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AMV RESEARCH ACTIVITIES AT ECMWF

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Abstract

Recently, there have been changes to three out of the five geostationary satellites operationally used at ECMWF with Meteosat-8, -11, GOES-15, -16 and Himawari-8 providing the current coverage. The Indian Ocean, where Meteosat-8 replaced Meteosat-7 as the provider of Atmospheric Motion Vectors (AMVs), has been a particular area of focus at ECMWF. The introduction of Meteosat-8 on 2nd March 2017 brought improvements as a newer generation of satellite such as reduction in the large negative speed biases present in Meteosat-7 in the high level extra-tropics.

A subsequent investigation explored the benefit of assimilating other satellites with good Indian Ocean coverage. Indian National Satellite - 3D (INSAT-3D), Feng-Yun-2E (FY-2E) and Meteosat-8 - operated by different centres - have been inter-compared. Differences in imaging instruments and derivation methods led to relatively large variation in the values and spatial patterns of the first guess departures. However, the impacts of each dataset on the forecast assessed through assimilation experiments were similar and much of the benefit from Meteosat-8 AMVs could be recovered from the other satellites. To better understand the contribution of each satellite to operational NWP, the value of the All Sky Radiance (ASR) product was also considered. Significant additional positive impacts were found in the fit of independent humidity sensitive observations to the model background.

During experiments conducted for the switch from Meteosat-7 to Meteosat-8 an area of apparent degradation at 850hPa was identified in the tropical Indian Ocean. Wind speed profiles of the low level winds revealed little variation in height compared to the model. However, the region was also identified as being partially affected by a model bias. Sparse conventional observations coupled with evidence that it is also a challenging area for the model have made it difficult to provide a confident explanation about what is responsible for this feature.

Note that much of the content presented here has also been submitted by the same authors as part of proceedings papers for the 2017 EUMETSAT Meteorological Satellite Conference (Rome, Italy, 2nd - 6th October 2017).

GEOSTATIONARY CHANGES

At ECMWF, five geostationary satellites traditionally provide coverage of AMVs and Clear sky/All Sky Radiances (CSR/ASRs) for the tropics and extra-tropics. Recently, there has been an active period in replacement of geostationary satellites:

- Meteosat-8 replaced Meteosat-7 (2nd March 2017, Indian Ocean Data Coverage (IODC))
- Meteosat-11 replaced Meteosat-10 (20th February 2018, 0° service)
- GOES-16 (activated 22nd May 2018, GOES-East location) replaced GOES-13 (removed 2nd January 2018)

In these proceedings, we will focus on the IODC AMVs, first considering the move from Meteosat-7 to Meteosat-8 then comparison to other IODC satellites and finishing with a discussion of a challenging area over the Indian Ocean. Regarding the other satellite changes, further details on the move from GOES-13 to GOES-16 can be found in Lean and Bormann (2018). In the case of Meteosat-11 replacing Meteosat-10 (same generation satellites), first guess departures (differences between observations and model background provided by T+12 forecast from the previous model cycle) were used to analyse the data quality. Patterns in the statistics were extremely similar between the two satellites as expected. There was a small shift in speed bias (~0.2m/s) with Meteosat-11 showing a more positive (less negative) bias. This was attributed to a small offset in assigned height where the Meteosat-11 AMVs are assigned to slightly higher pressures (~5hPa). Analysis of the ASR products from Meteosat-10 and -11 (Burrows, 2018) revealed a bias in the water vapour and infrared channel radiances of ~0.2-0.4K between the two satellites. This bias, uncorrected in the height assignment calculation, may have caused the discrepancy. However, as the change is small, assimilation experiments to assess any impact were not seen as necessary and Meteosat-11 was activated with the same configuration as Meteosat-10.

