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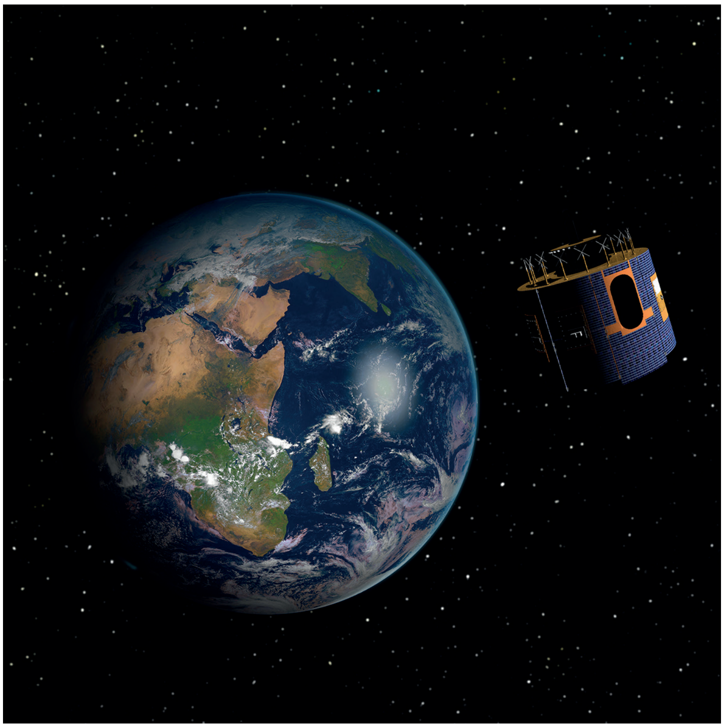
METEOROLOGY

Indian Ocean winds: changes and challenges



Montage – Meteosat-8 satellite image with a Meteosat Second Generation satellite © EUMETSAT

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Indian Ocean winds: changes and challenges

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On 2 March 2017, the geostationary satellite Meteosat-8 became the operational Indian Ocean Data Coverage (IODC) service in the ECMWF data assimilation system. With effect from that date, Atmospheric Motion Vectors (AMVs) and All Sky Radiances (ASRs) from the second-generation Meteosat-8 replaced the equivalent products from the retiring, first-generation Meteosat-7 satellite. AMVs and ASRs provide important information about wind and water vapour, respectively. Experiments have shown that assimilating the new data brings increased benefits compared to using Meteosat-7. However, they have also uncovered an area confined to the centre of the Indian Ocean at lower heights (around 850 hPa) where the benefit of the AMVs is less clear, due to a combination of model biases, suspected height assignment problems and difficulties in forecast verification.

A subsequent, more in-depth investigation of Indian Ocean AMVs considered other satellites providing good coverage. Meteosat-8 was compared with Indian National Satellite - 3D (INSAT-3D) and China's Feng-Yun - 2E (FY-2E) to consider their relative benefits or limitations. Despite different data quality characteristics, the impacts on the forecast from the different satellites were surprisingly consistent. This work also presented an opportunity to look more closely at the problematic low-level area over the ocean. The situation was revealed to be complicated with challenges for the model but also suspicious behaviour in the AMVs, in particular potentially too little variation of wind speed with height. Height assignment is a topic of great interest in the AMV community and the work presented here motivates a wider investigation and collaboration with AMV producers and other data users.

Meteosat-7 and Meteosat-8 compared

This is an active time for changes in geostationary satellites. Over the past three years, four out of the five geostationary satellites assimilated at ECMWF have been upgraded to a newer satellite. In most cases this also meant a newer generation of imaging instrument from which the AMVs are derived (see Box A for more details on the current use of AMVs). Failing to replace any of these satellites would

