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Atmospheric Motion Vector observations in the ECMWF system: Fourth year report

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1 Executive summary

Atmospheric Motion Vector (AMV) observations are assimilated operationally in the ECMWF 4D-Var system from five geostationary (Meteosat-7, Meteosat-10, GOES-13, GOES-15, MTSAT-2) and four polar orbiting (Aqua, NOAA-15, NOAA-18, NOAA-19) satellites. In addition, AMVs from five other satellites (FY-2D, FY-2E, Terra, METOP-A, METOP-B) are passively monitored in the operational system. INSAT-3D and dual Metop AMVs are currently monitored offline. Table 1 summarises the monitored and used AMVs in the ECMWF system in December 2014. NOAA-16 was decommissioned on 10th June 2014. Thus, compared to the operational AMV usage during 2013, one satellite has been lost. The main change in the operational use of AMVs was the introduction of the updated GOES AMV product into operations on 6th May 2014. Investigations on the data quality and results from impact studies are reported in Salonen and Bormann (2013a). The improvements in the updated wind product, especially over low level inversion regions, have been noted in the routine diagnostics of the operational ECMWF system.

EUMETSAT has introduced several changes to the processing of AVHRR AMVs from Metop-A and Metop-B satellites during recent years. The long term monitoring statistics indicate improvements in the data quality. EUMETSAT has also made available a new dual Metop-A/B AMV product. It is the first AMV product with global coverage. At high latitudes the dual-Metop AMVs have similar characteristics to the single Metop AMVs. In the tropics dual-Metop AMVs are suffering from high positive bias. Section 2 presents the latest investigations with the Metop-A and Metop-B AMVs.

Section 3 considers AMVs over the Indian Ocean. Currently Meteosat-7 is the prime satellite giving coverage over that area but it is approaching the end of its lifetime. EUMETSAT is planning to replace it with Meteosat-8 in the future. Other satellites giving coverage over the region are the CMA operated FY-2D and FY-2E, and IMD operated Kalpana-1 and INSAT-3D. The INSAT-3D AMVs have recently become available via GTS. The first monitoring results are generally in line with what is seen for other GEO satellites, suggesting promising data quality for INSAT-3D AMVs. However, some technical issues need still to be resolved. The quality of FY-2E AMVs has improved during recent years according to the long-term monitoring statistics, and it also shows promising data quality. An impact study with Meteosat-7 and FY-2E AMVs has been performed. The results indicate neutral to positive impact for both satellites.

The situation dependent observation errors are used in the ECMWF operational system from cycle 40r1 onwards. In the context of reanalysis activities the estimates for height and tracking errors are not always available. Section 4 presents results from experiments where the impact of using default values of 80 hPa for the height error and 2.5 ms^{-1} for the tracking error has been investigated. The results indicate mainly neutral impact compared to using the more tailored height and tracking error estimates. It can be concluded that although it may not be optimal to use the default values it is sufficient when the tailored values are not available.

The work on alternative interpretations of AMVs continues and a status update is given in Section 5. Based on the investigations presented in the third year fellowship report (Salonen and Bormann, 2013a) it was decided to perform impact studies with a layer averaging observation operator. Also the impact of re-assigning the AMV height based on model best-fit pressure statistics has been considered. Using the traditional single-level observation operator together with the height re-assignment indicates positive forecast impact. Experimentation with layer averaging gives more mixed results. All experiments where layer averaging is applied show statistically significant negative impact in the tropics at high levels.

Table 1: Overview of the use of AMV data in the ECMWF system in December 2014.

	IR	Cloudy WV	Clear WV	VIS
Meteosat-7	used	used	monitored	used
Meteosat-10	used	used	monitored	used
GOES-13	used	used	monitored	used
GOES-15	used	used	monitored	used
MTSAT-2	used	used	monitored	used
CMA FY-2D	monitored	monitored	monitored	-
CMA FY-2E	monitored	monitored	monitored	-
IMD INSAT-3D	monitored offline	monitored offline	monitored offline	monitored offline
MODIS AMVs from Aqua	used	used	used	-
MODIS AMVs from Terra	monitored	monitored	monitored	-
AVHRR AMVs from NOAA-15, -18 and -19	used	-	-	-
AVHRR AMVs from METOP-A, METOP-B and dual METOP-A/B	monitored (dual METOP-A/B offline)	- -	- -	- -

2 EUMETSAT processed Metop AMVs

2.1 Single Metop AMVs

AVHRR AMVs from Metop-A and Metop-B satellites are passively monitored in the ECMWF system. In the past, the monitoring statistics have shown larger values for bias and RMSVD for Metop AMVs than for the NOAA AVHRR AMVs. This is due to different processing used at EUMETSAT and NOAA/NESDIS.

Long-term monitoring of EUMETSAT processed Metop-A AMVs indicates that there has been improvements in the data quality during the past few years. The magnitude of the variability of the observation minus background (OmB) and observation minus analysis (OmA) bias has decreased significantly after May 2012. Metop-B AMVs became operational in spring 2013. Passive monitoring indicates that Metop-A and Metop-B share very similar characteristics.

EUMETSAT has introduced several updates to the polar AMV processing since Metop-B became operational. The changes introduced in 2013 include:

- Tropopause determination: no AMVs assigned above tropopause.
- Temperature inversion determination: if a temperature inversion is found and if the retrieved temperature corresponds to that level, the altitude of the AMV is then set to the bottom of the inversion layer.
- Coverage extended from 55° to 50° latitude.
- Stronger test to use IASI cloud top height (CTH) to set the altitude.

Based on the improved monitoring statistics it was decided to perform impact studies in the ECMWF system. The main advantage of Metop-A and Metop-B AMVs from an NWP point of view is that they fill in the gap between 50° and 60° where currently very few AMVs are used operationally. The performed impact studies concentrated only on high level Metop-A and Metop-B AMVs as they had close to zero bias at the time making the decision. The results indicate that the impact of using Metop-A and Metop-B AMVs processed prior the changes implemented on 27th May 2014 is mainly neutral with some indications of positive impact at high latitudes.

On 27th May 2014 EUMETSAT updated the polar wind processing again with significant changes including:

- Reference points used to compute the wind vector are changed to centres of target box from CCC barycentres.
- The window search size depends on the expected displacement.

The most recent updates have a considerable impact on the AMV characteristics and thus on the monitoring statistics. Figure 1 shows zonal plots of the OmB wind speed bias (upper panels), RMSVD (middle panels) and number of observations (lower panels) before (left) and after (right) the changes were implemented. The considered periods are two months before, 27.3. - 26.5.2014, and two months after, 28.5-27.7.2014, the update. At mid and low levels the changes have clearly improved the data quality. The long standing issue with positive speed bias is not present after the update and the magnitude of the speed bias is within ± 0.5 ms^{-1}. However, at high levels a negative speed bias up to -2 ms^{-1} is now seen whereas before the changes the bias was close to zero. RMSVD has generally decreased at all levels. The changes in the data quality are significant and thus the conclusions from the impact studies performed are not valid anymore. Experimentation with the updated wind product is ongoing.

2.2 Dual Metop AMVs

EUMETSAT has developed a new dual Metop AMV product. The AMVs are derived from pairs of Metop-A and Metop-B images. Two complementary products are provided, one considering Metop-A as the reference image and Metop-B as the second image of the pair (dual Metop-A/B), another one considering Metop-B as the reference and Metop-A as the second image of the pair (dual Metop-B/A). The temporal gap between the two images used for the tracking is about 50 minutes.

This is the first AMV data set which has global coverage. The NWP interest is especially in the regions between 50° to 60° latitude north and south, where AMV coverage and usage has been very limited so far. The first data set was made available for testing in January 2014 and the product has been operationally available since end of July 2014. Passive monitoring of the dual Metop AMVs in the ECMWF system has been done offline to enable separation between Metop-A/B and Metop-B/A AMVs.

Figure 2 shows zonal plots of the OmB wind speed bias, RMSVD and number of observations for 31.7-5.10.2014. The left panels are for dual Metop-A/B AMVs and the right panels for dual Metop-B/A AMVs. In general, at high latitudes the bias and RMSVD statistics are very similar to the single Metop AMVs (note different scale for bias compared to Fig. 1). The dual-Metop AMVs have large positive bias over the tropics, especially above 700 hPa. The bias is larger in magnitude and more wide spread compared to what is seen for AMVs from geostationary satellites. However, outside the tropics the data indicates promising potential for further investigations.