METEOSAT-8 REPLACES METEOSAT-7

Introduction

The change from Meteosat-7 to Meteosat-8 has meant a progression from using a first to second generation Meteosat satellite. Some of the instrument features relevant for AMVs have been summarised in table 1. The increase in the number of channels and better spatial/temporal resolution results in a large rise in the number of AMVs available, for example the total daily number of AMVs from the infrared channel is around ten times higher. Improved data quality from Meteosat-7 and a strong agreement with Meteosat-10 was also expected. First guess departure statistics have been used to assess the data quality of the new Indian Ocean Data Coverage (IODC) provider while assimilation experiments have been used to test the longer term impact on the forecast system.

	Meteosat-7	Meteosat-8	FY-2E	INSAT-3D
Position	57.5°E	41.5°E	86.5°E	82.0°E
Imaging instrument	MVIRI	SEVIRI	S-VISSR	IMAGER
Channel wavelengths for AMVs (µm)	IR (11.5) Vis (0.70) WV (6.4)	IR (10.8) Vis (0.64) WV1 (6.25) WV2 (7.35)	IR (10.8) WV (6.8)	IR (10.8) SWIR (3.9) Vis (0.65) WV (6.9)
Time frequency of AMVs	1.5 hourly	1 hourly	6 hourly	30 minutes
Pixel resolution	2.5km (Vis), 5km (IR and WV)	3km	5km	1km (Vis), 4km (SWIR/IR), 8km (WV)

Table 1: **Instrument details for Meteosat-7, Meteosat-8, FY-2E and INSAT-3D. (IR = Infrared, SWIR = Short wavelength IR, Vis = Visible, WV = Water vapour)**

Meteosat data quality comparison

Meteosat-7, -8 and -10 are provided with forecast independent and dependent Quality Indicator (QI) values. In general, AMVs from the three satellites show a reduction of the Root Mean Square Vector Difference (RMSVD) against the forecast background with forecast independent QI, and strong similarity between the pattern in Meteosat-8 and Meteosat-10. This leads to the choice of a threshold of QI = 85 for screening poorer quality observations prior to the calculation of further statistics.

Maps and zonal plots (figure 1) of the first guess departures illustrate differences in the horizontal and vertical characteristics of the AMVs. Between Meteosat-7 and -8 there are some clear areas of improvement such as the reduction of the large negative speed bias in the high level, extra-tropics and overall lower RMSVD values. Figure 1 also shows, reassuringly, the good agreement between Meteosat-8 and -10, despite different geographical coverage. The elevated values around 10-30°N in the low/mid-levels are in an area of very few AMVs. The AMVs causing the extreme values are subsequently screened by the first guess check procedure (observations are rejected if the difference from the model background estimate is too large) prior to assimilation (e.g. as shown later in figure 3).