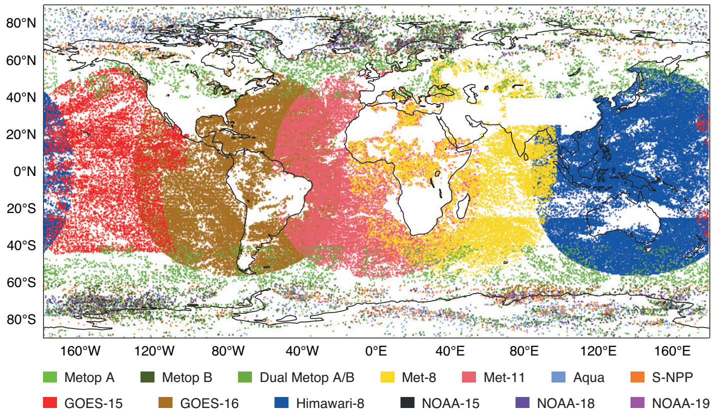
A

Current AMV use at ECMWF

AMVs are derived by tracking cloud or water vapour features in sequences of visible or infrared imagery from geostationary or polar-orbiting satellites. The observed cloud motions are assigned to a representative height, usually an estimate of the cloud top at higher levels, which is also derived from the satellite imagery. AMVs are an important source of tropospheric wind information. At ECMWF, AMVs are currently assimilated from seven polar orbiting satellites and five geostationary satellites while five further satellites are monitored. Typical coverage of assimilated AMV data for a 12-hour assimilation cycle (12 UTC on 22 May 2018) is illustrated in the figure below.

Recently, various satellite agencies have made changes to their key operational geostationary satellites, in many cases moving to a newer generation of satellite. This has led to changes (completed or in progress) to all five geostationary satellites used at ECMWF, resulting in moving from:

- MTSAT-2 to Himawari-8 (March 2016)
- Meteosat-7 to Meteosat-8 (March 2017)
- Meteosat-10 to Meteosat-11 (February 2018)
- GOES-13 to GOES-16 (May 2018)
- And in the coming months the last remaining older generation satellite, GOES-15, will be replaced by GOES-17.



Typical AMV data coverage for a 12-hour assimilation cycle (12 UTC on 22 June 2018).

mean a substantial gap in coverage. After a drift in orbit position to 41.5°E to focus on the Indian Ocean, Meteosat-8 was the natural choice to succeed Meteosat-7, which was at 58°E before retiring in March 2017. All Meteosat satellites are operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

The first step in assessing Meteosat-8 focused mainly on using the differences between observations and the model background (a short-range forecast) to diagnose the data quality. We refer to these differences as background departures. While looking to confirm an improvement from its predecessor, Meteosat-7, Meteosat-8 coverage also has significant overlap with the adjacent geostationary satellite at the 0° orbit position, Meteosat-10 at the time of testing. Meteosat-8 and Meteosat-10 are same-generation satellites, so similar results between the two are expected. It is also worth noting that in moving to a more advanced imaging instrument, the number of AMVs increases by around an order of magnitude from Meteosat-7 to Meteosat-8.

Statistics of background departures confirm an overall improvement when moving from Meteosat-7 to Meteosat-8. For instance, Figure 1 compares the speed bias for the AMVs derived using the infrared imager channel for Meteosat-7, -8 and -10. Between Meteosat-7 and -8 there are some clear areas of improvement. An example is the reduction of the large negative speed biases at high levels in the extratropics, where the AMVs are slower than the model equivalent. Improvement is generally expected when moving to a newer generation of satellite. There is also a strong similarity between Meteosat-8 and -10, with patterns and magnitudes of values very close despite the satellites' slightly different fields of view. At the same time, Meteosat-8 and Meteosat-10 show relatively strong positive speed biases at mid-levels in the tropics, an area that has been found challenging for AMVs in the past. Mid-level tropical AMVs are therefore blacklisted in the present assimilation of AMVs from Meteosat-10, and similar quality control appears advisable for Meteosat-8 as well.

After the initial data quality assessment, the new AMVs were tested in assimilation experiments to understand their impact on forecasts. The experiments used the 12-hour 4D-Var assimilation system at ECMWF with a reduced model resolution of TCo399 (55 km) and were run from 21 October 2016 to 7 March 2017. The control run used the same configuration but with no IODC AMVs actively used.

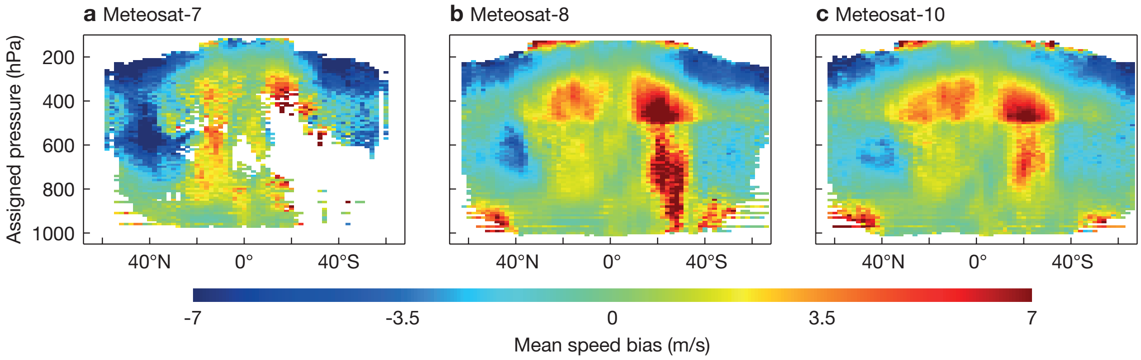


Figure 1 Distribution of speed bias by latitude and assigned pressure level for (a) Meteosat-7, (b) Meteosat-8 and (c) Meteosat-10. The Meteosat-8 statistics are improved over Meteosat-7 and reassuringly similar to Meteosat-10. Data are from the infrared channel over the period 21 October to 24 November 2016. They were passed through basic quality screening before binning (2° latitude x 10 hPa boxes). Boxes containing fewer than 20 AMVs are left blank.