The zonal plots reveal quite significant differences in the OmB speed bias and RMSVD for dual Metop-A/B and Metop-B/A AMVs. EUMETSAT has investigated the issue and the explanation is that the planned small drift of the satellites on the orbit was not taken into account in the AMV derivation. Initially the time difference between Metop-A and Metop-B has been 45 min / 55 min but is now closer to 49 min / 51 min. A fix to correct this issue and to prevent it happening again has been introduced to the operational processing on 4th

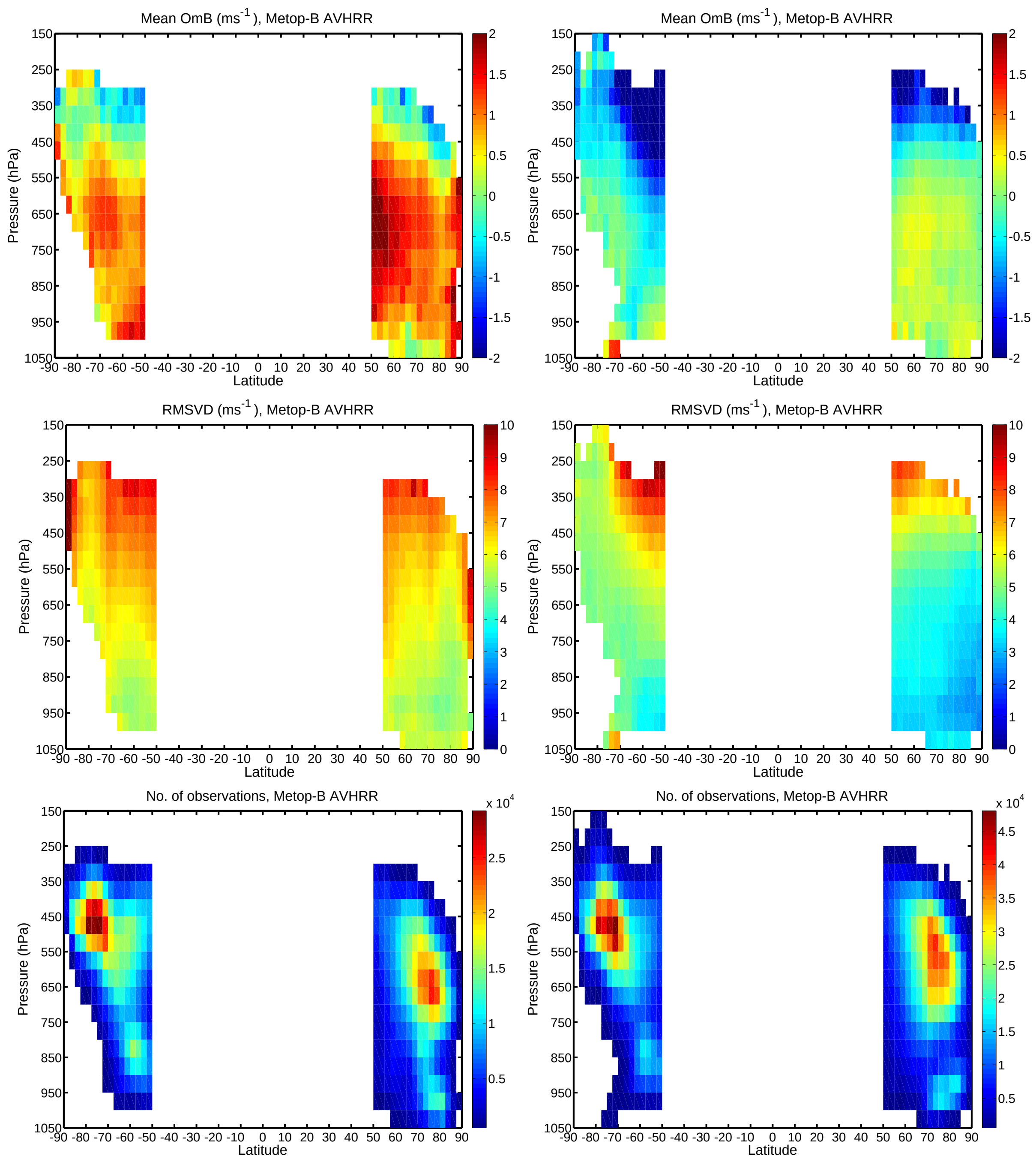

Figure 1: Zonal plots of the OmB wind speed bias (upper panels), RMSVD (middle panels) and number of observations (lower panel) for Metop-B AMVs. The covered periods are two months before, 27.3. - 26.5.2014 (left), and two months after, 28.5-27.7.2014 (right), the changes were implemented.

December 2014. Figure 3 shows the same as Fig. 2 for a one month period after the change was implemented (5.12.2014-4.1.2015). The statistics for Metop-A/B and Metop-B/A are very similar to each other.

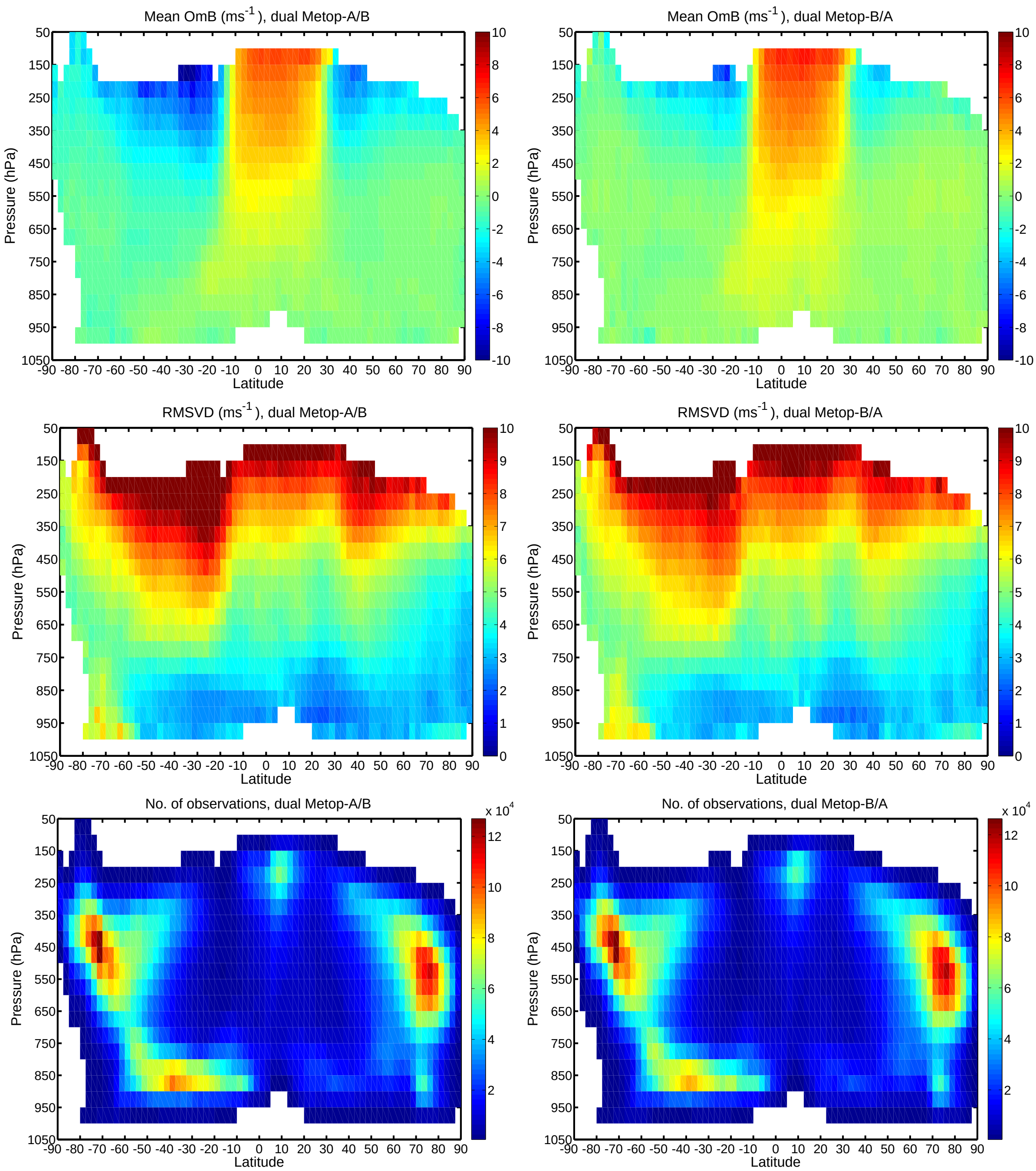

Figure 2: Zonal plots of the OmB wind speed bias (upper panel), RMSVD (middle panel) and number of observations (lower panel) for dual Metop-A/B AMVs (left) and dual Metop-B/A AMVs (right). The covered period is 31.7 - 5.10.2014.