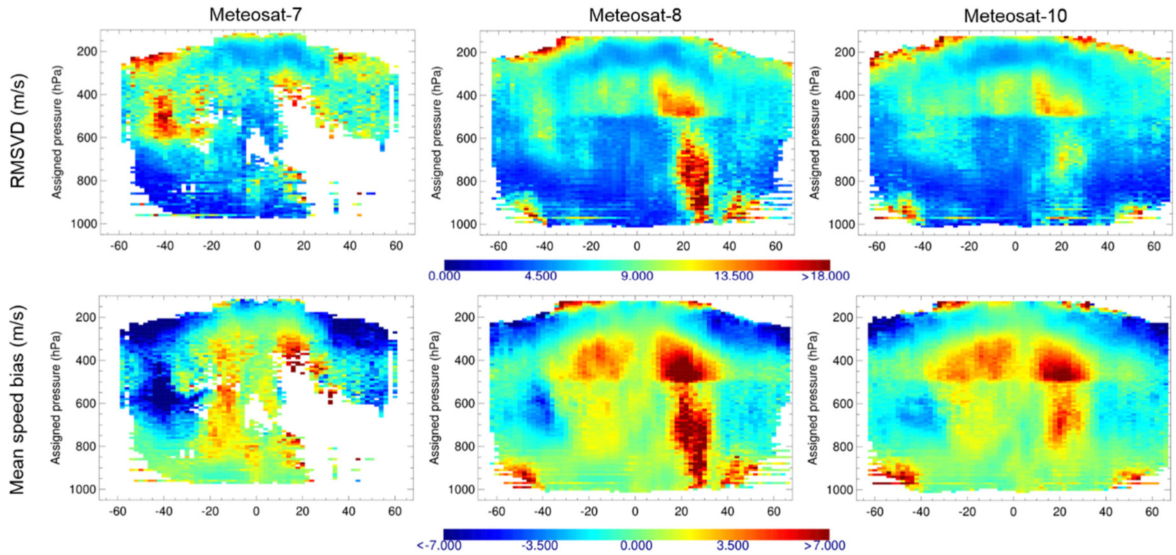


Figure 1 **Zonal dependence of RMSVD (top row) and speed bias (bottom row) for the infrared channel on Meteosat-7 (left column), Meteosat-8 (middle column) and Meteosat-10 (right column) using data from 21st Oct - 24th Nov 2016. AMVs have been screened using forecast independent QI > 85 and boxes (2° latitude x 10hPa) containing fewer than 20 AMVs have been removed.**

Focusing on the overlap regions of the satellites, maps of the differences in the statistics (without matching individual observations) also supported agreement between Meteosat-8 and Meteosat-10 and general improvement from Meteosat-7 (not shown). Compared to Meteosat-7 there is wide spread reduction in RMSVD (much in excess of 20% for the high level infrared winds after QI screening) and speed bias.

Assimilation experiments

As the differences in Indian Ocean data number and departure characteristics are significant, assimilation experiments were required to test the longer term forecast impact of switching to Meteosat-8. Experiments were run with a reduced resolution version ($T_{Co}399$) of cycle 43R1 of the operational system. Due to the similarity between satellites, the existing channel specific blacklisting choices and observation errors for Meteosat-10 were chosen as the initial configuration to apply to Meteosat-8. Results from early testing indicated degradation at very high levels which were mitigated by additionally screening out AMVs with assigned pressures < 150hPa. In the control for the experiment, IODC AMVs have been removed (i.e. no Meteosat-7). A further experiment which reintroduces Meteosat-7 was run in order to allow comparison of the impacts of the two satellites.

Changes assessed over large areas are generally neutral. However, there are localised impacts seen in the verification against own analysis such as a region just south of India where there is a reduction in vector wind error at 200hPa (figure 2) which is persisting out to forecast lead times of 72 hours. While the feature is present for both Meteosat-7 and -8, it is more prominent and longer lasting for Meteosat-8. Another important measure of the impact of the data is the change in fit of independent observations to the model background. Reduction in the standard deviation of the first guess fit indicates closer agreement with other observation types through improvements to the model background fields. Focusing again on an area mostly covering only the Indian Ocean (60°N-60S, 30-120°E) there are indications of positive impact on the conventional wind observations at higher levels, in particular for Meteosat-8 (shown later in figure 4 as part of the wider IODC investigation), and for humidity sensitive channels from Advanced Technology Microwave Sounder (ATMS) (not shown).

Verification against own analysis at lower pressures and independent observation fits support the inclusion of Meteosat-8. However, at low levels there is a localised feature showing apparent degradation at 850hPa in the vector wind field verified against own analysis. This topic will be revisited later. On 2nd March the AMV (and Clear Sky Radiance (CSR)) product was successfully switched to Meteosat-8 in the operational system (additionally moving to ASRs).