The large-scale hemispheric impacts for the use of IODC AMVs are relatively small and close to neutral, but there are indications of localised forecast benefits over the Indian Ocean. For instance, comparisons between short-range forecasts and radiosonde observations in the region of the IODC coverage show better agreement at higher levels when AMVs from Meteosat-7 or Meteosat-8 are included in the data assimilation (Figure 2). The reduction in standard deviation values at 250 hPa and 300 hPa is significant (using 95% confidence intervals) for Meteosat-8. These heights coincide with a layer of high-density AMVs. Consistent with this, analysis-based forecast verification also suggests a reduction in the error in the vector wind field at high levels over the Indian Ocean (Figure 3a,b). The feature is present for both Meteosat-7 and Meteosat-8 but more prominent and persisting into longer forecast lead times for Meteosat-8 (not shown). At low levels there is a localised feature showing apparent degradation at 850 hPa in the vector wind field when the forecasts from each experiment are

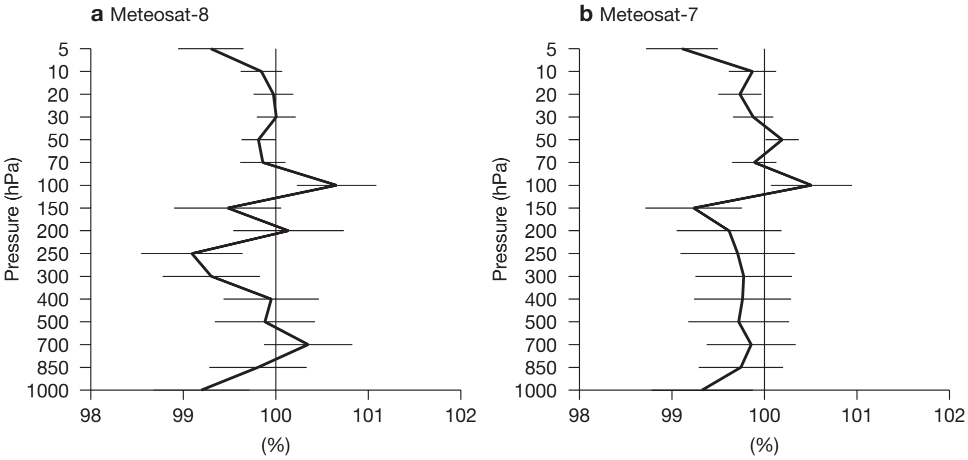


Figure 2 Normalised difference in standard deviation of radiosonde U-wind background departures between a control experiment without AMV assimilation (the 100% line) and an experiment with the assimilation of AMVs from (a) Meteosat-8 and (b) Meteosat-7. Significant reductions in standard deviation in the upper troposphere for Meteosat-8 and Meteosat-7 indicate improvements to the model background as a result of including IODC AMVs. Data are from the Indian Ocean region only for the period 1 November 2016 to 28 February 2017. Horizontal bars indicate 95% confidence intervals.