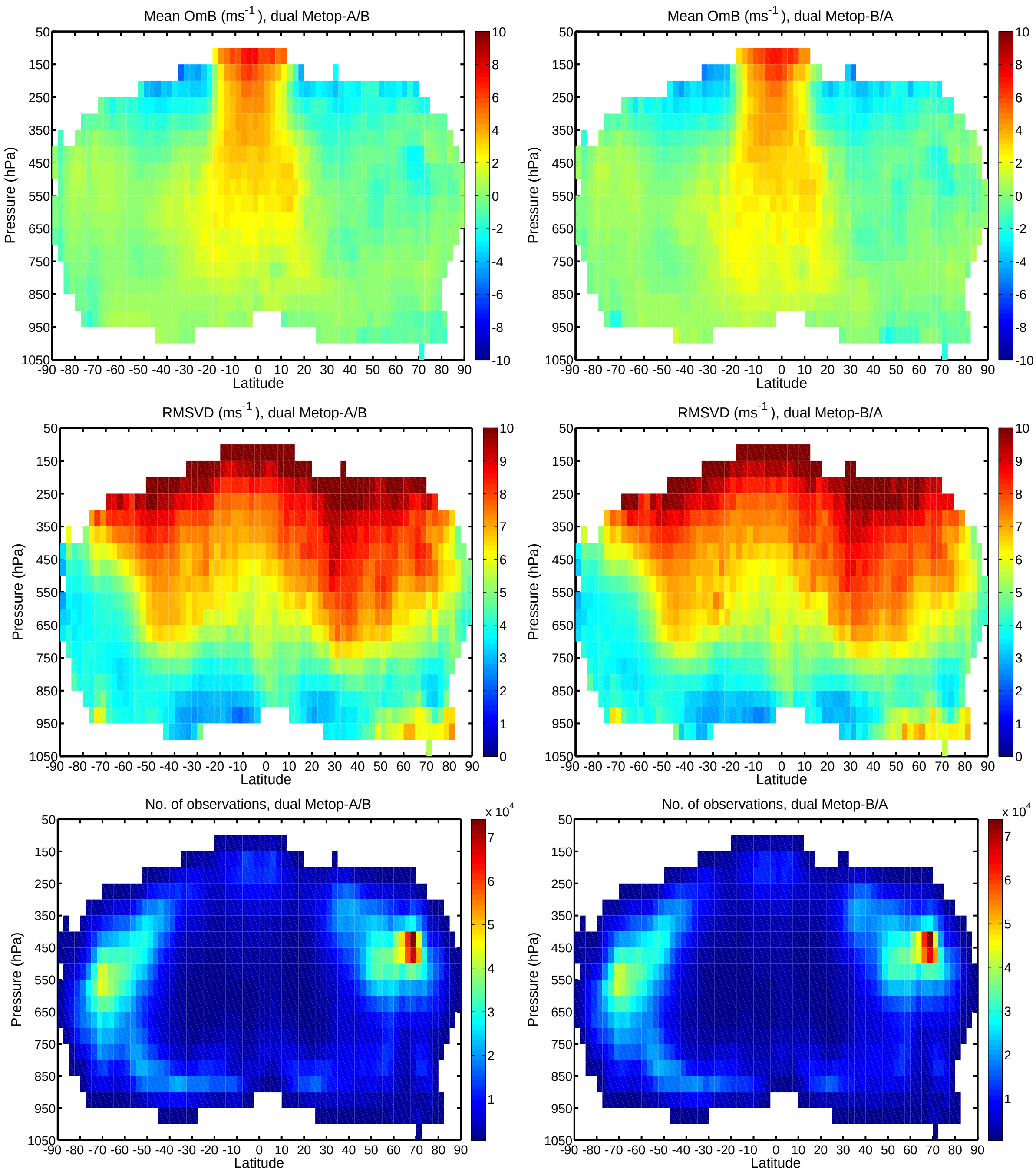

Figure 3: Same as 2 but after the fix implemented on 4th December 2014. The covered period is 5.12.2014-4.1.2015.

3 AMVs over the Indian Ocean

Currently, Meteosat-7 is the prime satellite to provide AMV coverage over the Indian Ocean. Securing the AMV coverage over that area after Meteosat-7 has reached its lifetime is considered to be very important. A comprehensive comparison of the options with impact assessment is presented in Cotton (2013). EUMETSAT has expressed also a strong interest in results investigating the available options in the ECMWF system to support the decision making process.

AMVs covering the Indian Ocean region are available from Meteosat-7 (57.5°E; EUMETSAT, Carranza et al. (2014)), FY-2D/E (86.5°E/105°E; CMA, Zhang et al. (2014)), Kalpana-1 and INSAT-3D (74°E and 82°E; IMD, Deb (2012)). In the future EUMETSAT is planning to provide coverage for the Indian Ocean by moving Meteosat-8 over the region. AMVs and radiance data from Meteosat-8 positioned over the Indian Ocean is expected to provide better quality data than Meteosat-7.

AMVs from Meteosat-7 are operationally used in the ECMWF system. In addition, the quality of AMVs from FY-2D and FY-2E are operationally passively monitored. The latest addition to the AMVs providing coverage over the Indian Ocean are the INSAT-3D AMVs. Currently INSAT-3D AMVs are processed for offline monitoring at ECMWF but they are planned to be added to the operational monitoring in the next update to the IFS cycle.

In the following, first results from monitoring the quality of INSAT-3D AMVs and a comparison of the characteristics to Meteosat-7 and FY-2E AMVs are presented. The impact of Meteosat-7 and FY-2E has been investigated and these results will be discussed. Impact assessment of the INSAT-3D AMVs has not been completed yet as the data was not available at the time when the impact studies with Meteosat-7 and FY-2E were performed.

3.1 Monitoring of Indian Ocean AMVs

AMVs from INSAT-3D have recently become available via the GTS. Processing of the data started at ECMWF 2nd October 2014. Here, first results of the passive monitoring are presented and the quality of INSAT-3D AMVs is compared with the quality of Meteosat-7 and FY-2E AMVs.

INSAT-3D AMVs are available from IR (10.8 m), VIS (0.65 m), Short-wave IR (3.8 m) and WV (6.9 m) channels. There is no separation between cloudy and clear sky WV AMVs. The quality information provided for the AMVs is the forecast independent QI. Figure 4 shows the RMSVD for different QI values. There are very few observations with QI > 80. In addition, there is no clear dependence between RMSVD and QI. Thus, in the following monitoring statistics no QI criterion is applied to the INSAT-3D data.

Meteosat-7 AMVs are available 1.5-hourly from IR (11.3 m), VIS (0.7 m) and WV (6.3 m) channels. Here, only cloudy WV AMVs are considered. FY-2E AMVs are available 6-hourly from IR (10.8 m) and WV (6.8 m) channels. FY-2E WV AMVs are also a mix of cloudy and clear sky AMVs. For the Meteosat-7 and FY-2E statistics the forecast independent QI > 80 criterion is applied. This is the standard NWP SAF monitoring QI threshold. However, it is worth to note that for FY-2E the forecast independent and dependent QI are set to the same value and in practise it is the forecast dependent QI.

The number of available INSAT-3D AMVs is strongly fluctuating over time. Figure 5 shows the number of available observations each day between 2nd October and 30th November 2014. Until 20th November 2014 most of the time at most 1000 observations per time and channel have been distributed. Frequently, the number of winds is precisely 1000 per time-slot, suggesting a technical limitation. After 20th November the number of available observations has increased significantly. However, there are dates at the end of October and beginning

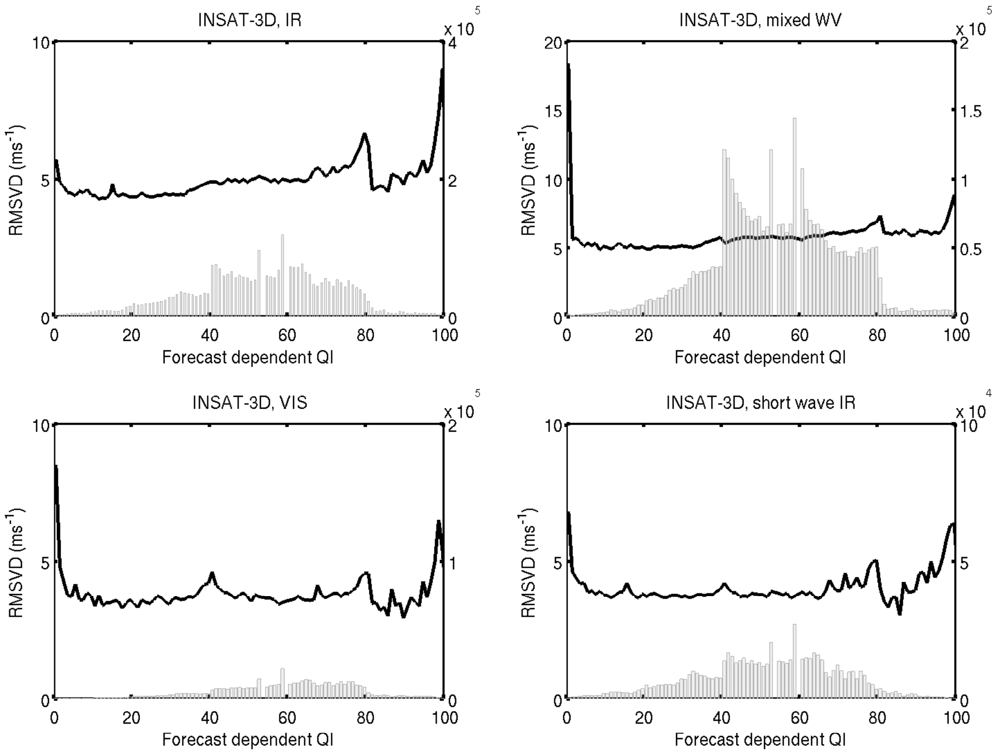

Figure 4: RMSVD as a function of forecast independent QI for INSAT-3D IR (upper left), mixed WV (upper right), VIS (lower left) and short-wave IR (lower right) AMVs. The considered period is 1.-31.11.2014.

of November when the limitation of 1000 observations has not been applied.

Figures 6, 7 and 8 show the zonal plots of number of observations, wind speed bias, mean vector difference and normalised RMSVD for the INSAT-3D, Meteosat-7 and FY-2E IR AMVs respectively. The considered period is 1.-30.11.2014. The comparison shows that:

- At high levels mid-latitudes INSAT-3D AMVs have mainly a positive speed bias whereas the Meteosat-7 and FY-2E AMVs have a negative bias.
- At mid levels Meteosat-7 AMVs have negative speed bias in the mid-latitudes and positive speed bias in the tropics. FY-2E and INSAT-3D AMVs show similar pattern but for INSAT-3D the bias is significantly smaller in magnitude.
- At low levels INSAT-3D AMVs have more pronounced positive speed bias compared to Meteosat-7 or FY-2E AMVs.
- The zonal pattern of normalised RMSVD is rather similar for all three satellites but MET-7 and FY-2E AMVs show more pronounced values than INSAT-3D.

