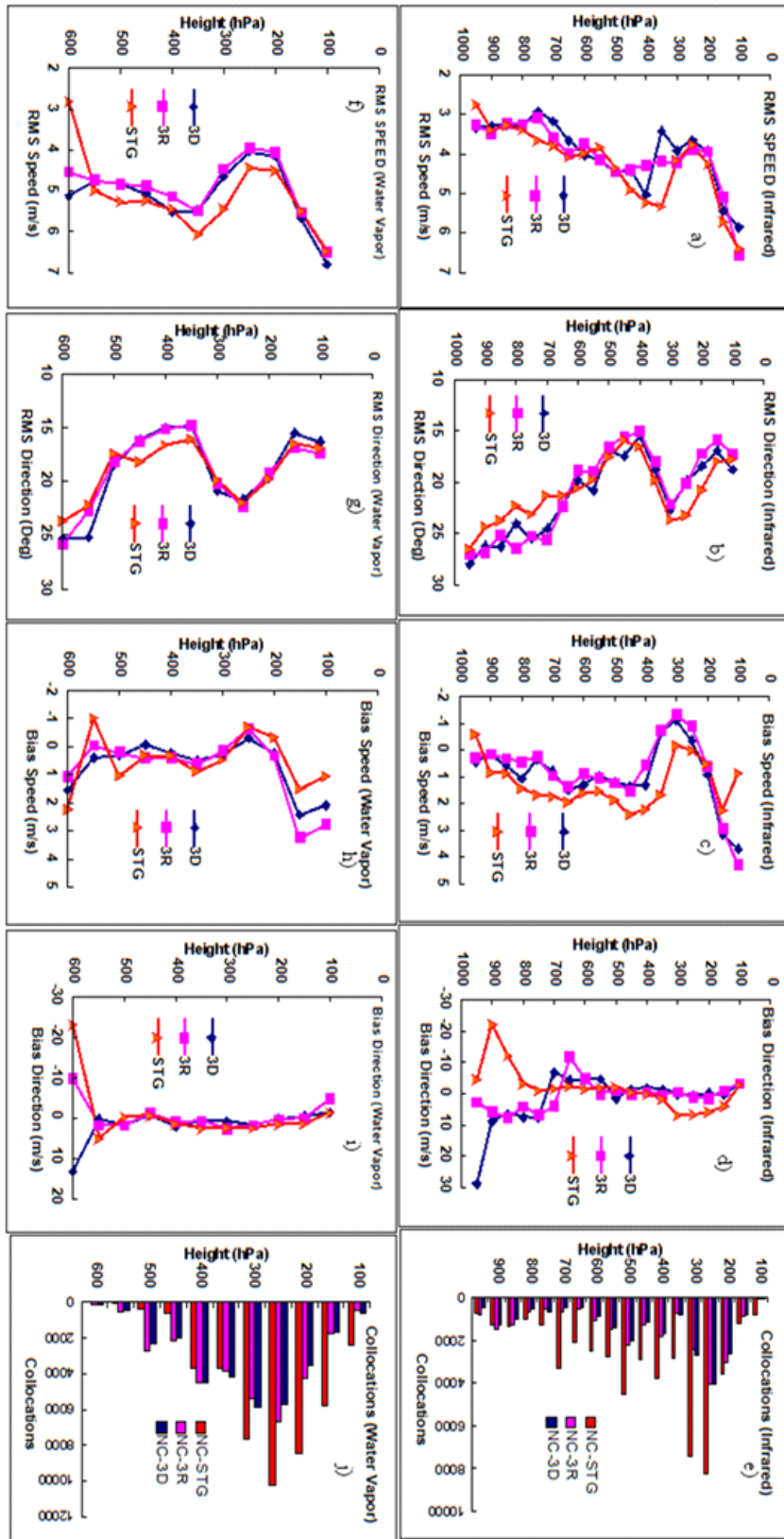
Figure 5: The mean vertical profiles of RMS differences, biases in speed and direction and total numbers of collocation points for infrared (upper panel) and water vapor (lower panel) atmospheric motion vectors (AMVs) of *INSAT-3D, INSAT-3DR* and staggering version of INSAT-3D/3DR when validated with radiosonde data for the months of January 2017