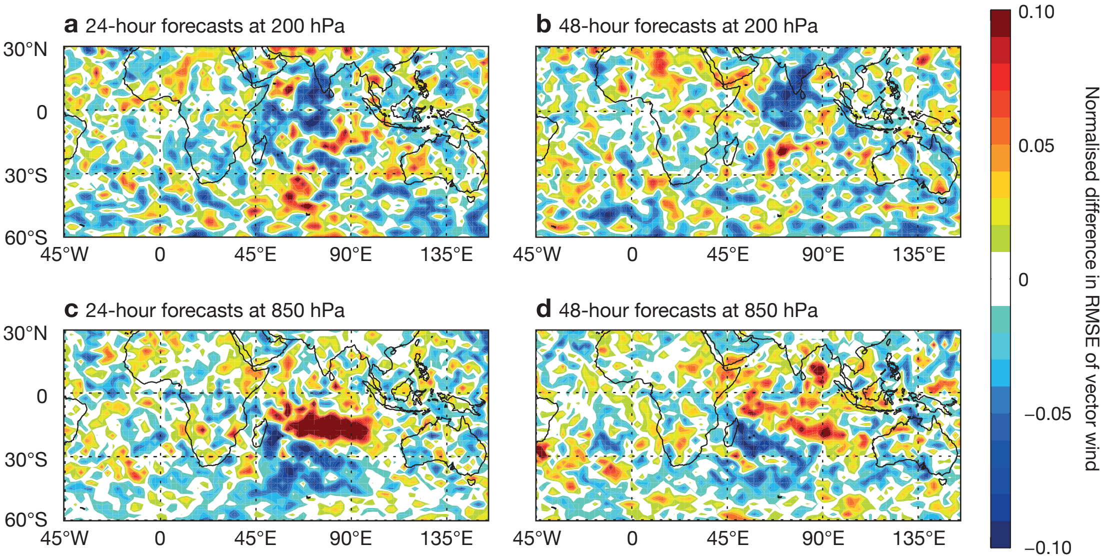


Figure 3 Normalised difference in root-mean-square error (RMSE) of the vector wind with and without Meteosat-8 AMV assimilation for vector wind forecasts (a) at 200 hPa 24 hours ahead, (b) at 200 hPa 48 hours ahead, (c) at 850 hPa 24 hours ahead and (d) at 850 hPa 48 hours ahead. Blue shading indicates a reduction in errors with AMV assimilation, red shading an increase. AMV assimilation notably reduces vector wind errors over parts of the Indian Ocean at 200 hPa but increases them in the central Indian Ocean at 850 hPa. The forecasts were verified against own analysis over the period 21 October 2016 to 7 March 2017.

verified against each experiment's own analysis (Figure 3c,d). The feature is most prominent in the early weeks of the experiment and appears to weaken in the latter half (not shown). The main influence of the AMVs here is to increase the westward flow of wind in the analysis in the same area (Figure 4). The issue is further explored below following an evaluation of the data provided by other IODC satellites.

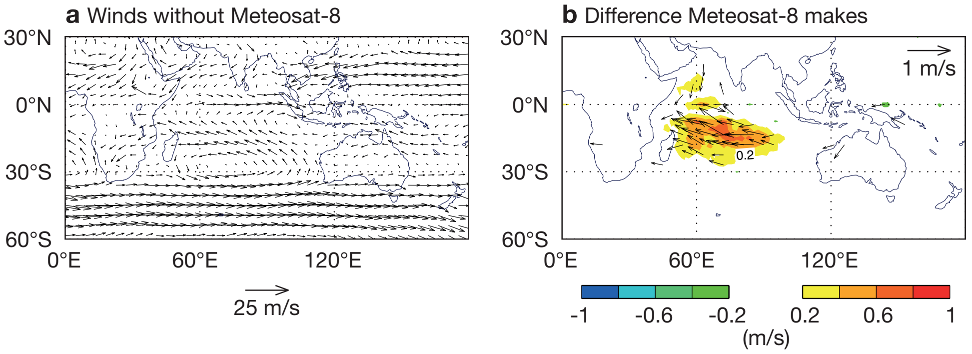


Figure 4 The charts show (a) the mean wind analysis field at 850 hPa without the assimilation of Meteosat-8 AMVs and (b) the difference in the mean wind analysis with and without Meteosat-8 AMVs. Plot (b) shows the strengthening of the westward flow when Meteosat-8 AMVs are included in the data assimilation. The experiments cover the period 21 October to 21 December 2016.

Comparison against other Indian Ocean satellites

After the successful move to Meteosat-8, the next aim was to evaluate other potential options for the IODC. At the time of the study, INSAT-3D, operated by the Indian Meteorology Department (IMD), and FY-2E, operated by the China Meteorological Administration (CMA), also had good coverage extending over the Indian Ocean. Refinements in the AMV derivation algorithms used at IMD and CMA have led to improved data quality in recent years, as seen in the Satellite Application Facility for Numerical Weather Prediction (NWP SAF) satellite data monitoring, so these two data sources may be viable providers of geostationary data coverage in this area.

Differences in the imaging instruments, in addition to each AMV production centre having a different technique for deriving the AMVs, lead to large variation in the number of AMVs. For example, for the infrared channel available on all three satellites, the number of AMVs derived on FY-2E and INSAT-3D is around half the number from Meteosat-8. In addition, the distribution of the AMVs and their data quality characteristics are also affected. For instance, Meteosat-8 and FY-2E show more similarity in the patterns of root-mean-square vector difference (RMSVD) values, whereas INSAT-3D generally shows similar or in many cases better agreement with the model background (Figure 5). However, the height assignment and quality control process used at IMD is more strongly dependent on model forecast information, so this result may reflect the extent to which the global US model (GFS) short-range forecast used in this process and ECMWF model data agree.