For WV AMVs the distribution of AMV heights is different for the three satellites (Fig. 9, Fig. 10 and Fig. 11). The majority of Meteosat-7 cloudy WV AMVs originate from somewhat higher altitudes than the mixed WV for INSAT-3D and FY-2E. This reflects the presence of the clear sky WV AMVs in the INSAT-3D and FY-2E data. For some INSAT-3D AMVs the height assignment appears erroneous as the WV channel can not see below 500 - 600 hPa. Meteosat-7 and FY-2E AMVs show a positive speed bias in the tropics and a negative

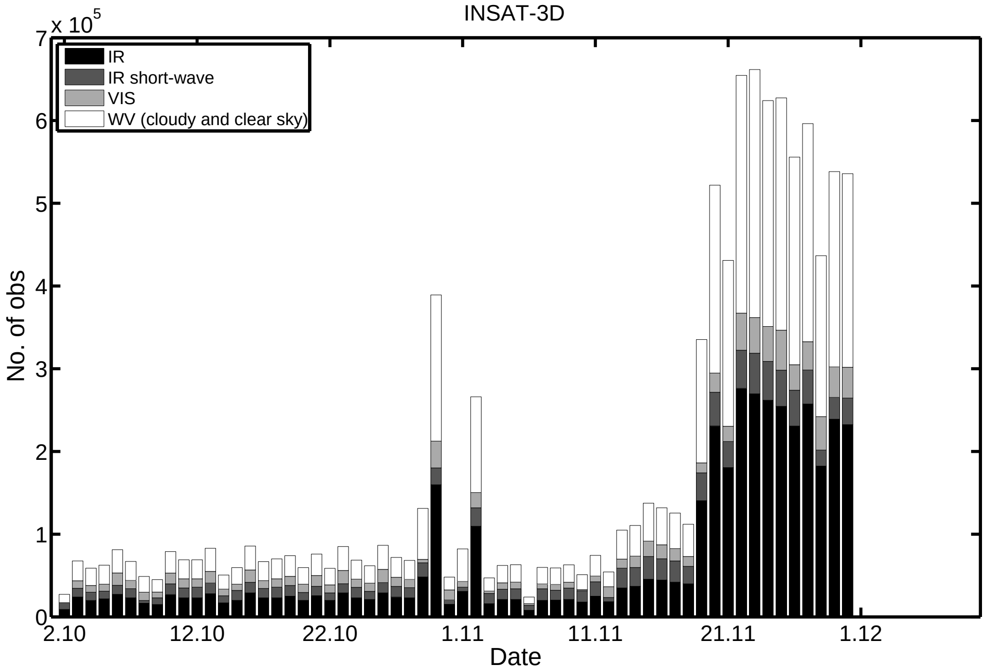

Figure 5: The number of available INSAT-3D AMVs each day between 2nd October and 31st November 2014. Black colour indicates IR, dark grey short-wave IR, light grey VIS and white mixed WV AMVs.

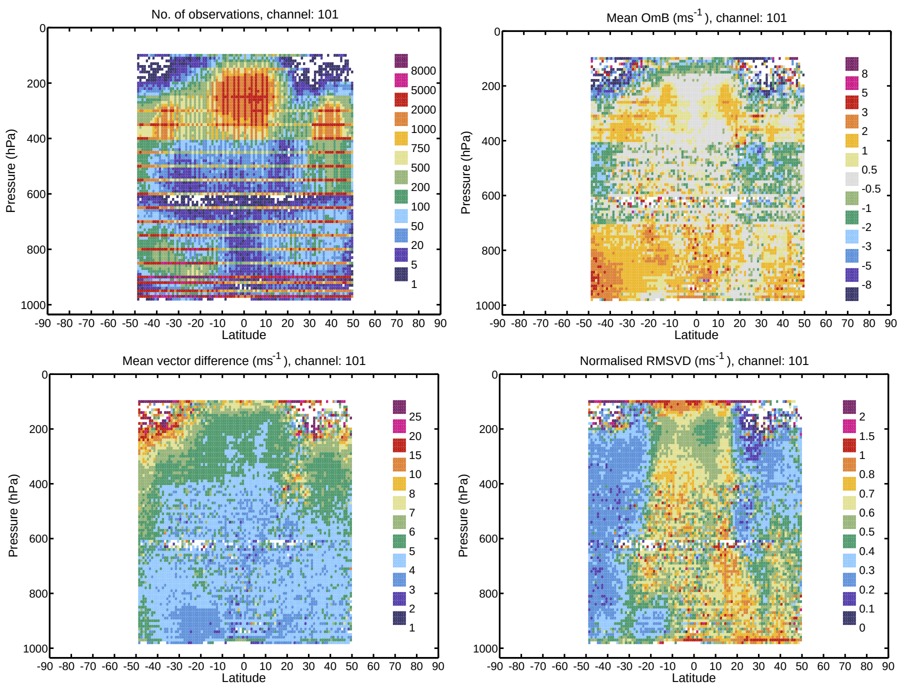

Figure 6: Zonal plots of number of observations (upper left panel), wind speed bias (upper right panel), mean vector difference (lower left panel) and normalised RMSVD (lower right panel) for the INSAT-3D IR AMVs. The considered period is 1.-30.11.2014.

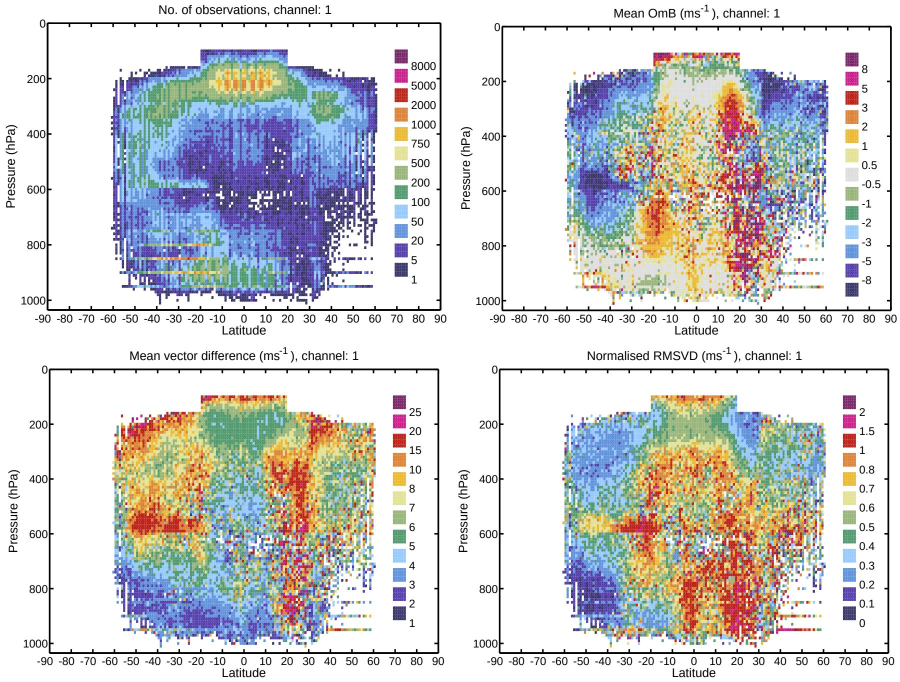

Figure 7: Same as 6 but for Meteosat-7 IR AMVs.

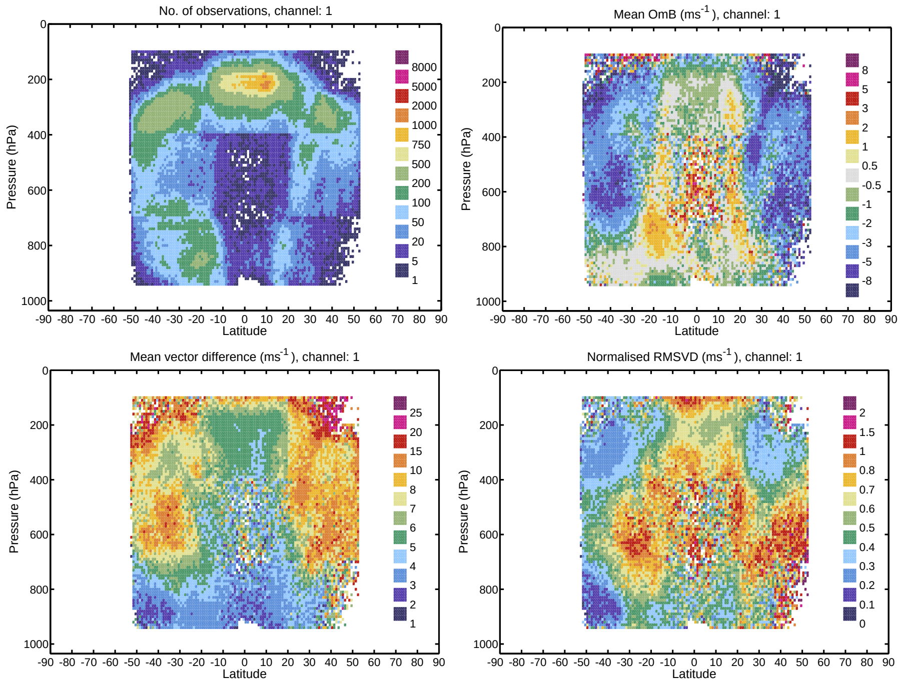

Figure 8: Same as 6 but for FY-2E IR AMVs.

bias in the mid-latitudes. The magnitude of the bias is more pronounced for the Meteosat-7 AMVs. INSAT-3D AMVs do not have this kind of pattern. In general there are more regions with positive speed bias than with negative for the INSAT-3D AMVs. Again, the RMSVD is rather similar for all three satellites.