Table 2. Monthly mean comparison of INSAT-3D, INSAT-3DR and STG-3D/3R infrared atmospheric motion vectors (AMVs) with MISR stereo motion vectors (SMVs) for different atmospheric levels

Variable	INSAT-3D TIR vs. MISR						INSAT-3DR IR vs. MISR						STG-3D/3R IR vs. MISR					
	RMS			BIAS			RMS			BIAS			RMS			BIAS		
	HIG	MID	LOW	HIG	MID	LOW	HIG	MID	LOW	HIG	MID	LOW	HIG	MID	LOW	HIG	MID	LOW
Zonal wind (U)	5.65	6.35	3.38	0.39	2.71	0.73	5.80	6.24	3.51	-0.69	2.03	0.54	6.83	7.11	3.33	-1.3	3.30	0.33
Meridional wind (V)	6.99	5.94	3.56	2.52	0.51	0.20	7.12	6.21	3.53	2.62	0.69	0.14	7.66	5.44	3.70	1.42	0.27	-0.37
Wind speed	6.50	6.55	3.44	0.87	1.55	1.18	6.49	6.57	3.47	0.64	1.04	1.16	7.32	6.70	3.17	0.61	2.12	0.05
Wind direction	36.2	30.6	27.0	-10.0	-6.76	1.21	36.4	29.7	27.3	-10.1	-12.1	1.45	38.2	37.1	32.3	3.58	28.6	17.5
Height	191	172	83.2	-145	-109	0.66	188	163	87.4	-144	-96.9	-1.10	205	199	92	-168	-161	-18.0

The unit of zonal wind, meridional wind and wind speed is m s⁻¹, while the unit of wind direction and height are deg and hPa.

4.2 Assessment with MISR Stereo Motion Vectors

The large errors in AMVs are mainly because of errors in height assignment. The height assignment of SMVs are considered to be more accurate than that of AMVs. As mention in section 3.2, no vertical collocation threshold is used during collocation of AMVs with MISR SMVs because both are available at particular level that of cloud and it is not guarantee that they are at similar height. Thus a vertical collocation threshold of ±50 hPa value during collocation between AMVs and SMVs does not guarantee that wind represents the same levels or clouds. The different statistical parameters of 3D, 3R and STG AMVs (infrared and water vapor winds separately) with MISR SMVs for low-, mid- and high levels for the month of January 2017 are shown Tables 2 and 3 respectively

In the case of infrared AMVs (Table 2), it is noticed that the collocation is mostly AMVs at all levels. For zonal wind components mid-level bias is higher, while for meridional components high-level bias is higher in all three cases. The biases in both zonal and meridional components of STG AMVs are slightly higher compared to other two sets. The RMSD for both zonal and meridional components is comparable for all three sets, however, the STG version AMVs have slightly higher values compared to other two sets. The mean wind bias and RMSD values are gradually increasing from lower level to higher level, and the values for all three sets are comparable. The RMSD in height for all three sets is not significantly different from each others. The bias in height for high-, mid- and low levels is negative for 3R and STG versions, while it is positive for low levels in *3D* version. The negative height bias at mid- and high levels shows that SMV height is larger than AMV height and this might be because of low bias in AMV height in semi-transparent clouds. Similar assessments were noticed when MISR SMVs

Table 3. Monthly mean comparison of INSAT-3D, INSAT-3DR and STG-3D/3R water vapour atmospheric motion vectors (AMVs) with MISR stereo motion vectors (SMVs) for high level

	INSAT-3D WV vs. MISR		INSAT-3DR WV vs. MISR		STG-3D/3R WV vs. MISR	
Variables	HIGH		HIGH		HIGH	
	RMSD	BIAS	RMSD	BIAS	RMSD	BIAS
Zonal wind (U)	7.42	1.46	7.53	1.51	8.10	2.12
Meridional wind (V)	7.71	1.53	6.59	1.06	7.44	1.25
Wind speed	7.89	2.74	7.78	2.67	8.51	2.42
Wind direction	27.46	-3.56	26.25	-7.82	28.06	-1.24
Height	208	-170	200.5	-157.2	203.49	-163.0
The unit of zonal wind, meridional wind and wind speed is m s^{-1}, while the unit of wind direction and height are deg and hPa.						

