INSAT-3D low-level atmospheric motion vectors: Capability to capture Indian summer monsoon intra-seasonal variability

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In India, Atmospheric Motion Vectors (AMVs) are derived operationally from the advanced Indian meteorological geostationary satellite INSAT-3D since July 2013 over Indian Ocean region and are used in the numerical model for forecast improvement. In this study, first-time the low-level monsoon winds derived from INSAT-3D satellite have been used to see how these winds are successful in capturing the intra-seasonal variability over the Indian Ocean region for the year 2016. A validation of AMVs is done on regular basis. In this study, the validation of low-level AMVs with National Center for Environmental Prediction (NCEP) analysis winds carried out during June to September 2016. The observed mean monthly features of the Indian Summer Monsoon (ISM) in July and August 2016 from low-level AMVs from INSAT-3D match well with those of NCEP analysis winds. INSAT-3D low-level AMVs are quite successful in capturing the northward propagation of low level jet and their locations during active and break monsoon conditions which are known features of the ISM. They are also able to explain the two dominant modes of variability: (i) one with a periodicity between 32 and 64 days, and (ii) another with a periodicity between 8 and 16 days, for the monsoon season of 2016 when Morlet wavelet transform analysis is performed for time series analysis. An EOF analysis is performed for the study of the spatial structure of intra-seasonal variability and temporal variability of INSAT-3D low-level AMVs over the Indian Ocean region for ISM 2016 and quantifies the results of EOF analysis by performing RMSE analysis between EOFs of INSAT-3D and NCEP wind data.

Keywords. Monsoon; INSAT-3D AMVs; Indian Ocean; EOF analysis.

1. Introduction

The operational derivation of Atmospheric Motion Vectors (AMVs) by considering the movement of cloud and water vapour tracers in successive images of geostationary satellites (Schmetz *et al.* 1993; Nieman *et al.* 1997; Velden *et al.* 1997;

Shimoji and Hayashi 2012) are considered as one of the most reliable source of wind information with higher spatial-temporal coverage over the ocean as well as land regions. In India, initially the AMVs were retrieved operationally using the images from Kalpana-1 (Kishtawal *et al.* 2009) and later many upgradations (i) improvement in

height assignment, (ii) improvement in quality control technique, and (iii) derivation of low-level winds using visible and mid-infrared channel, were made in the operational AMV retrieval algorithm when advanced meteorological satellite INSAT-3D was launched during July 2013 (Kaur *et al.* 2013; Deb *et al.* 2016). The AMVs is one of the important inputs to the global and regional assimilation systems for the improvement of Numerical Weather Prediction (NWP). The role of AMVs is particularly significant over the oceans and high latitudes where *in-situ* observations are scarce. The importance of AMV observations increases particularly over the tropics, where the geostrophic coupling between the mass and the flow fields is weaker in comparison to higher latitudes. In the tropical atmospheric processes, the significant improvement is observed in the weather forecast (Kelly *et al.* 2004; Bedka and Mecikalski 2005; Deb *et al.* 2010; Kumar *et al.* 2016) when AMVs is assimilated in both regional and global models. The vertical coverage of AMVs spreads through high to low-levels as per the channel used during retrieval, viz., AMV retrieved using: (i) infrared channel data covers entire ranges of atmosphere, i.e., from 100–950 hPa, (ii) water vapour channel data covers only high-level, i.e., from 100–500 hPa, while (iii) visible and mid-infrared channel data covers low-levels, i.e., from 600–950 hPa, respectively. The low-level analyzed winds from the different operational numerical models and Oceansat-2 scatterometer (OSCAT) surface winds (Sathiyamoorthy *et al.* 2012) were used to explore the characteristic behaviour of the Indian Summer Monsoon (ISM). Apart from numerical model wind other parameters, viz., convection, rainfall (Webster *et al.* 1998; Goswami and Ajaya Mohan 2001; Joseph and Sijikumar 2004) and humidity, etc., are used to explain the intra-seasonal variability of ISM; however, no-one has demonstrated the capabilities of low-level AMVs for capturing the intra-seasonal variability of ISM. In this study, an attempt has been made to demonstrate the capabilities of low-level AMVs (i.e., 700–950 hPa region) by studying the characteristics of the ISM for the year 2016. The following section 2 briefly summarizes the information about INSAT-3D level-2 data and details about AMVs derived using different spectral channel data and National Centre for Environmental Prediction (NCEP) numerical model analysis data. In section 3, the results from the analysis are discussed with different perspectives. Finally,

section 4 summarizes the conclusions from this study.