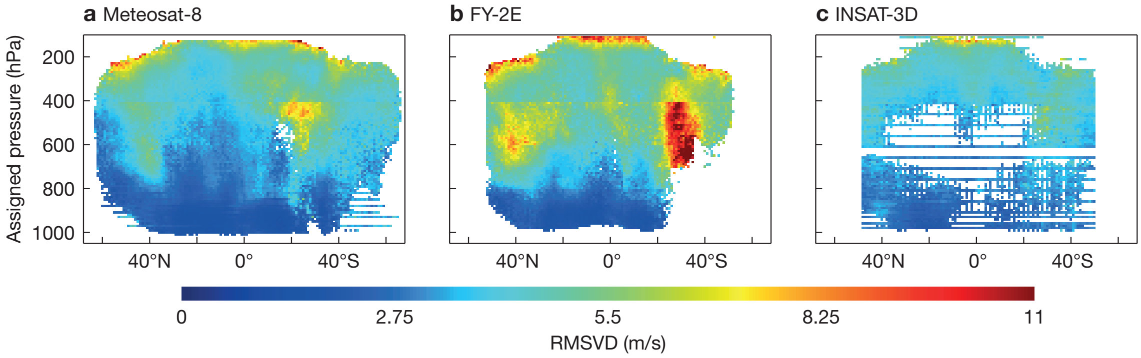


Figure 5 Distribution of the root-mean-square vector difference (RMSVD) between AMV-derived wind vectors and the model background by latitude and assigned pressure level for (a) Meteosat-8, (b) FY-2E and (c) INSAT-3D. The plots show similar patterns for Meteosat-8 and FY-2E while INSAT-3D shows better agreement with the model background. Data are from the infrared channel over the period 1 December 2016 to 15 January 2017. They were passed through basic quality screening before binning (1° latitude x 10 hPa), with boxes containing fewer than 20 AMVs left blank. Striping in INSAT-3D is due to a particular step in the height assignment that favours a set of regularly spaced pressure levels.

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To test the impact of using data from the respective satellites on the forecast, experiments were run in which each satellite was assimilated individually against a control experiment without any IODC satellite AMV assimilation for the period 1 December 2016 to 30 June 2017. Data selection criteria were broadly similar for the three satellites, although specific data characteristics motivated some modifications. For instance, more mid-level water vapour winds were excluded for INSAT-3D AMVs, as these do not distinguish between clear and cloudy scenes.

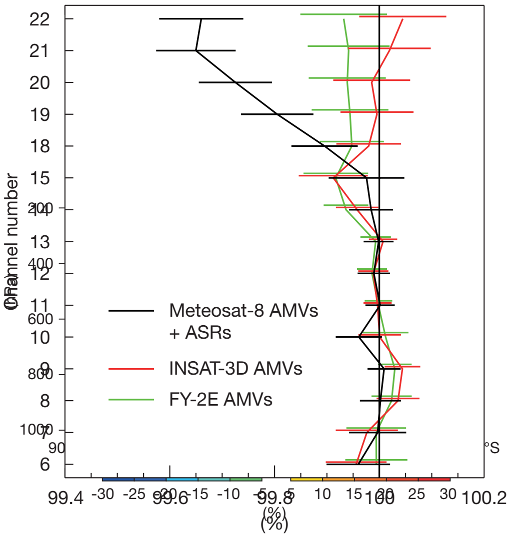
Despite the differences in AMV numbers and data characteristics, the impacts of the three satellites are surprisingly similar. For all three satellites, comparisons against conventional data suggest small improvements for short-range forecasts in the IODC area, similar to those shown for Meteosat-8 in Figure 2. In verification against own analysis, the high levels show positive impacts, more significant for INSAT-3D and FY-2E than for Meteosat-8, localised over the tropical Indian Ocean (Figure 6). 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 850 hPa is not apparent in the other satellites.

The positive results for INSAT-3D and FY-2E are encouraging. They suggest that these satellites are viable sources for operational AMV coverage over the Indian Ocean, provided data provision is reliable. For now, however, we continue to use Meteosat-8 in the operational system. This is partly motivated by the additional availability of an All-Sky Radiance (ASR) product for NWP from Meteosat-8. This provides further significant benefit, as summarised in Box B. For any potential future IODC satellite, the valuable added positive impact of the ASR product should not be overlooked.