dominated in the low-level and for water vapor AMVs (Table 3), the collocations is dominated at the upper level, as these AMVs are retrieved around 100-500 hPa levels. In case of infrared wind (Table 2), 3R and STG versions have negative bias in the high-level and positive bias in the mid- and low-levels for both the zonal and meridional component of the winds, while it is positive in case of 3D version of

and Meteosat-9 AMVs were inter-compared and increasing trends were found in bias and RMSD values with height for both wind magnitude as well as in height assignment (Lonitz and Horváth 2011).

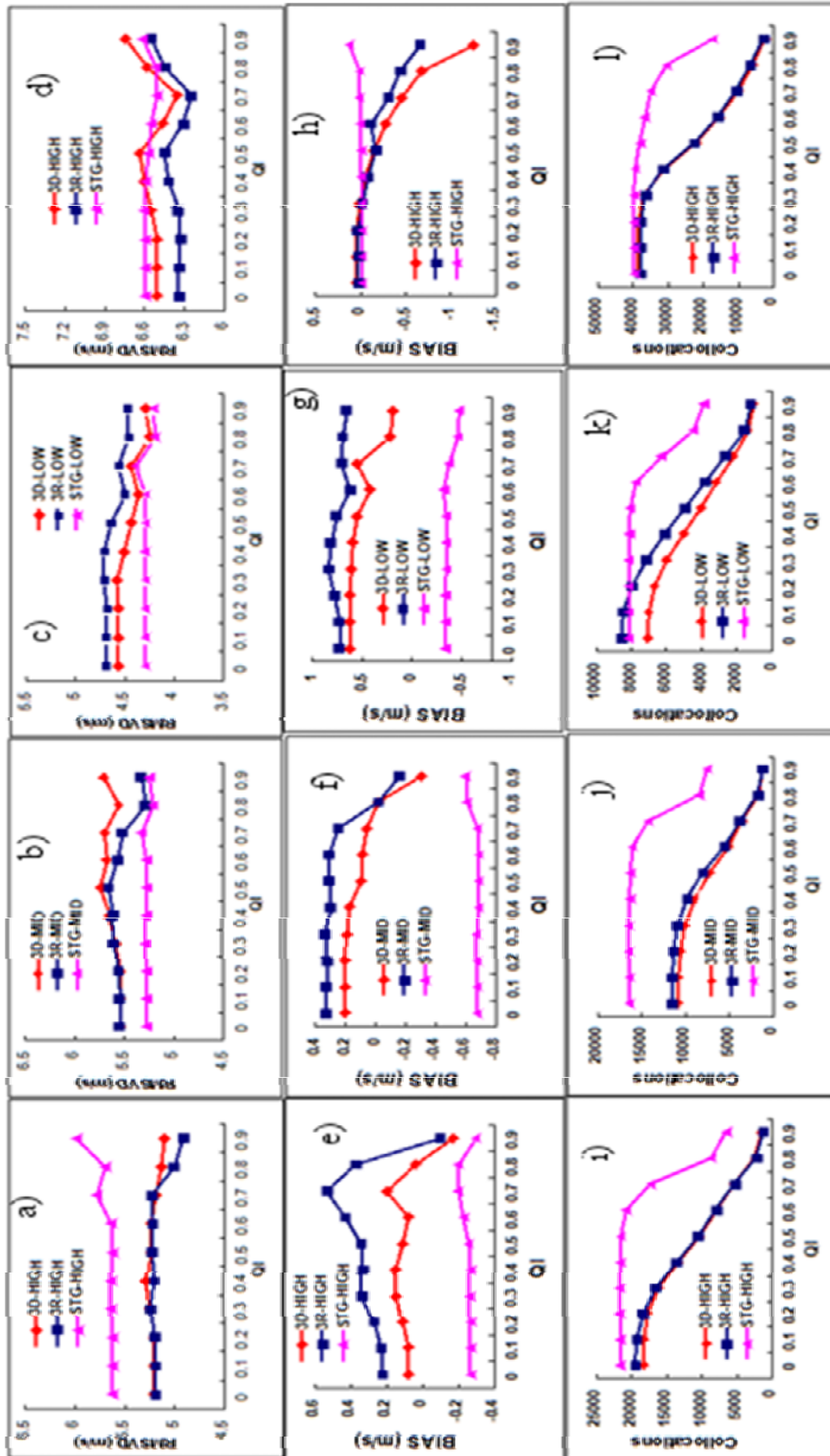In the case of water vapor AMVs, the assessment for the high level is shown in Table 3.