2. Data used

2.1 INSAT-3D AMVs

The advanced Indian meteorological geostationary satellites INSAT-3D is placed at 82°E over the Indian Ocean region. It carries a six channel imager for the purpose of enhanced meteorological research and operational needs. The imager has 6 spectral channels and these are: (i) Visible (VIS) for [0.55–0.75 μm], (ii) Short-wave infrared (SWIR) for [1.55–1.70 μm], (iii) Mid-wave infrared (MIR) for [3.8–4.0 μm], (iv) Water vapor (WV) for [6.5–7.1 μm], and (v) two split-window thermal infrared (TIR1 and TIR2) for [10.2–11.3 μm] and [11.5–12.5 μm] ranges of spectrum, respectively. For the operational retrieval of AMVs, data from the VIS, MIR, WV and TIR1 re-sampled at 4 km spatial resolution with a coverage area [30°–130°E, 50°S–50°N] over the Indian Ocean region are used. The retrieval process is done at each acquisition, i.e., at every 30 min interval with same coverage area. The operational INSAT-3D AMVs are received and archived at satellite data archival centre at Space Applications Centre, Ahmedabad (<https://www.mosdac.gov.in>) and IMD Delhi for operation use in the models. For the present study, operational low-level AMVs retrieved using visible (VIS) and mid-infrared (MIR) channel of INSAT-3D data from 01 June 2016 to 30 September 2016 are used. The visible AMVs are retrieved during day, while MIR AMVs are retrieved during night. The following steps: (i) tracer selection, (ii) tracer height assignment, (iii) tracking of tracer in the subsequent images, and (iv) wind buffer generation and quality controls, are followed for the operational derivation of low-level AMVs from visible (VIS) and mid-infrared (MIR) channel of INSAT-3D. The descriptions of each step are presented in Deb *et al.* (2016).

2.2 NCEP analysis data

The National Center for Environmental Prediction (NCEP) analysis wind data are available (<http://nomads.ncdc.noaa.gov/>) at 0.5° latitude $\times$ 0.5° longitude resolution globally with 47 vertical pressure levels at every 6 hr interval (i.e., 4 times daily). The 6 hr model analysis winds from 01 June 2016 to 30 September 2016 are used for this study and

out of 47 vertical pressure levels, 12 (700–950 hPa low) vertical pressure levels are used for this study. Here, 0.5° latitude $\times$ 0.5° longitude resolution data converted to 1° latitude $\times$ 1° longitude resolution for the verification.

3. Results and discussions

3.1 Preliminary validation

In this section, the quality of INSAT-3D AMVs are assessed with respect to NCEP analysis winds over the Indian Ocean region. Since AMVs are available at very coarser resolution (at around 110×110 km horizontal resolution) with scattered manner, before starting the assessment analysis, daily composite AMVs are generated from the available 30 min AMVs. Both VIS AMVs available during day and MIR AMVs available during night are combined together to make the gridded daily composite. In the daily composite, low-level VIS and MIR AMVs available in the 700–950 hPa region are averaged to represent a single low-level AMVs. The averaging reduces the data gap in the AMVs. One possible reason for the data gap is the absence of appropriate cloud tracers during the retrieval of AMVs over that region. For doing collocation the NCEP analysis available 4 times a day are averaged to make daily averaged value. Again model analysis winds available at different levels between 700 and 950 hPa are averaged to make single low-level winds. Finally, two sets of

daily-averaged gridded low-level winds are used for this study: (i) INSAT-3D AMVs and (ii) NCEP wind analysis over region 30° – 110° E and 30° N– 30° S. Figure 1(a and b) shows density scatter plots between INSAT-3D low-level AMVs and NCEP analysis wind speeds and wind directions. The bias and root mean square error (RMSE) are calculated for wind speed and wind direction is also shown in the figure. It is found that the INSAT-3D AMVs wind speed RMSE is around 3.2 ms^{-1} , while that for wind direction is 20° , respectively for the period of analysis. These values are similar to the values of other AMVs available from different other satellites over this region (Deb *et al.* 2016).