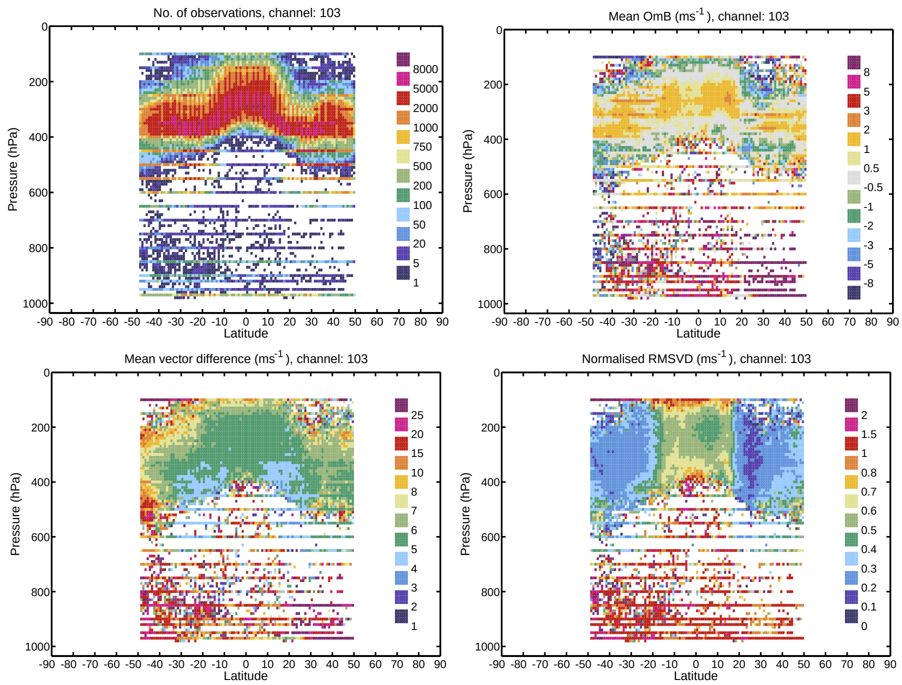

Figure 9: Same as 6 but for INSAT-3D mixed WV AMVs.

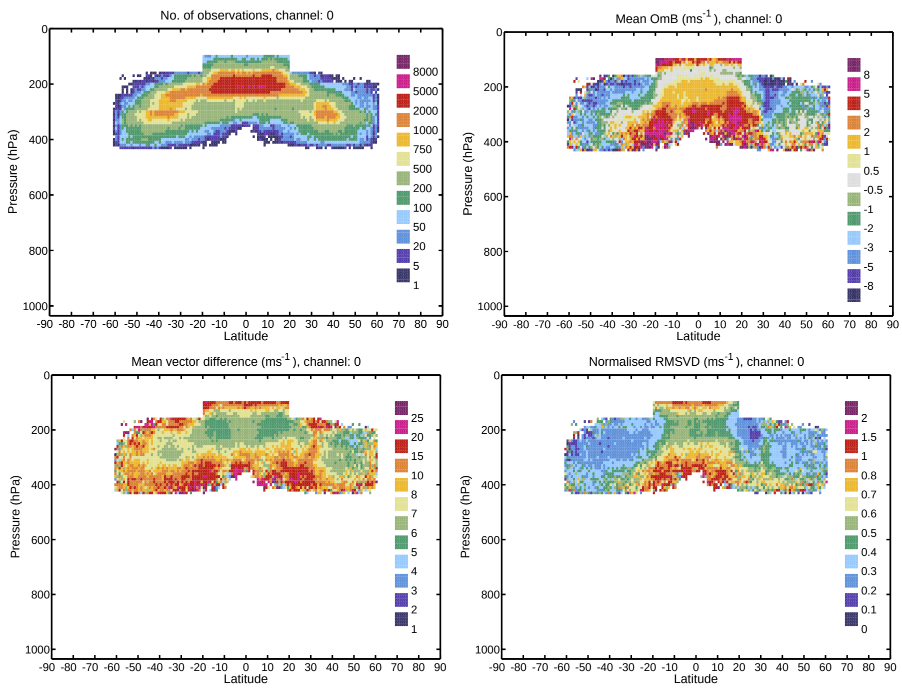

Figure 10: Same as 6 but for Meteosat-7 cloudy WV AMVs.

For the VIS AMVs the monitoring statistics are quite similar for INSAT-3D and Meteosat-7 satellites (Fig. 12 and Fig. 13). INSAT-3D AMVs are available below 500 hPa, Meteosat-7 below 700 hPa and in general there are more Meteosat-7 AMVs available than INSAT-3D AMVs. For FY-2E VIS AMVs are not produced.

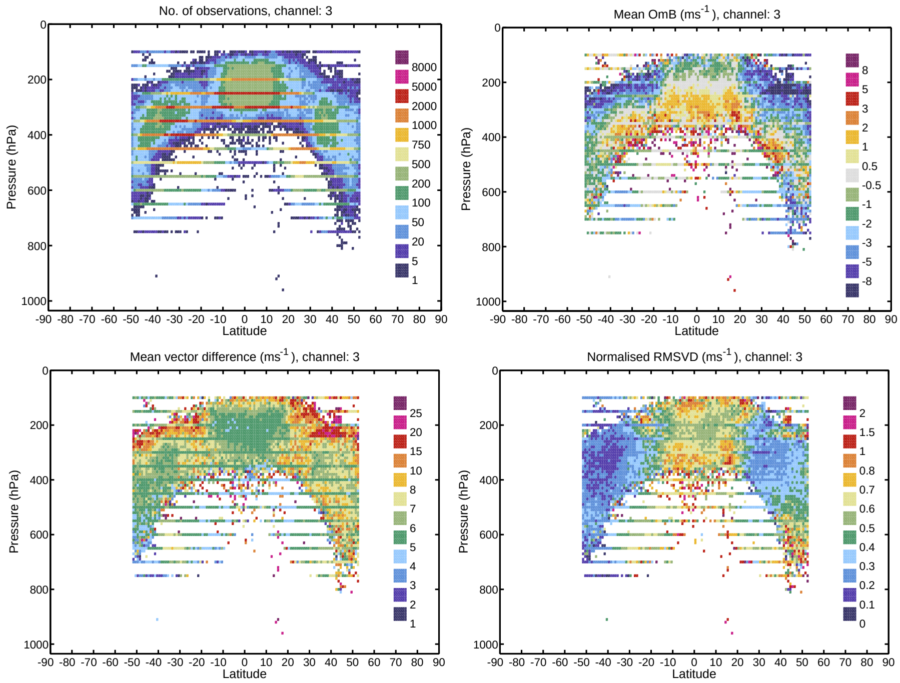

Figure 11: Same as 6 but for FY-2E mixed WV AMVs.

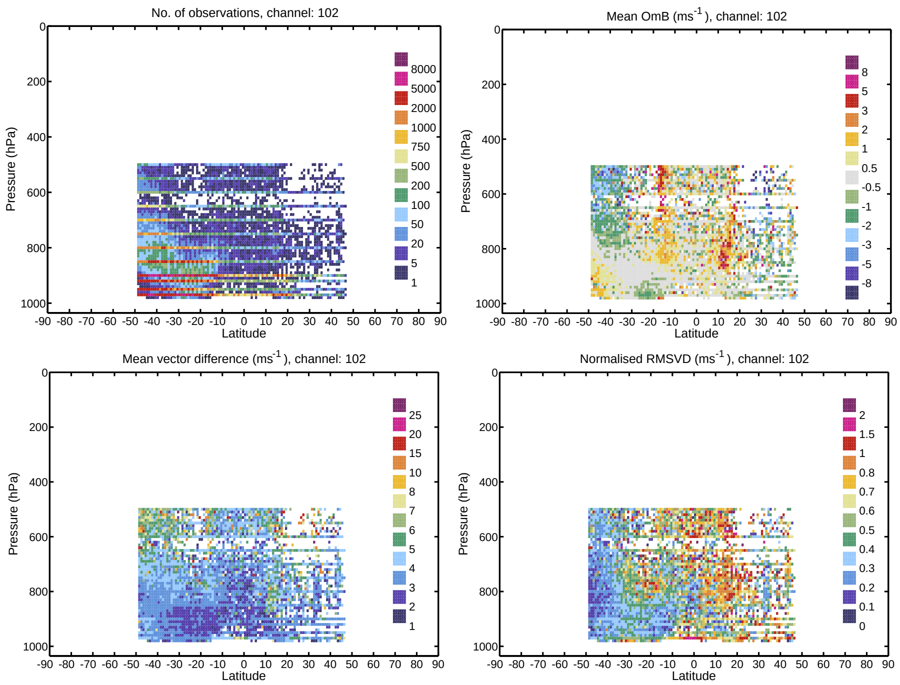

Figure 12: Same as 6 but for INSAT-3D VIS AMVs.

First conclusions from the monitoring indicate that the INSAT-3D and FY-2E AMVs show promising data quality comparable to Meteosat-7, and there is potential for further investigations. From the NWP point of view, it would be beneficial to separate cloudy and clear sky WV AMVs as they tend to show very different

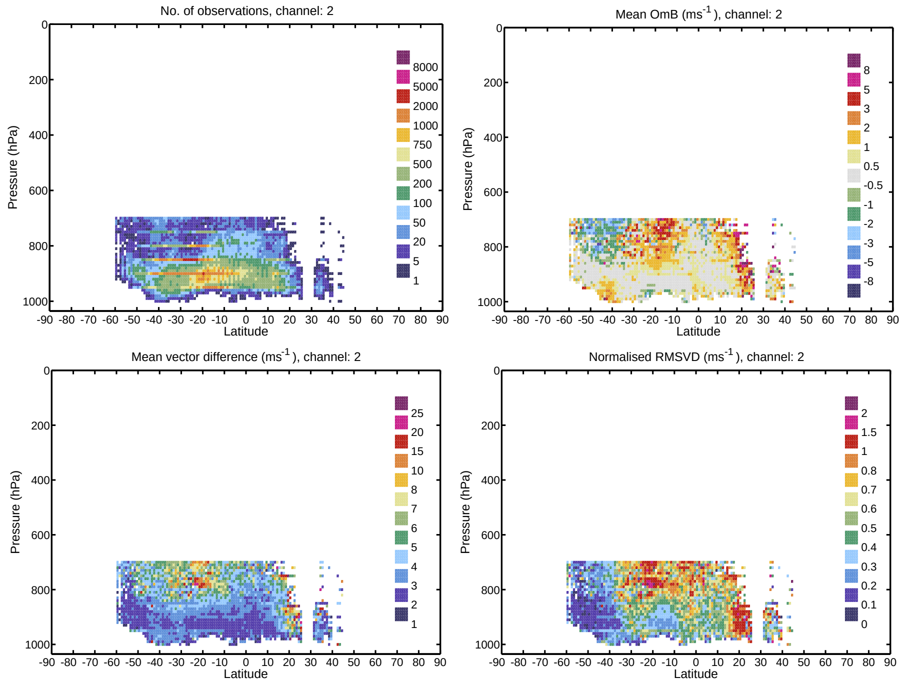

Figure 13: Same as 6 but for Meteosat-7 VIS AMVs.

characteristics. It would also be important to have more meaningful quality information for each AMV. For INSAT-3D, it would be interesting to know the reason for the 1000 limit for number of observations per channel and time and if the limit has now been removed for good. INSAT-3D AMVs are planned to be added to the operational monitoring in the ECMWF system.