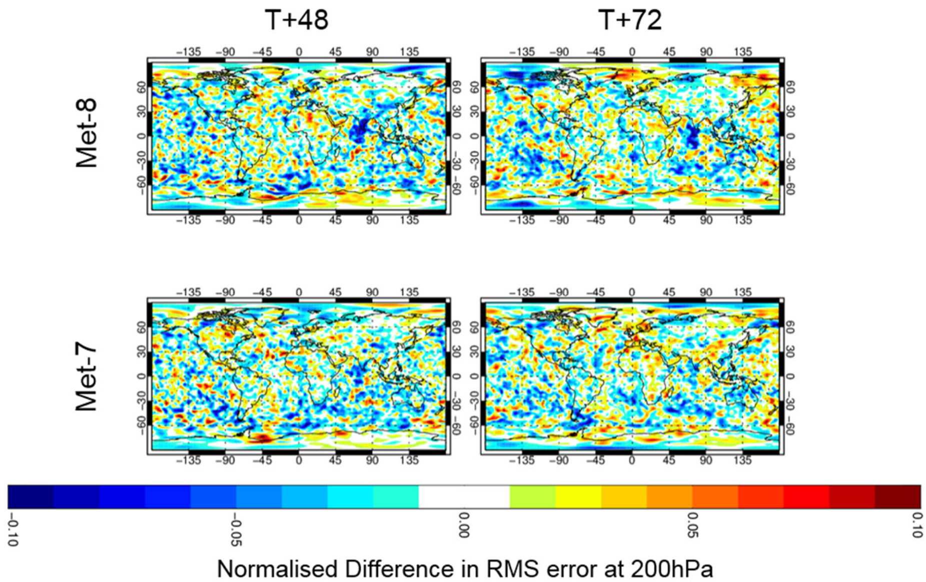


Figure 2 **Maps showing the change in vector wind error at 200hPa verified against own analysis for Meteosat-8 (top row) and Meteosat-7 (bottom row) at forecast lead time of 48 (left column) and 72 (right column) hours. Experiment period is 21st Oct 2016 - 7th Mar 2017.**

FURTHER IODC OPTIONS

Introduction

Results presented in the previous section demonstrated that the IODC service provides benefit to the NWP system. The second part of this document aims to evaluate potential options for the IODC beyond Meteosat-8. At the time of investigation, in addition to Meteosat-8, INSAT-3D (operated by the Indian Meteorology Department (IMD)) and the Chinese satellite, FY-2E (operated by the China Meteorological Administration (CMA)) provide the best alternative coverage. While the primary focus of this study is the AMVs, when assessing the relative benefits of the different IODC satellites for completeness we must also consider the impact from the CSR/ASR products and an effort will be made here to show the value of both AMVs and radiances. First guess departures are used as before to assess the data quality while assimilation experiments explore the longer term forecast impacts.

Each AMV production centre has a different technique for deriving the AMVs (MSG Meteorological Products Extraction Facility Algorithm Specification Document (2015); Xu et al. (2002); Zhang et al. (2016); Deb (2012); Deb et al. (2016)), and there are also differences in the imaging instruments leading to a range in available channels, spatial and temporal resolution (table 1). One key difference in the algorithms is that INSAT-3D AMVs have more dependence on forecast information through use of an auto-editor where many heights are recalculated based on minimising a cost function that combines the observations with first guess forecast values within 50hPa limits. As a consequence, the AMV heights favour a set of regularly spaced pressure levels throughout the troposphere.

Data quality

Zonal plots and maps reveal variation in spatial density and data quality as a result of the instrument and derivation differences highlighted above. High level AMVs for both Meteosat-8 and FY-2E show negative speed biases in the extra-tropics (figure 3 shows the infrared channel AMVs as an example), although smaller in magnitude for Meteosat-8. However, for INSAT-3D the bias is generally positive in the same region. As illustrated in the example in figure 3, regardless of the differences in speed bias pattern, INSAT-3D generally shows similar or in many cases better agreement with the first guess. However, this is likely at the expense of the independence from NWP. Figure 3 also demonstrates the large differences in the number of AMVs and their distribution, highlighting the unusual striping effect due to the derivation method in INSAT-3D.

Assimilation experiments for IODC satellites

Taking into consideration the first guess departure analysis, a set of satellite specific blacklisting choices were constructed for use prior to assimilation. These include some similarities across the satellites, such as more conservative screening in the tropics, and also differences e.g. QI thresholds tailored to the data quality variation. Satellite specific statistics for the calculation of the situation dependent observation errors (Salonen and Bormann, 2013) were also generated. Estimated errors in the height assignment were similar between all three satellites at high levels while at mid/lower levels INSAT-3D generally shows better agreement with the model.