Figure 6: The RMSVD (a, b, and c upper panel), speed bias (e, f and g, middle panel) and numbers of collocations (i, j and k, lower panel) of infrared and AMVs for different levels using variable quality indicators values. The RMSVD (d, upper panel), speed bias (h, middle panel) and collocations (l, lower panel) of water vapor AMVs for high-level using various quality indicators values
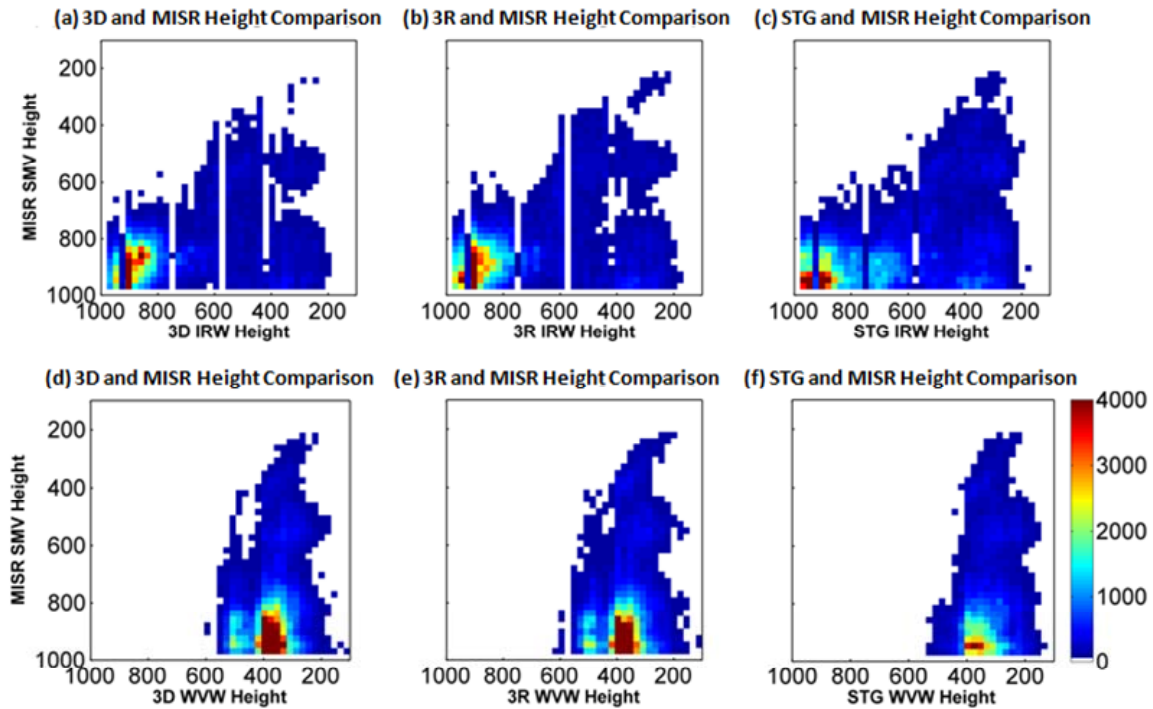
Figure 7: The density plot of heights of: a) *INSAT-3D*, **b) INSAT-3DR and c) staggering version using INSAT-3D/3DR infrared AMVs and (d-f) same for water vapor AMVs collocated with MISR SMVs height for the month of January 2017.**