3.2 Experimentation with Meteosat-7 and FY-2E

From the current geostationary satellites, Meteosat-7 (57.5°E) has the best geographical as well as temporal AMV coverage over the Indian Ocean. IR, WV (cloudy and clear sky) and VIS AMVs are available every 1.5 hours. From FY-2E IR and mixed WV AMVs are available 6-hourly. The location of FY-2E is more in the east (105°E), thus the Indian Ocean coverage is not as good as for Meteosat-7. At the time of performing these impact studies, INSAT-3D AMVs were not yet available.

Comparison of the monitoring statistics for INSAT-3D, Meteosat-7 and FY-2E in the previous section showed that Meteosat-7 and FY-2E AMVs share during the test period very similar characteristics. Long term monitoring statistics indicate that the quality of FY-2E AMVs has improved significantly during past years. Figure 14 shows timeseries for the OmB and OmA bias (upper panel), standard deviation (middle panel) and number of observations (lower panel) for FY-2E mixed WV AMVs at high levels. The covered period is 2010 - early 2015. After autumn 2011 the magnitude of bias and standard deviation has significantly decreased. In late 2014 the number of available AMVs has increased by a factor of 4 with some changes in the bias characteristics.

In order to investigate and compare the impact of Meteosat-7 AMVs and FY-2E AMVs two sets of three-month long experiments have been performed covering a summer season, 2.8-31.10.2013, and a winter season, 1.1-31.3.2014. Thus, both periods are prior to the latest changes in the FY-2E AMV quality. The ECMWF IFS cycle 40r2 at T511 resolution, 137 vertical levels and 12-hour 4D-Var has been applied in the experiments. Results from the following experiments are compared:

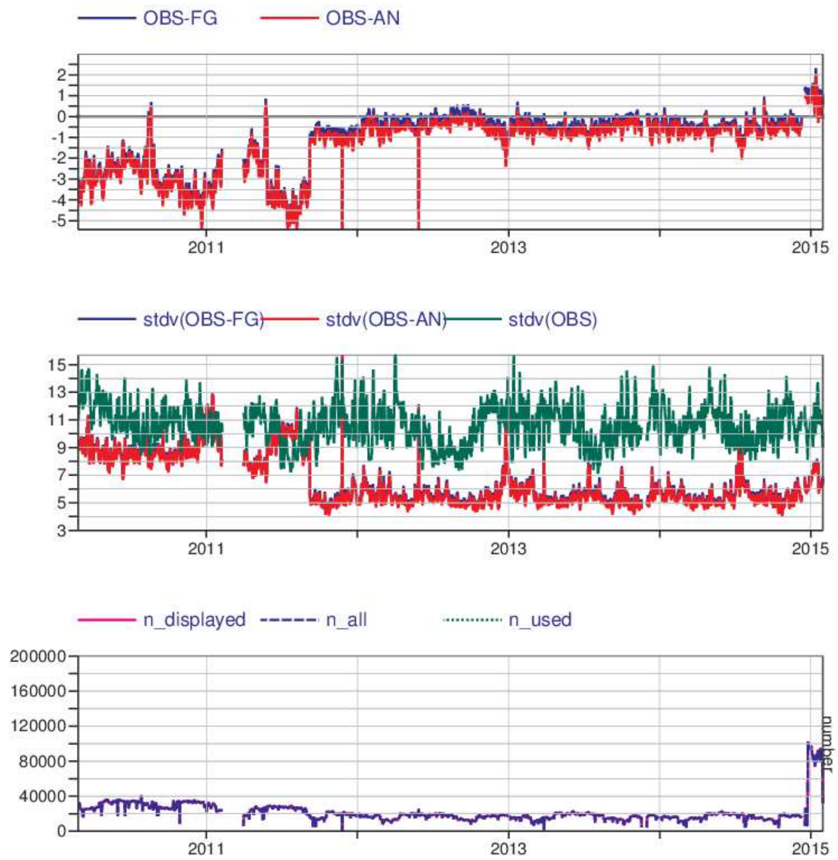

Figure 14: Timeseries for the OmB (blue line) and OmA (red line) bias (upper panel), standard deviation (middle panel) and number of observations (lower panel) for FY-2E mixed WV AMVs at high levels. The covered period is 2010 - early 2015.

- **Control**: All operationally assimilated conventional and satellite observations are used except Meteosat-7 AMVs and clear sky radiances.
- **Met-7**: Similar to **Control** but Meteosat-7 AMVs and clear sky radiances are used.
- **FY-2E**: Similar to **Control** but FY-2E IR and mixed WV AMVs are used.

It is worth to note that from Meteosat-7 only cloudy WV AMVs are used but in addition the clear sky radiances (CSR) are used. Peubey and McNally (2009) have shown that assimilation of clear sky radiances has a positive impact on wind analyses throughout the troposphere. The best results are found at heights which correspond to the peaks of the weighting functions of the assimilated WV channels. For FY-2E it is not possible to separate cloudy and clear sky WV AMVs and thus both are used. FY-2E radiances are not available at ECMWF.

3.2.1 Quality control and observation errors

The quality control for AMVs includes blacklisting, thinning and a first guess check. Table 2 summarises the QI thresholds used for Meteosat-7 and for FY-2E AMVs. The forecast dependent QI is used for both satellites.

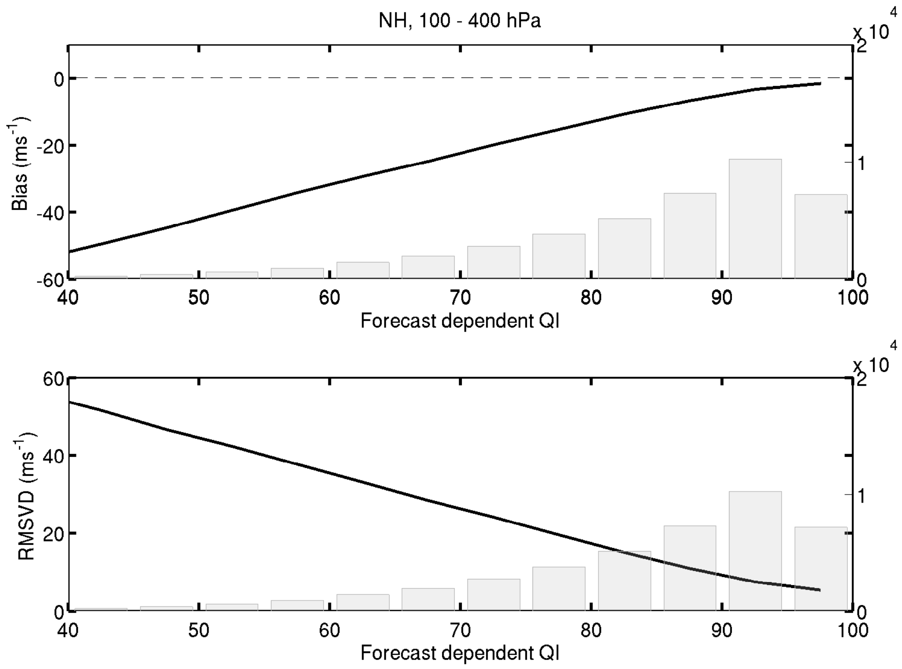

Figure 15: Wind speed bias (upper panel) and RMSVD (lower panel) for different QI values for FY-2E IR AMVs at northern hemisphere extratropics high levels.

Table 2: QI (with first guess check) thresholds for Meteosat-7 and FY-2E AMVs. Tropics is 20°S-20°N, and extratropics polewards from 20°S/N. High levels 100-400 hPa, mid levels 400-700 hPa and low levels below 700 hPa.

	High levels, midlatitudes	Mid levels, midlatitudes	Low levels, midlatitudes	High levels, tropics	Mid levels, tropics	Low levels, tropics
Metaosat-7 IR	60	90	85	85	90	85
Metaosat-7 VIS	-	-	65	-	-	65
Metaosat-7 cloudy WV	60	-	-	85	-	-
FY-2E IR	90	90	85	80	80	80
FY-2E mixed WV	85	85	-	80	80	-

The QI thresholds used for Meteosat-7 are the same as what are used in the operational ECMWF system. The QI thresholds used for FY-2E are similar to what are used in the Cotton (2013) study. Depending on height and location, 80% or more of the FY-2E AMVs have QI greater than 80. Typically for the AMVs with QI greater than 80 the magnitude of RMSVD is 10 ms^{-1} or less. In the midlatitudes FY-2E AMVs have negative bias in wind speed that is strongly QI dependent. Figure 15 shows the wind speed bias (upper panel) and RMSVD (lower panel) for different QI values for northern hemisphere midlatitudes at high levels as an example. The bias is somewhat stronger for IR AMVs than for WV AMVs. The tighter QI thresholds for the FY-2E midlatitude AMVs at the high and mid levels are designed to reduce the impact of the negative speed bias observed in the data.