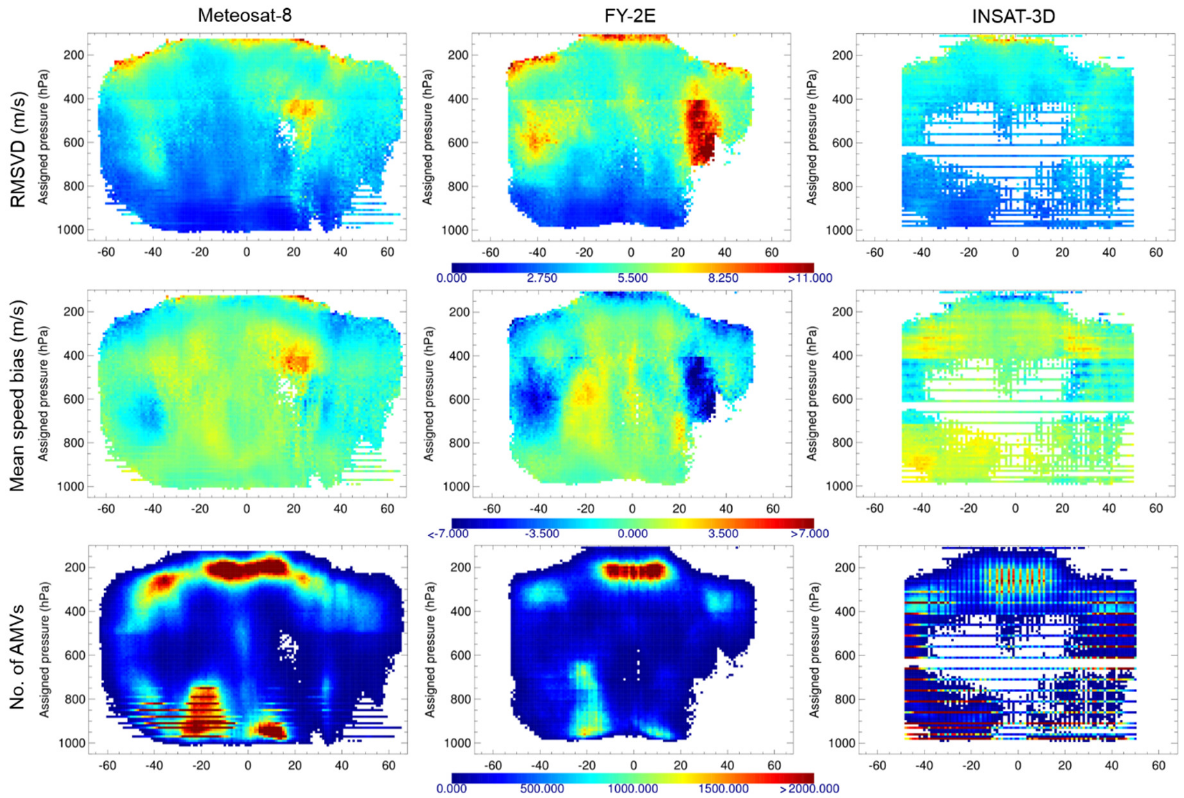


Figure 3 **Zonal plots of RMSVD (top row), speed bias (middle row) and number of AMVs (bottom row) for Meteosat-8 (left), FY-2E (middle) and INSAT-3D (right) for the infrared channel from 1st Dec 2016 - 15th Jan 2017. For FY-2E and Meteosat-8 only AMVs with forecast independent QI > 80 are shown, all data are shown for INSAT-3D, a first guess check has been applied in all cases and only boxes with more than 20 AMVs are displayed.**

For the assimilation experiments, a reduced resolution version ($T_{Co}399$) of cycle 43R1 of the operational system was used. The control contained no AMV or CSR/ASR products from an IODC satellite and then AMVs from each satellite are added in isolation with a further experiment to test the additional benefit from the Meteosat-8 ASRs.