3.2 Monthly mean features

Figure 2(a and d) shows the monthly mean low-level AMVs from INSAT-3D and figure 2(b and e) shows the similar low-level winds from NCEP reanalysis for the summer monsoon months of July and August 2016, respectively. Though, the resolution of INSAT-3D AMVs is coarse, it is quite successful in capturing the important features of the IMS circulation. From the figures it is noticed that AMVs are able to capture: (i) cross-equatorial flow of winds along the East African coast, (ii) lower level jet (LLJ) over the Arabian Sea, (iii) comparatively calm winds near equator on either side, and (iv) southern hemispheric easterly trade winds. The strength of LLJ is almost

Figure 1. Density scatter plot between INSAT-3D and NCEP analysis (a) wind speed and (b) wind direction during June to September 2016. The bias, SD and RMSE are also provided in the figure.

Figure 2. Monthly averaged low-level winds (ms^{-1}) obtained from INSAT-3D during July 2016 (a) and August 2016 (d). Similar figures monthly averaged low-level winds (ms^{-1}) for July 2016 (b) and August 2016 (e) from NCEP analysis. Spatial correlation of INSAT-3D and NCEP low-level wind during July 2016 (c) and August 2016 (f).

similar in both July and August 2016. Figure 2(c and f) shows the spatial correlation of INSAT-3D low-level AMVs and NCEP low-level wind data of July and August 2016, respectively. It is seen from the figure that wind speed spatial distribution and its monthly variation INSAT-3D low-level AMVs during summer monsoon months matches closely with that of NCEP analysis, indicates the usefulness of INSAT-3D low-level AMVs for this kind of studies.

3.3 Intra-seasonal variability

Many studies (Sikka and Gadgil 1980; Zeng and Wang 2009) have revealed that the IMS rainfall activity has strong intra-seasonal variability in time scale of 30–60 days in the form of active and lull days, which is linked closely with intra-seasonal variability of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ repeatedly propagates northward on intra-seasonal time scales from equatorial Indian Ocean to the monsoon trough region situated over the Indo-Gangetic areas during summer monsoon. This northward propagation is prominently active over the Bay of Bengal and adjoining longitudinal area between 70° and 100°E . The study of Joseph and Sijikumar (2004) reveals that when monsoon is active, the rainfall activity and strength of the LLJ increase and the axis of LLJ is located near 15°N , while during lull days, rainfall activity and strength of the LLJ decreases and the jet axis is found south of Sri Lanka.

AMVs are available at different heights in scattered manner in the places where valid tracers are available. To reduce the data gap to a certain extent, daily composite mean of low-level INSAT-3D AMVs are generated from the coarser 30 min data. To study the characteristics of intra-seasonal variability during the 2016 summer monsoon season, daily low-level AMVs are averaged over the central part of Bay of Bengal covering the area 80° – 95°E ; 10° – 20°N , and a time series is presented in figure 3. The central part of Bay of Bengal is chosen because intra-seasonal variability is quite prominent over the Bay of Bengal and also low-level VIS and MIR AMVs available over the oceanic region to avoid land/coast contamination. Some discontinuities in the time series is noticed because of missing data for these dates. It is seen from this figure that the INSAT-3D low-level winds fluctuated a few times during the monsoon season. The stronger ($>10\text{ ms}^{-1}$) AMVs are noticed during four occasions: (i) 08 June 2016, (ii) 30 June 2016,

(iii) 01 August 2016 and (iv) 17 August 2016 and weaker ($<6\text{ ms}^{-1}$) during four occasions: (i) 20 June 2016, (ii) 25 July 2016, (iii) 22 August 2016 and (iv) 19 September 2016.