Additional benefit from ASRs

B

The All-Sky Radiance (ASR) product uses radiances from channels particularly sensitive to water vapour at around 300–500 hPa in a combination of clear-sky and overcast conditions. Typically the assimilation of water vapour channel radiances has greatest impact on humidity and related fields. ASRs often also indirectly impact wind fields: physical parametrizations and model equations within 4D-Var are used to generate changes in the wind in order to advect observed features in humidity. These are broader-scale motions with changes limited mostly to clear sky situations and the mid-troposphere. In contrast, AMVs are capable of capturing small-scale motions, are located in cloudy regions and are generally restricted to layers in the high (200 hPa) and low (850 hPa) troposphere. For the IODC satellites, the AMVs show little influence on the humidity fields. The inclusion of ASRs from Meteosat-8 gives clear added benefit in the fit of independent humidity-sensitive observations to the model background compared to AMVs alone on INSAT-3D or FY-2E. This is illustrated in the example below showing the reduction in the standard deviation of the brightness temperature background departures for the humidity sounding channels (18–22) of the Advanced Technology Microwave Sounder (ATMS) when including Meteosat-8 ASRs. Here, the effects are large enough for the reduction in standard deviation to be significant even when verifying over much larger areas than just the region covered by the IODC satellites.



Normalised difference in global standard deviation of brightness temperature background departures between an experiment without the assimilation of AMVs or ASRs (the 100% line) and experiments in which AMVs are assimilated from INSAT-3D and FY-2E, and AMVs and ASRs are assimilated from Meteosat-8.