The bias and RMSD values for the zonal and meridional components of AMVs for 3D, 3R and STG are in good agreement. The negative bias in the height of 3D, 3R and STG versions of WV AMVs is observed when compared with MISR SMVs. The density plots of heights of 3D, 3R and STG versions of infrared (Figures 7a-c) and water vapor (Figures 7d-f) AMVs collocated with MISR SMVs height for the month of January 2017 are shown in Figure 7. The density plots will help us to understand better ways, why there is large errors in the height of infrared and water vapor AMVs when compared SMV heights. The significant differences noticed in the data clusters where MISR SMV height is within 600–975 hPa, while AMV height is within 100–500 hPa, which constitutes around 22% collocations pairs. Apart from this cluster, the most of wind height comparison is in one-to-one agreement with each other. Similarly, the large discrepancies are observed in case of water vapor AMVs (Figures 7d-f), where MISR SMV height is within 800-900hPa, while AMV height is within

300-500hPa, which constitutes around 66% of collocations pairs.

The density plots for different height assignment methods used during retrieval i.e corresponding to infrared window technique (Figure 8a), H_2O intercept method (Figure 8b) and the cloud base method (Figure 8c) for height assignment of 3D infrared AMVs are shown when collocated with MISR SMVs. The Figure 8a-b, where the infrared-window technique and the H_2O intercept method are taken shows major discrepancies. The Figure 8d-f and g-i shows the density plots for other two sets (i.e. 3R and STG) of infrared AMVs. The similar features are noticed in these cases, like that of *INSAT-3D*. Like in infrared AMVs, the comparison of water vapor AMVs with MISR SMVs shows (Figures not shown) major disagreements in both water vapor histogram method and H_2O intercept method for all three sets. This discrepancies arises because water vapor AMVs are mostly dominated in the mid to high level, while MISR SMVs are available mostly in the
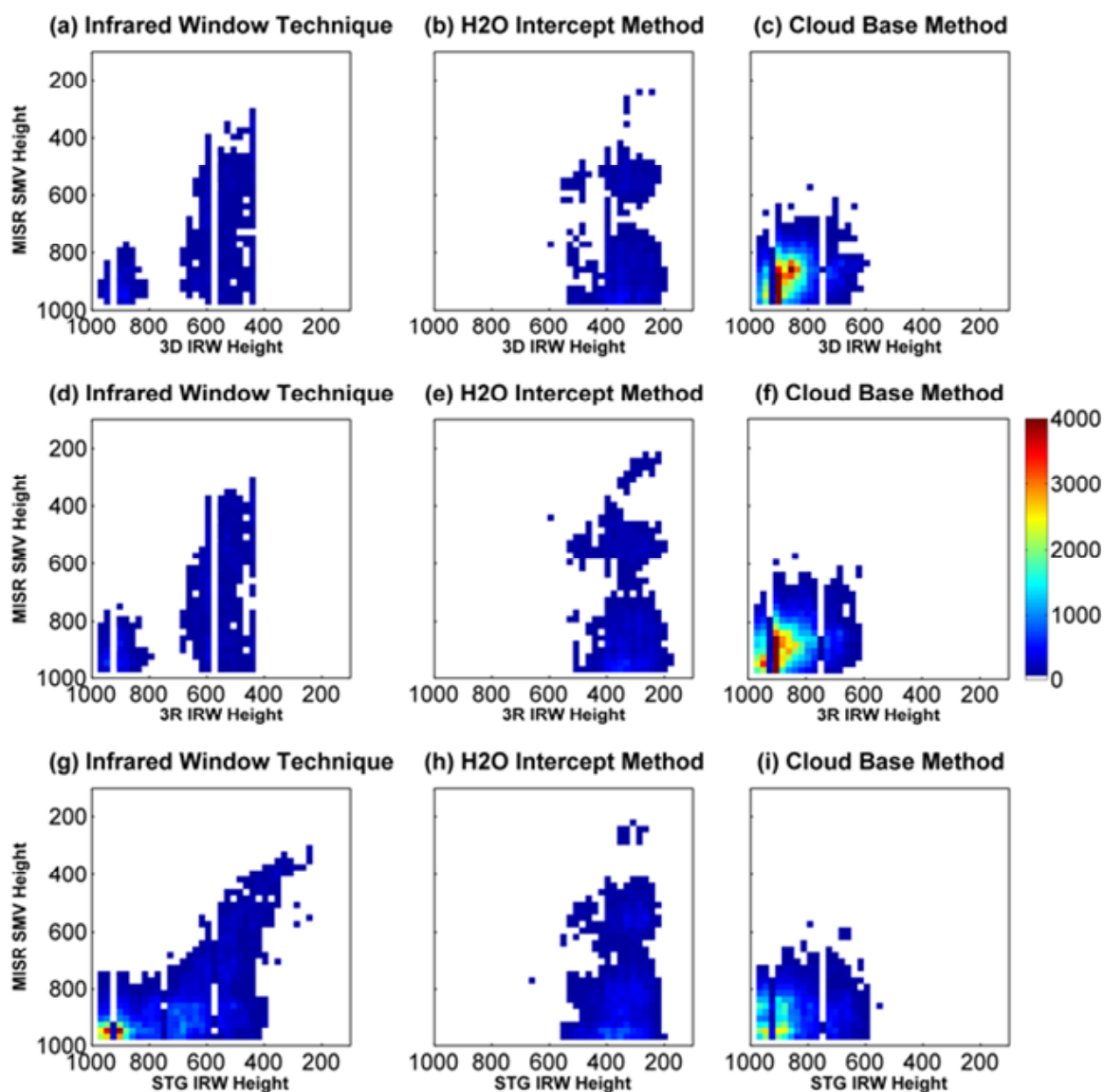
Figure 8: Density plots of MISR SMV heights with that of *INSAT-3D* infrared AMVs heights for different height assignment methods: a) infrared-window technique, b) H2O intercepts method and c) cloud-base method. (d-f) and (g-i) are similar to (a-c) but for *INSAT-3DR* and staggering version using INSAT-3D/3DR infrared AMVs