The multi-frequency non-stationary powers present in a time series can be determined by using Wavelet Transform (Lau and Weng 1995). The complex Morlet wavelet has the capability to detect time-dependent amplitude and phase for different frequencies present in a time series. In this study, a complex Morlet wavelet transform (WT) is used to find the multi-scale frequencies embedded in the wind time series shown in figure 3. The data gaps in the time series are filled using interpolation before the wavelet transform is applied. The total number of data points in the time series is taken as 128 (i.e., 2^7 , from 26 May 2016 to 30 September 2016). The figure 4 shows the two-dimensional time-frequency representation of the wavelet transform, in which the x-axis represents the days from 26 May 2016 to 30 September 2016, while in the y-axis; the periods in days are shown. The shades in the figure represent the amplitude of INSAT-3D low-level winds and as expected, two prominent modes of variability are visible in INSAT-3D AMVs during 2016 monsoon season. One with higher wavelengths with a periodicity between 32 and 64 days. This is called as intra-seasonal (30–60 days) variability and this variability is noticed three times in 2016 with a period of around 30 days. The repeated northward propagation of LLJ is the main cause of this variability. The other with lower wavelengths with a periodicity between 8 and 16 days. The presence of 8–16 days variability in INSAT-3D low-level AMVs is associated with the movement of low pressure systems and other short-period variability present over the monsoon region. It is noticed that about 10 low pressure areas formed over the Indian monsoon region during the 2016 monsoon season, of which one formed in June, one in July, five in August and three in September (Rao *et al.* 2017).

3.4 Active and lull monsoon periods

The occurrences of active and lull periods are very important phenomena of any monsoon seasons. Active and lull period are well defined phenomena in literature (Webster *et al.* 1998; Goswami and Ajaya Mohan 2001; Joseph and Sijikumar 2004). Webster *et al.* (1998) have defined an active and break period by using a zonal wind criterion over the north Bay of Bengal and used a fixed cut-off anomaly ($+3$ or -3 ms^{-1}) to define active

Figure 3. Time series of daily area averaged (i) INSAT-3D low-level winds (ms^{-1}) over the Bay of Bengal box (10° – 20° N; 80° – 95° E) during 26 May 2016 to 30 September 2016 and (ii) NCEP zonal wind at 850 hPa in the lat.–long. box (10° – 20° N; 70° – 80° E). The active and lull phases used for further analysis are also shown in the figure. The discontinuities in the time series arise from data gaps.

Figure 4. Morlet wavelet analysis of the INSAT-3D low-level winds (ms^{-1}) averaged over the Bay of Bengal box (10° – 20° N; 80° – 95° E) during the monsoon season of 2016.

and break conditions. Goswami and Ajaya Mohan (2001) have used similar wind criteria for defining active and break monsoon spells. Joseph and

Sijikumar (2004) have defined an active period as one in which for each day of the period, the area-averaged zonal wind at 850 hPa in the

latitude–longitude box 10° – 20° N and 70° – 80° E in 5 days period centred on that day is 15 ms^{-1} or more. The identification of the active and break days is not very sensitive to small changes in the position of the reference point (Webster *et al.* 1998). In the present study, active and break period is calculated using INSAT-3D AMVs. The days for which the wind speed averaged over the box (80° – 95° E and 10° – 20° N) are greater than 10 ms^{-1} for at least 3 consecutive days as considered as active days, while those less than 6 ms^{-1} for at least 3 consecutive days (over the box “ 80° – 95° E and 10° – 20° N”) are considered as break days. It is seen from the figure 3 that during 2016, the active period was during 8–12 July 2016, while lull period was from 24–29 July 2016. To study the characteristics of INSAT-3D AMVs during active and lull monsoon periods, AMVs and NCEP analysis are averaged during the 8–12 July for active period and 24–29