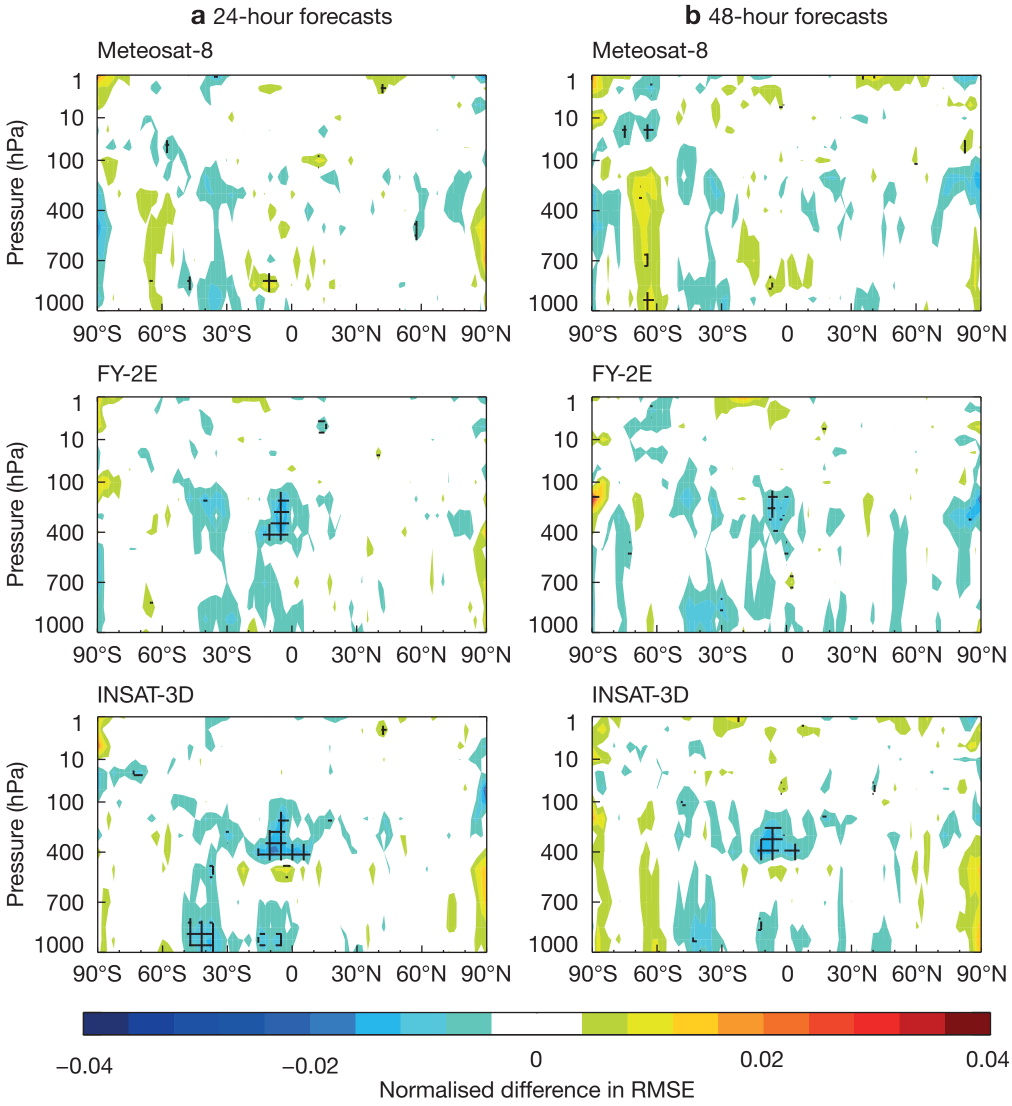


Figure 6 Distribution of differences in vector wind RMSE verified against own analysis between forecasts with and without the assimilation of AMVs, normalised by the RMSE of forecasts without AMV assimilation, for (a) 24-hour forecasts and (b) 48-hour forecasts. Cyan and blue colours in the tropics show reductions in error as a result of including IODC AMVs. Data are from the period 1 December 2016 to 30 June 2017 and hatching indicates significance at the 95% level.

In the future, it would be interesting to consider the new Chinese FY-4A satellite as an additional or alternative source of Indian Ocean coverage. It carries a more advanced imaging instrument than FY-2E and the first infrared hyperspectral sounding instrument on a geostationary satellite. The availability of hyperspectral instruments represents an exciting development in the direct assimilation of radiances from geostationary orbit.

Challenges for low-level winds

As noted earlier, there is an area of apparent short-range forecast degradation at lower levels over the Indian Ocean when Meteosat-8 AMVs are assimilated. The area is associated with a westward wind which is made faster in the analysis by the addition of the Meteosat-8 AMVs. The experiments with INSAT-3D and FY-2E reveal that all three satellites have the same effect of increasing the zonal (east–west) wind in the tropics. This may indicate the presence of a model bias. However, for Meteosat-8 the change is larger (around 0.5 m/s compared to 0.2 m/s for INSAT-3D).

To investigate this aspect further, the mean forecast error (difference between forecast and analysis) in the wind field for different lead times was evaluated (not shown). This revealed an area coinciding with the degradation feature in which the mean forecast error of the U component increases with forecast

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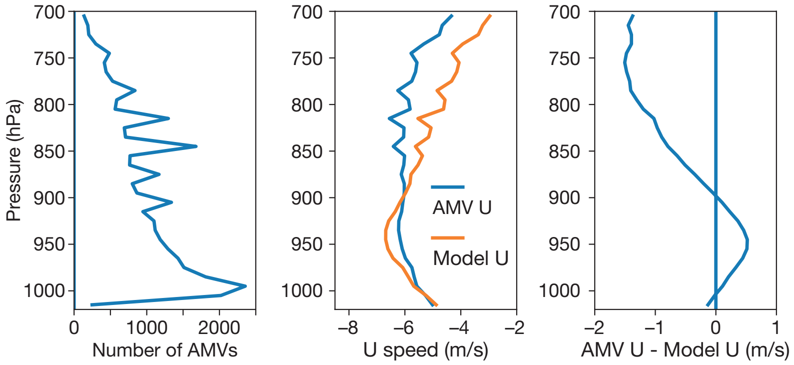
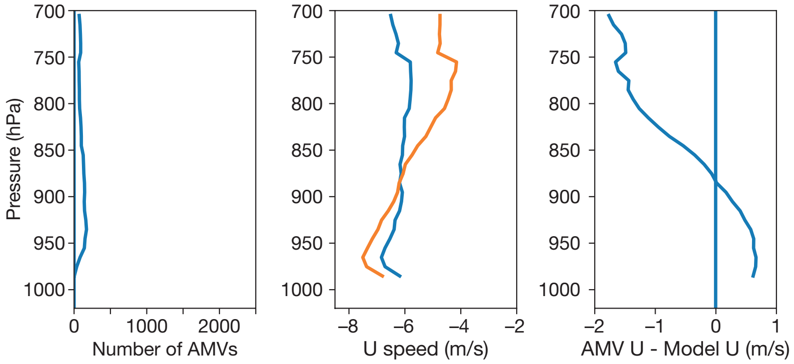
lead time, indicating that the forecast winds become progressively slower compared to the analysis. This slow bias in the forecast approximately doubles over the ten-day period, suggesting a model bias in the area in question. When verifying against own analyses, the assimilation of the Meteosat-8 AMVs therefore results in a larger forecast error, as the slow model bias is in disagreement with the faster analysis. The evidence here points to model bias being at least partly responsible for the signal. However, while this feature is strong in the early part of the experiment period, from February/March the signs of model bias are no longer present. Nevertheless, the degradation feature persists and the Meteosat-8 AMVs continue to effect a relatively large change to the mean wind analysis (not shown).