low-levels. The assessment found in this sub-section are in agreement with the findings of our earlier study (Deb et al. 2016), where the characterization of *INSAT-3D and* Meteosat-7 AMVs with MISR SMVs were done. It was observed that these large disagreements are not because of biases in height assignment algorithm, but is due to arte-facts of retrieval algorithm of AMVs and SMVs. These large mismatch points are because of multi-level clouds. During the retrieval of AMVs height is estimated using

cloud-top temperature from the upper-level clouds, while SMV retrieval is dominated in the low-level as MISR stereo-matcher algorithm favors a lower-level higher-contrast cloud targets in multi-level clouds patch.

4. Conclusions

In this study an attempt has been made to develop AMV retrieval algorithm using *INSAT-3D* and *INSAT-3DR* data in staggering mode to exploit the availability in higher temporal samples images. It also summarizes

the quality assessment of staggered infrared and water vapor AMVs retrieved using *INSAT-3D/3DR* data over the Indian Ocean region. The study uses three sets of derived AMVs: i) *INSAT-3D*, ii) *INSAT-3DR* and iii) Staggered AMVs using *INSAT-3D/3DR*

starting from 01 January 2017 to 31 January 2017. In these sets, *INSAT-3D* and *INSAT-3DR* AMVs are generated using 30-minute images,while staggered AMVs are generated using 15-minutes images. To get the confidence of staggered 15-minute AMVs, all three sets are compared with independent observations: i) in-situ radiosonde wind measurements and ii) cloud tracked winds derived using stereo-technique from MISR instrument. The comparison shows that the qualities of staggered AMVs are comparable or sometimes even better specially in the mid- and low-levels in case of infrared AMVs when compared with corresponding individual *INSAT-3D* and *INSAT-3DR* AMVs. Though the present study is mainly focused on the development of staggering algorithm and its initial quality assessment, however this preliminary analysis has demonstrated an insight into the quality of newly derived staggered AMVs. In future, the assessment of this new data sets will be evaluated by assimilating them in the numerical weather prediction models for forecast impact studies. This will further showcase its scope of use-ability at the major operational forecasting agencies viz. India Meteorological Department (IMD) and National Centre for Medium Range Weather Forecast (NCMRWF), as they are the main users of this new AMV data-set for assimilating into the operational numerical weather prediction models.

Acknowledgements

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