The same spatial blacklisting is applied for FY-2E AMVs as for AMVs from other geostationary satellites (`http://nwpsaf.eu/monitoring/amv/amvusage/ecmodel.html`). Thinning is done in 200 km

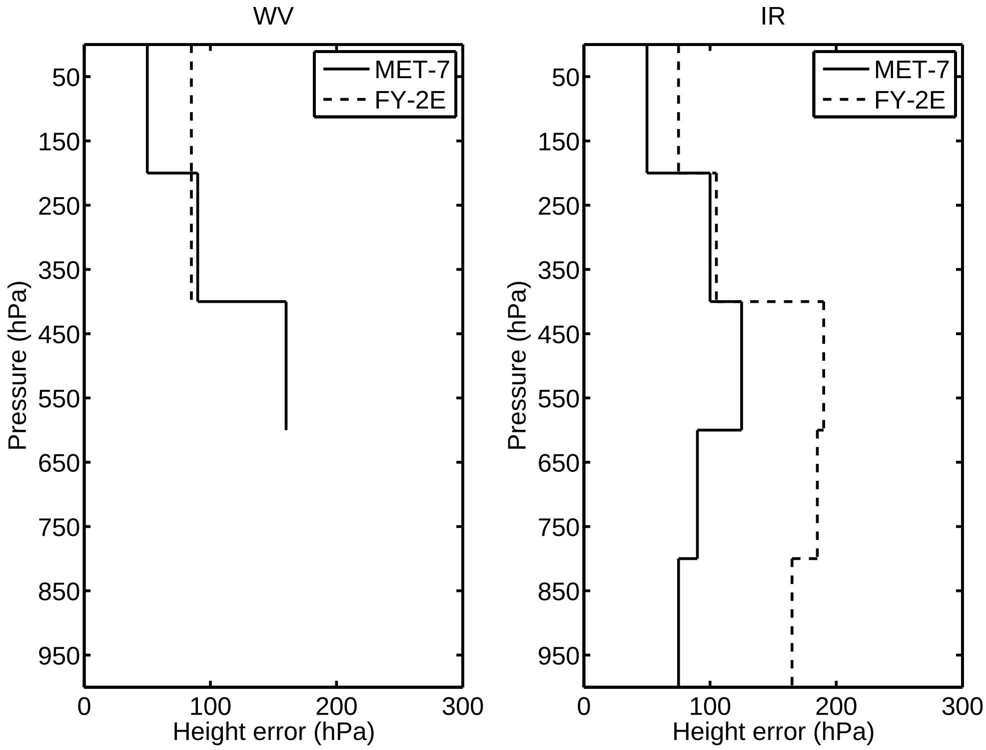

Figure 16: Height error estimates for WV (left panel) and IR (right panel) Meteosat-7 (solid line) and FY-2E (dashed line) AMVs.

by 200 km by 50-175 hPa boxes. The vertical extent of the box varies according to the nearest standard pressure levels. The observation with highest QI is selected. In general, the use of forecast independent QI is preferred and it is used for all other satellites than for Meteosat-7, MTSAT-2 and FY-2E. For Meteosat-7 and MTSAT-2 impact studies have shown that it is difficult to get positive forecast impact if the forecast independent QI is used. For FY-2E AMVs only forecast dependent QI is available. AMV observations are assimilated in 30 minute time-slots.

In the model first guess check the observation is compared to the model counterpart and rejected if it differs from it more than a predefined limit. In addition variational quality control is applied during the calculation of the analysis.

Situation dependent observation errors are calculated individually for each AMV (Salonen and Bormann, 2013b). For that, estimates of the height assignment errors and tracking errors are required. In the ECMWF system, the height assignment errors are defined separately for all satellites, channels and height assignment methods. Figure 16 shows the height error estimates used in these experiments for Meteosat-7 (solid line) and FY-2E (dashed line). At high levels the height error estimates are rather similar in magnitude for both satellites. For IR AMVs below 400 hPa the height errors are larger for the FY-2E than for Meteosat-7. The same tracking errors are used for FY-2E AMVs as for AMVs from other geostationary satellites. The tracking errors vary between 2 and 3 ms^{-1} depending on height.

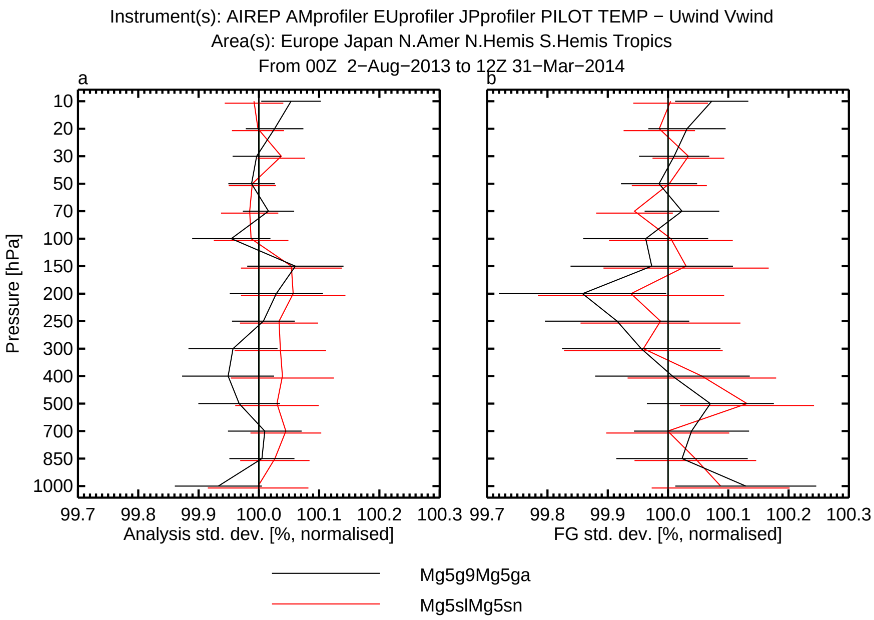

Figure 17: The normalised change in the OmA (right) and OmB (left) standard deviation calculated against radiosondes, pilot, aircraft and wind profiler observations. The horizontal bars indicate 90% confidence range. Black line indicates the **Met-7** *experiment and red line the* **FY-2E** *experiment. The considered periods are 2.8-31.10.2013 and 1.1-31.3.2014.*

3.2.2 Impact assessment

To investigate the impact of using Meteosat-7 and FY-2E data on the short range forecasts, Fig. 17 shows the normalised change in the OmA (left panels) and OmB (right panels) standard deviation calculated against radiosondes, pilot, aircraft and wind profiler observations. The summer and winter periods are combined to cover a total of 6 months. The horizontal bars indicate 90% confidence range. In general the OmB statistics indicate slightly degraded observation fit below 400 hPa and improved fit above 400 hPa. The changes are mainly statistically insignificant. However, in the tropics the improvements at the high levels are statistically significant both for the **Met-7** and **FY-2E** experiments. The OmA statistics indicate small improvements for the **Met-7** experiment and small degradations for the **FY-2E** experiment.

The upper panel of Fig. 18 shows the mean analysed wind field at 250 hPa for the **Control** experiment for the summer period, 2.8-31.10.2013. The mid latitude jets are located over northern India and the southern Indian Ocean. Middle and lower panels of Fig. 18 show the mean vector difference (arrows) and mean speed difference (colour shading) between the **Met-7** and **Control** and between **FY-2E** and **Control**, respectively. The most significant changes in the mean wind field are seen in the tropics over the Meteosat-7/FY-2E coverage area. The magnitude of the changes is mainly less than ± 0.6 ms^{-1}. The results are similar for the winter period.

Verification against each experiment's own analysis indicates on average neutral to positive impact for all forecast lengths. Figure 19 shows the maps of the normalised difference of the 72-h wind forecast RMS error at the 200 hPa level as an example of the results. The strongest signal of positive impact is seen over the Meteosat-7/FY-2E coverage areas. For the **FY-2E** experiment some indications of degradation of the forecast quality are seen over South Pacific Ocean from 48-hour forecast onwards downstream of the FY-2E disk.