AMV impacts

While the total number of AMVs available in the originally received files is highest for Meteosat-8, below 250hPa INSAT-3D generally has a higher number of observations actively assimilated (up to twice as many as Metesoat-8 at 400hPa). This is due to a combination of more relaxed blacklisting but also better agreement with the model background means that a lower percentage of winds are removed during the first guess check quality control step. FY-2E generally adds the fewest new observations with less than 5% change to the global total compared to 10-20% for the other satellites.

Despite the differences in data numbers and first guess departures discussed earlier, the impacts of the three satellites were surprisingly similar. When verifying with the fit of independent observations, changes over larger areas are mostly neutral for FY-2E and INSAT-3D as was also seen in the

Meteosat-7/8 comparison. Focusing only on the region covered by the IODC satellites as before, small positive impacts are found in the conventional wind observations as illustrated in figure 4. Here in the V component of the PILOT winds in particular, all three satellites show a significant reduction in the fit to the model background. Figure 4 also demonstrates the similarity in the short range forecast impact between the satellites. In the verification against own analysis, the high levels show positive impacts, more significant for INSAT-3D and FY-2E, localised over the tropical Indian Ocean. At lower levels there are also some reductions in error, particularly for INSAT-3D to the south of the equator. The degradation feature in Meteosat-8 at 850hPa (mentioned earlier) is not apparent in the other satellites.