July for lull period. The spatial plots INSAT-3D AMVs (figure 5a and b) and corresponding NCEP wind analysis (figure 5c and d) for active and lull periods are shown in figure 5. Though deep and organized convection is largely absent during monsoon lull periods, low level cumulus and stratiform clouds do present. The AMV retrieval algorithm is able to track the movement of low-level potential cloud tracers for the retrieval of valid AMVs even during lull-period. Few data gaps are noticed in INSAT-3D AMVs, while comparing with similar plots of NCEP analysis. As expected, both INSAT-3D AMVs and NCEP winds show the northward propagating nature of low-level jet (LLJ) and its locations during active and lull periods. The weak LLJ is present during lull period and the 12 ms^{-1} wind is confined to a small area near Somalian region. Both INSAT-3D low-level AMVs and NCEP analysis are weak

Figure 5. Average INSAT-3D low-level wind speed (ms^{-1} , shaded) and wind vectors during (a) lull (24–29 July 2016) and (b) active (8–12 July 2016) phases during the 2016 monsoon season. Similarly from NCEP low-level wind speed (ms^{-1} , shaded) and wind vectors during (c) lull (24–29 July 2016) and (d) active (8–12 July 2016) phases during the 2016 monsoon season.

(<6 ms⁻¹) over the entire Bay of Bengal. The axis of LLJ is located south of Sri Lanka and the weak southern hemispheric cross-equatorial flow is also noticed (figure 5a and c). During the active period, the stronger LLJ is over the entire Arabian Sea, and its axis is located north of 15°N over the central Bay of Bengal (figure 5b and d). Thus, it can be summarized here that during the active time, both INSAT-3D low-level AMVs and NCEP wind analysis are stronger over the Bay of Bengal and the Arabian Sea while during lull time they are weaker in the same region, and the axis of LLJ is located north of 15°N (south of Sri Lanka). The locations of LLJ axis as illustrated by INSAT-3D low-level AMVs during the active and lull periods matches well with the locations of LLJ during the active and lull periods reported in the literature (Joseph and Sijkumar 2004).

3.5 The monsoon LLJ over the Bay of Bengal

It is well known fact that the ITCZ and LLJ repeatedly move northward on intra-seasonal time scales during the monsoon season. As discussed in the earlier section, the signatures of northward-propagating LLJs are noticed close to the surface, while its maximum strength is found at 850 hPa level height. A Hovmoller (time–latitude plot) diagram of the INSAT-3D low-level AMVs averaged between 80° and 95°E longitudes is presented to assess its northward propagation (figure 6a). Due to data gap in INSAT-3D AMVs for better understanding, a similar figure for NCEP low-level winds is shown in figure 6(b). It is seen from these figures that low-level winds near surface shows a northward propagation pattern, which is clearly visible in NCEP wind analysis, while very poorly depicted in the INSAT-3D AMVs due to large data gap. In 2016, relatively strong winds propagated northward around three times from near-equatorial latitudes to the northern Bay of Bengal. The first propagation started around 16 June 2016, the second one around 20 July 2016 and the last one around 16 August 2016.

3.6 The principal components of AMVs

In the earlier section, the intra-seasonal variability is explained by spectral analysis of area averaged time series over Bay of Bengal region. However, the method of principal components analysis often referred to as empirical orthogonal function (EOF)

Figure 6. Hovmoller (time–latitude) plot of (a) INSAT-3D low-level wind speed (ms⁻¹) and (b) NCEP low-level wind speed (ms⁻¹) averaged between 80° and 95°E longitude during the summer monsoon season of 2016. Wind speed contours above 6 ms⁻¹ are shown.

analysis, can be utilized effectively to link the spatial and temporal patterns of a data field (David 1983). Hence, spatial structure of intra-seasonal variability and associated variability in time can be extracted by using EOF analysis of wind speed over a larger domain. The EOFs analysis of the INSAT-3D AMVs and NCEP low-level winds are calculated over the Indian Ocean region (30°N–30°S, 40°–100°E). Their time series are also been normalized. In the present study, first four dominant EOFs of the daily low-level wind time series are performed for the intra-seasonal variability of ISM 2016 that arises from its inherent oscillations of systems through this region. The first EOF of AMVs (figure 7a) explains only 17% of the total variance, while the second, third and fourth EOFs (figure 7b–d) jointly put together explain 29%