The next step was therefore to try to determine whether the increase in the analysis wind speed is correct by investigating the possibility of AMV biases. To better understand the structure of the low-level AMVs, vertical profiles of the wind speed and number density were studied using data taken only from a box covering the affected area (50–100°E, 5–25°S). Figure 7 shows that the shape of the profile of the U component is very similar between Meteosat-8 and FY-2E. In both cases there is very little variation in height while the model background wind, sampled at the AMV locations of the respective satellites, suggests more wind shear. Although there is good agreement with Meteosat-8, FY-2E has relatively few winds in the region, which may result in any signal being too weak to show in the verification. INSAT-3D agrees more with the model winds, but this may be due to the higher dependence on forecast model data in the derivation process.

a Meteosat-8



b FY-2E



c INSAT-3D

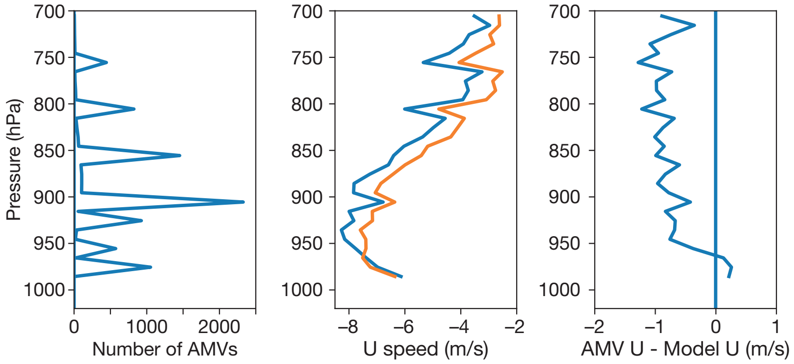


Figure 7 Mean of the daily vertical profiles of the number of observations, the U component of wind for AMV and model background wind sampled at the AMV locations, and the difference between AMV and model wind for (a) Meteosat-8, (b) FY-2E and (c) INSAT-3D. Here the model background is generated without assimilating any IODC AMVs. Data are from both infrared and visible channels over the period 1 to 31 December 2016 within the box 50–100°E and 5–25°S. Basic quality screening has been applied. Spikes in the profiles of Meteosat-8 correspond to inversion levels, where many more AMVs are assigned.

Unfortunately, this area of the ocean is very sparsely covered by conventional wind observations, which would allow an independent assessment. Nevertheless, profiles from two radiosonde sites (Cocos Island and Réunion Island) on the periphery of the affected area both support similar variation with height as exhibited by the model. This suggests that the AMVs might have a height assignment error where the faster winds are being placed too high, or that the height assignment cannot reliably distinguish different levels between 700 and 950 hPa. While the discussion here on the low-level winds has focused on the Indian Ocean, profiles of winds from Meteosat-10 in the tropical Atlantic Ocean show similar characteristics, indicating that it is potentially a wider problem.

Our analysis therefore suggests that the apparent degradation in the short-range forecasts of low-level wind over the Indian Ocean is the result of a combination of model bias for at least some parts of the experiments and deficiencies in the height assignment of the low-level AMVs in the area. The feature of apparent degradation is confined to short-range forecasts, which are difficult to verify in this area, and it does not appear to negatively affect medium-range forecasts. We therefore consider that it is still beneficial to continue the assimilation of these low-level AMVs in an otherwise poorly constrained area for wind.

Future work on low-level height assignment

Subsequent to the investigation presented here, the issue with the low-level height assignment has been added to the features requiring study in the latest AMV monitoring report compiled for the NWP SAF (*Warrick & Cotton*, 2018). There has so far been interest from EUMETSAT, the UK Met Office and the German national meteorological service (DWD) to work together with ECMWF to understand the issue.

In the near-absence of conventional observations, other routes to gaining information about the AMVs could include comparing the height assignment of the winds, which typically uses the cloud top height, with cloud heights from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). The Multiangle Imaging SpectroRadiometer (MISR), which uses a stereoscopic method to derive winds, may also give some insight into the heights and provide further information about the typical wind shear. In the future, the Aeolus satellite, capable of high-resolution vertical profiles of the wind, will allow an independent assessment. Looking into relationships between the AMV and model cloud parameters could also reveal more about any systematic differences.

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Further reading

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

Warrick, **F.** & **J. Cotton**, 2018: NWP SAF AMV monitoring: the 8th Analysis Report (AR8). Available online at: *https://www.nwpsaf.eu/site/monitoring/winds-quality-evaluation/amv/amv-analysis-reports/*

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