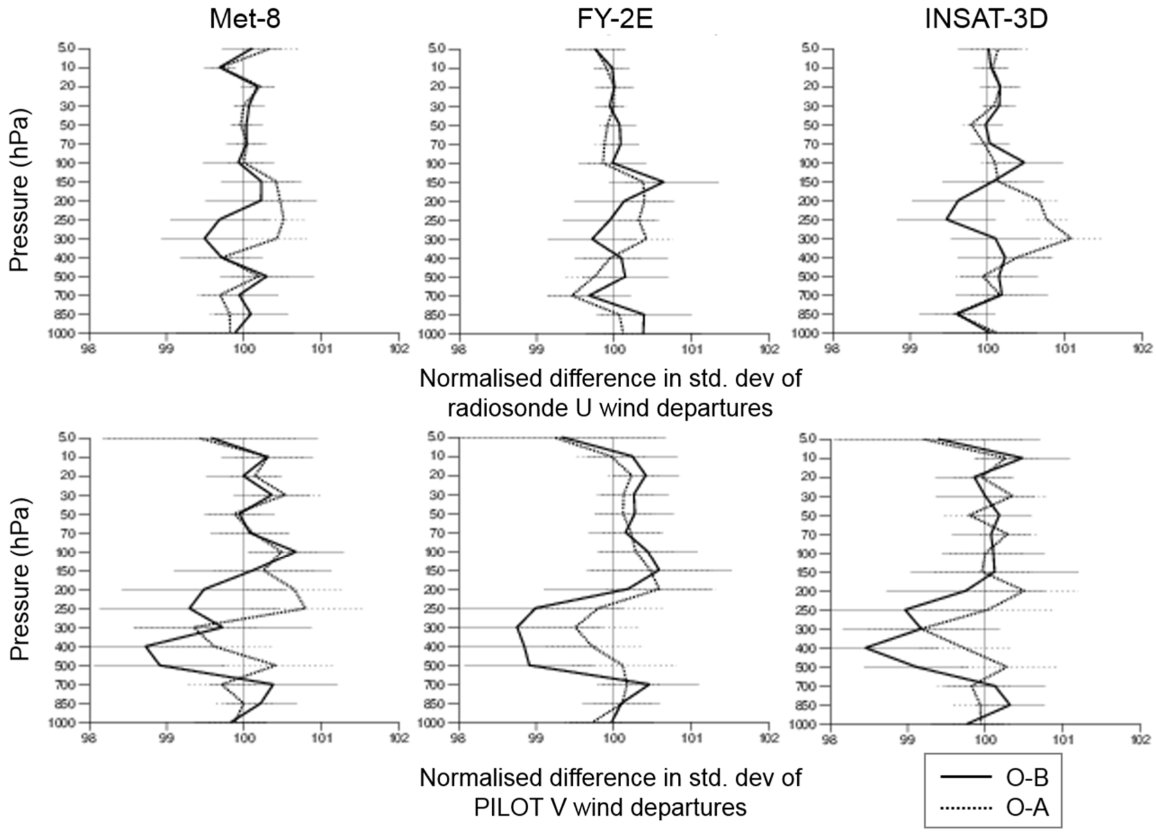


Figure 4 **Change in standard deviation of observation departure from background/analysis for the U component of radiosonde winds (top row) and V component of PILOT winds (bottom row) in the experiment assimilation Meteosat-8 (left), FY-2E (middle) and INSAT-3D (right). Data from 1st Dec 2016 - 28th Feb 2017 and restricted to Indian Ocean area.**

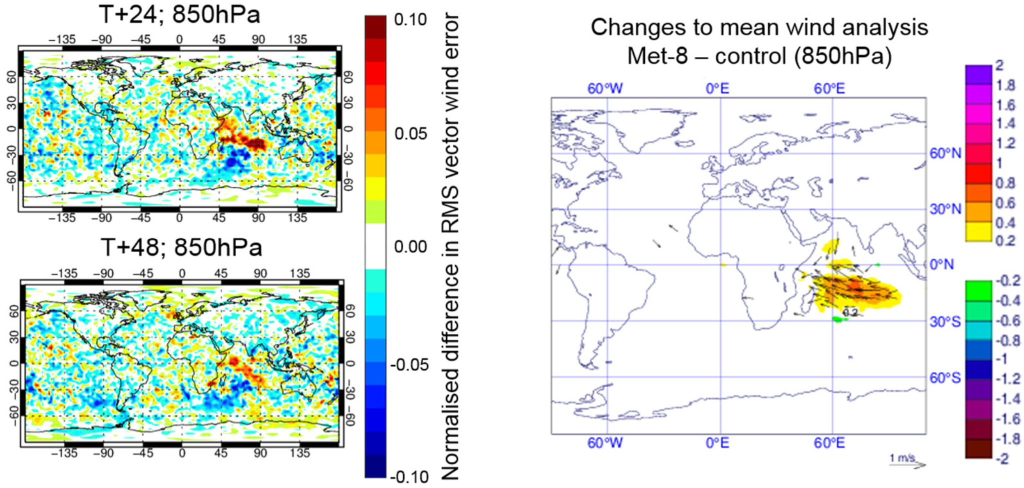
ASR impacts

Typically, the assimilation of the water vapour channel radiances has greatest impact on humidity and related fields. The AMVs from the IODC satellites showed very little influence on the humidity fields. It is very clear that in the IODC, the ASR product provides added benefit in the fit of independent humidity sensitive observations compared to AMVs alone on INSAT-3D or FY-2E (not shown). The effects are large enough that the reduction in standard deviation is clear even when verifying over a much larger area than earlier for the AMVs. Changes to the wind fields, which can be made indirectly through the 4D-Var tracing effect (Peubey and McNally, 2009), were neutral (not shown).

CHALLENGES AT 850HPA

During the testing for the switch from Meteosat-7 to Meteosat-8, an area of apparent degradation was seen in a localised region over the Indian Ocean in the Meteosat-8 experiments while the other IODC satellites showed no similar feature. The signal was stronger at first then lessens into February/March before resuming again such that over a long experiment time the feature persists (figure 6a). In the affected region of the Indian Ocean there is a general westward flow which is strengthened by the addition of the AMVs (figure 6b). This signal is seen consistently, although more weakly, in the other

IODC satellites. After the initial change applied at the analysis time, this strengthening influence of the AMVs propagates very little into the short range forecast.



(a) *(b)*

Figure 6 ***(a)*** **Change in vector wind error at 850hPa at forecast lead times 24 and 28 hours (1st Dec 2016 - 30th Jun 2017) and *(b)* Map showing the change to the mean wind analysis (21st Oct - 18th Dec 2016) between the experiment containing Meteosat-8 AMVs and control.**

Further investigations show that during October - December 2016, mean analysis increments act to strengthen the westward flow in the area also in the absence of the AMVs. This is indicative of a bias in the forecast model, leading to short-range forecasts that are too slow, and observations hence act to reduce this bias during the analysis. However, in the latter half of the experiment, such mean analysis increments are only present when AMVs are assimilated, so an AMV-specific bias is also possible.