(14, 9 and 6%, respectively) of the total variance of the low-level wind. Thus, the first four EOFs explain 46% of the total variance of the low-level wind. Similarly, the EOF of NCEP low-level winds is calculated. The first EOF of NCEP wind (figure 7e) explains only 20% of the total variance, while the second, third and fourth EOFs (figure 7f–h) jointly put together explain 29% (15, 8 and 6%, respectively) of the total variance of the NCEP wind. Thus, the first four EOFs explain 49% of the total variance of the NCEP wind. Though the percentage explanation of EOFs of both INSAT-3D AMV and NCEP winds are not very different, their patterns are

similar in nature. The corresponding time series of first four principal components of INSAT-3D low-level wind and NCEP wind are also calculated. In figure 8, PC1 (a), PC2 (b), PC3 (c) and PC4 (d) are shown for INSAT-3D AMVs and NCEP wind. The amplitude of the PC1 (figure 8a) gradually increases and peaks during the month of July and later decreases during August and September which depicts the actual behavior of observed rainfall. The EOF2 maps (figure 7b and f) for INSAT-3D AMVs and NCEP winds are not matching, as INSAT-3D AMVs (figure 7b) shows negative correlation over Arabian Sea, while the opposite features are observed in the NCEP (figure 7f).

Figure 7. Spatial pattern of the first four EOF modes of INSAT-3D AMV and NCEP low-level winds for ISM 2016.

Figure 7. (Continued.)

This is clearly visible in the time-series of principal components (figure 8b) possesses an oscillation of high amplitude. The third EOFs of INSAT-3D AMVs and NCEP winds present some interesting results even though they explain much lower proportion of the variance. EOF3 (figure 7c and g) divide ISM region just into two parts, with negative correlations over Arabian Sea and positive correlations in the southern Indian Ocean. This clearly shows an east–west intra-seasonal variation of the summer time circulation. The amplitude of PC3 (figure 8b) for INSAT-3D and NCEP winds also matches very closely throughout the Indian summer monsoon season. The maps of

EOF4 (figure 7d and h) show the contribution of weather-scale disturbances to intra-seasonal variability. The time series of EOF4 (figure 8d) is apparently composed of rapid oscillations as compared to the time series of other EOFs. The RMSE analysis between EOFs of AMVs and NCEP data are carried out to quantify the performance of AMV in capturing spatial and temporal pattern of intra-seasonal variability. The RMSE of EOF1, EOF2, EOF3 and EOF4 between NCEP and INSAT-3D AMVs are 0.0004, 0.0039, 0.0010 and 0.0009, respectively. The corresponding RMSE for PC1, PC2, PC3 and PC4 are 3.07, 35.05, 5.99 and 5.88, respectively.

Figure 8. Time series of principal component of the first four modes of INSAT-3D and NCEP low-level wind for ISM 2016.

4. Conclusions

In this study, first time the capabilities of INSAT-3D low-level AMVs are explored to study the ISM intra-seasonal variability as captured by it during the year 2016. INSAT-3D low-level AMVs are quite successful in capturing all the observed features of the ISM. When a complex Morlet wavelet transform is used to wind time-series, it shows two prominent modes of variability one with 32–64 days periodicity and the other with 8–16 days periodicity in 2016 in INSAT-3D low-level AMVs.

The rainfall activities over the Indian monsoon region are significantly due to these two variability of different periodicity. The locations of the LLJ axis present in INSAT-3D AMVs and NCEP wind analysis during the active and lull periods of 2016 matched well with the average LLJ locations during the active and lull periods. This study has illustrated the capabilities of INSAT-3D low-level AMVs for any further studies related Indian monsoon circulation. The spatial structure of intra-seasonal variability and associated variability in time are also explained by performing EOF

analysis of INSAT-3D AMVs over a larger south Asian monsoon domain. With the launch of INSAT-3DR and SCATSAT-1 in September 2016 and subsequent operationalization of data from these two new satellites along with existing INSAT-3D AMVs have enhanced the scope for better analysis for future monsoon seasons.

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