The possibility of AMV biases was also investigated. To better understand the structure of the low level AMVs, vertical profiles of the wind speed and number density were studied using data only from a box covering the affected area (50-100°E, 5-25°S). The Meteosat-8 AMV wind profile (figure 7) shows very little variation in height while the model winds, sampled at the AMV locations, suggests more wind shear. Small spikes in the profiles of Meteosat-8 correspond to inversion levels where many more AMVs are assigned, as shown in the number density plot. FY-2E has a very similar pattern (not shown) but with comparatively very few winds in the region which may have resulted in any signal being too weak to show in the verification. INSAT-3D (not shown) agrees more with the model however this is likely due to the increased NWP dependence in the derivation process.

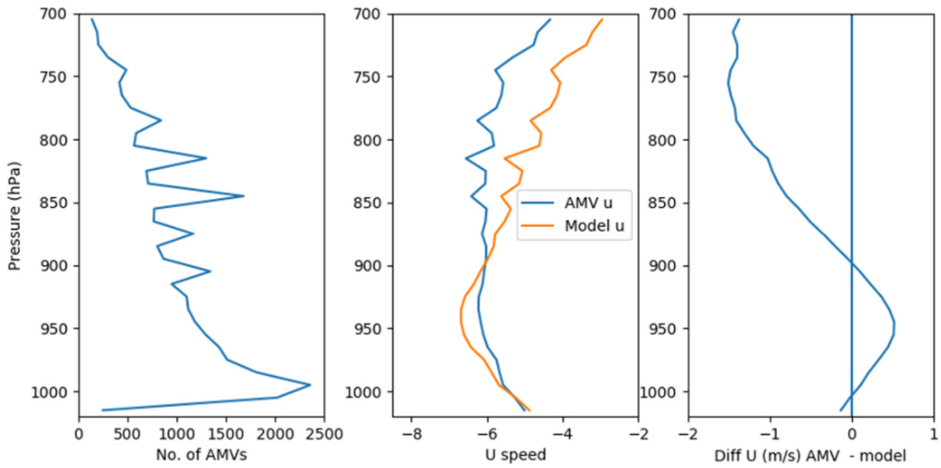


Figure 7 **Mean of the daily profiles of number of observations (left), U component of wind for AMV and model wind sampled at AMV locations (middle) and U bias (right) for Meteosat-8 within the area 50-100°E, 5-25°S, screened by QI and first guess check for 1-31st Dec 2016 and compared to a background where no IODC AMVs were assimilated.**

Unfortunately, this area is very sparsely covered by conventional wind observations. Profiles from two radiosonde sites (Cocos Island and Réunion Island) on the periphery of the affected area were considered and both supported some variation with height. This suggests that the AMVs might have a height assignment error where the faster winds are placed too high or that the height assignment cannot reliably distinguish different levels between 700 and 950hPa. However, this is also a challenging region for the model so the inclusion of AMVs may still have a positive influence in an otherwise poorly constrained area for wind.

In subsequent work (Lean et al., 2018), wind shear estimation using Multiangle Imaging SpectroRadiometer (MISR) winds supported more variation than the AMVs but showed less shear than the radiosondes. Other routes to gaining information about the AMVs could include comparing the cloud heights to Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and Aeolus (launched August 2017) will provide a valuable independent source of wind profile information.

SUMMARY

Key findings from the Indian Ocean studies are:

- There has been an improvement in switching from Meteosat-7 to Meteosat-8
- There is clear continued benefit from assimilating IODC AMVs
- INSAT-3D and FY-2E could recover some of the impact if Meteosat-8 were absent
- However, the ASR product from Meteosat-8 gives very clear additional positive impact that is not available from the other IODC satellites
- A challenging area for low level winds has been identified in the tropical Indian Ocean

ACKNOWLEGDEMENTS

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