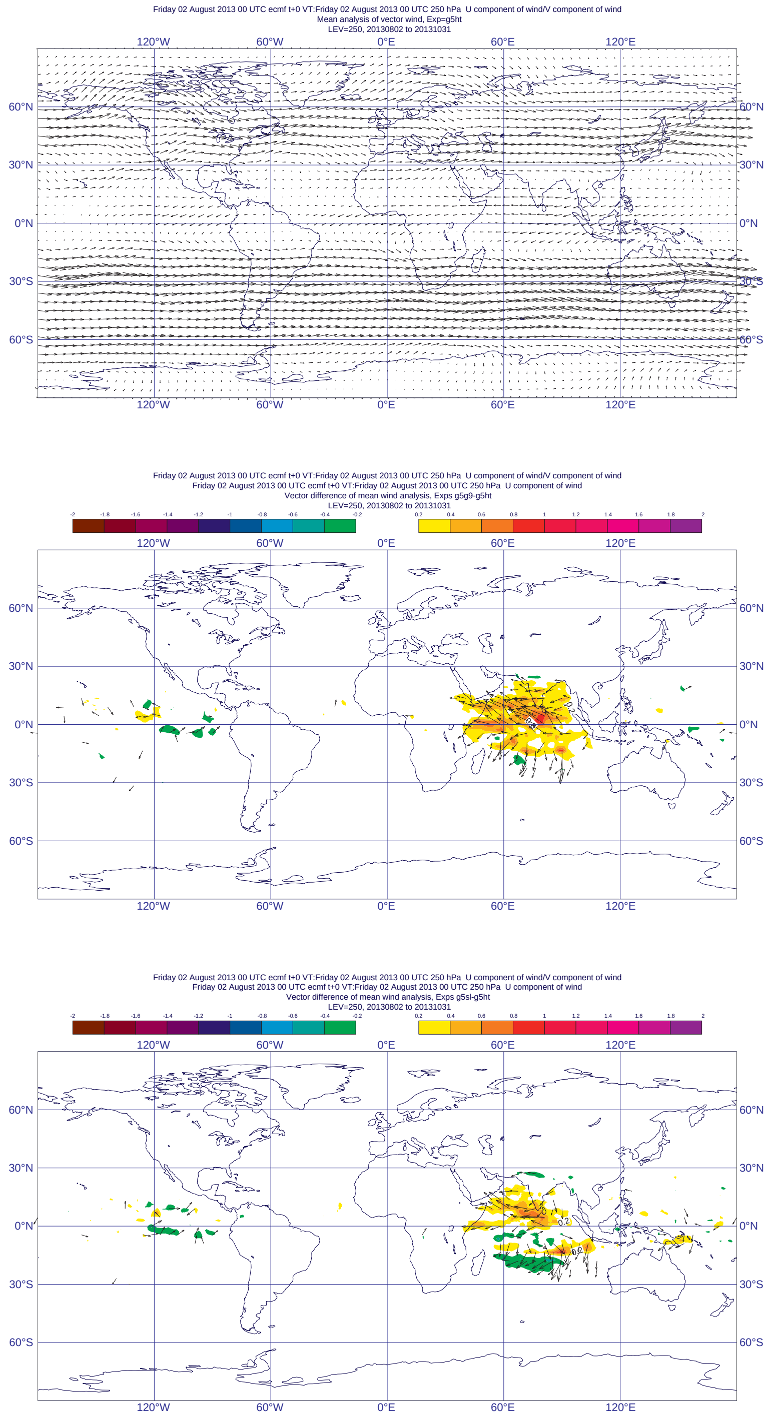

Figure 18: The mean analysed wind field at 250 hPa for the **Control** *experiment (upper panel). Difference in the mean wind analysis at 250 hPa between the* **Control** *and* **Met-7** *experiments (middle panel) and between the* **Control** *and* **FY-2E** *experiments (lower panel). The considered period is 2.8-31.10.2013.*

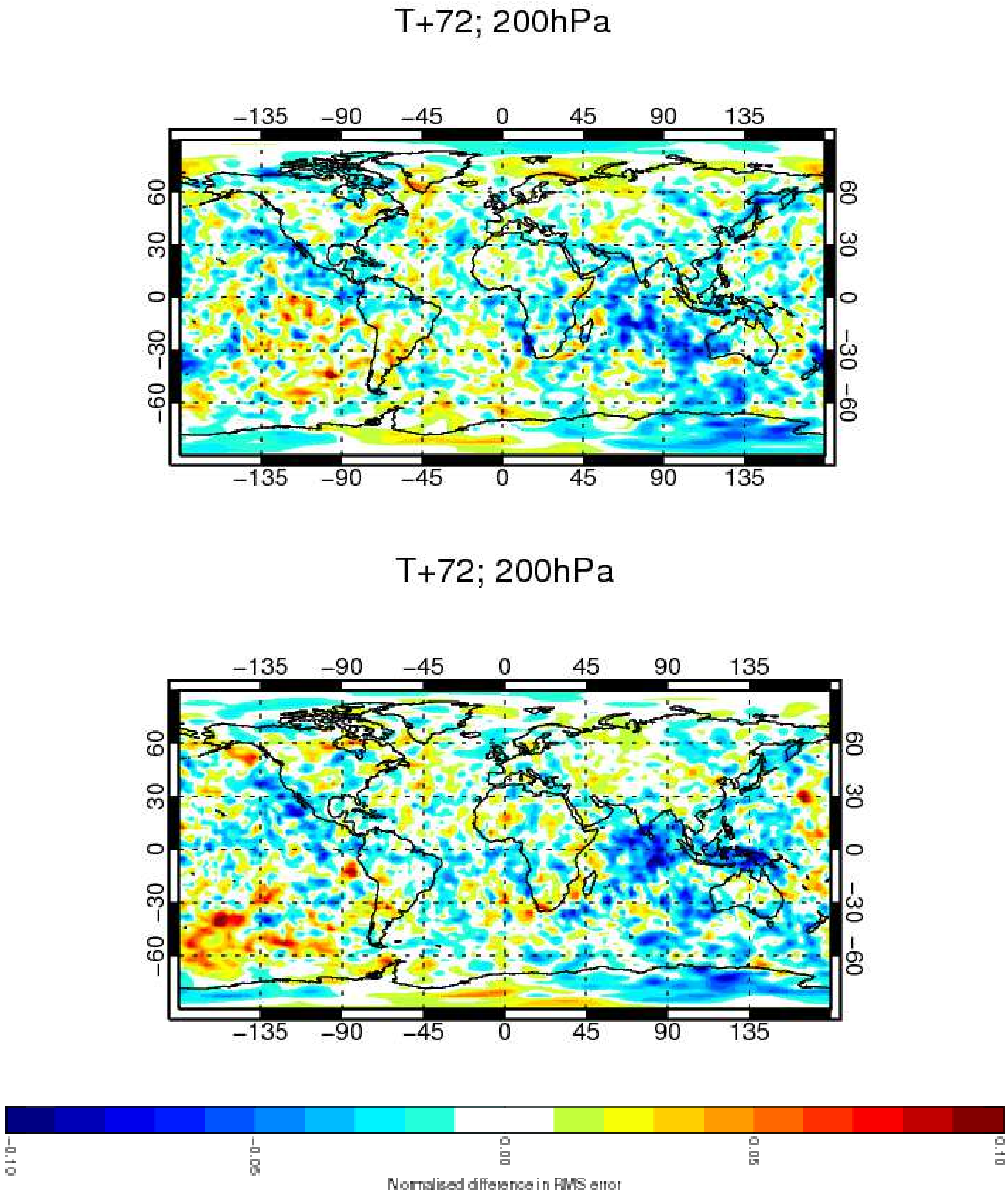

*Figure 19: Map of the normalised difference (***Met-7** *-* **Control***, upper panel and* **FY-2E** *-* **Control***, lower panel) of the 72-h wind forecast RMS error at 200 hPa level. Blue shades indicate positive impact and green and red shades negative impact. The considered periods are 2.8-31.10.2013 and 1.1-31.3.2014.*

3.3 Conclusions

This study investigated the use of AMVs and CSRs from Meteosat-7 over the Indian Ocean, and considered alternative data sources, that is, data from the FY-2E and INSAT-3D satellites. Meteosat-7 AMVs and CSRs are used operationally in the ECMWF system. The satellite is approaching its end of life, and follow-on scenarios therefore need to be considered, such as re-positioning of Meteosat-8 or the use of data from alternative satellites.

The CMA operated FY-2E and IMD operated INSAT-3D AMVs are also providing coverage over the Indian Ocean. The FY-2E AMVs are available 6-hourly, compared to the 1 1/2 hourly availability of Meteosat-7 AMVs, whereas the INSAT-3D AMVs have varying time intervals. Long term monitoring of the FY-2E AMVs indicate that there has been significant improvements in the data quality during the past years. The current monitoring statistics for the FY-2E and INSAT-3D AMVs are generally in line with what is seen for other geostationary satellites. However, there is no separation for the clear sky and cloudy WV AMVs and neither of the satellites provide CSR or ASR (all sky radiance) observations. There are also some issues with the provided QI information. For FY-2E AMVs only forecast dependent QI is available. For INSAT-3D AMVs the provided QI is not currently very meaningful. AMVs from both satellites indicate good potential for further investigations but the Metosat-7 observations still have advantages over INSAT-3D or FY-2E. It is also worth noting here that AMVs and radiance data from Meteosat-8 positioned over the Indian Ocean is expected to provide better quality data than Meteosat-7.

Our impact study shows positive forecast impact when Meteosat-7 AMVs and CSRs or FY-2E AMVs are assimilated, with a slight advantage for the Meteosat-7 data. It is therefore clear that maintaining the Indian Ocean coverage is important. An impact assessment of the INSAT-3D AMVs has not been done yet, but will be considered in the near future.

4 Situation dependent observation errors with default values

The use of AMVs in the ECMWF system has been revised (Salonen and Bormann, 2013b). The aim of the changes is to ensure effective and realistic use of AMVs in data assimilation in order to improve their impact on model analyses and forecasts. The main amendment is the introduction of situation dependent observation errors. This is done to ensure that the errors assigned in the data assimilation better account for height assignment errors of the observations. The use of situation dependent observation errors allowed also notable simplifications to the AMV quality control. The modifications are included in the ECMWF IFS cycle 40r1 which became operational in November 2013.

One of the core activities at ECMWF is to produce reanalyses which aim to provide the best estimate of the state of the atmosphere over several decades. This is achieved by using the same state-of-the-art NWP system for the entire period and by using improved versions of the available observational datasets. Several satellite agencies have recently made available reprocessed AMVs for reanalyses purposes.

In the operational ECMWF system the height and tracking error estimates are defined for all satellites, channels and height assignment methods and they vary with height. The error estimates are updated every time when a new satellite is introduced to the system or when AMV providers make changes in their processing. Estimating the height and tracking errors for all historical AMVs would be an extensive effort. Thus, the impact of using default error values for height assignment and tracking errors instead of the more tailored error estimates has been investigated.

In the operational system default values of 80 hPa for the height error and 2.5 ms^{-1} for the tracking error are used in case the tailored values do not exist. These values can be thought to be on average valid for AMVs but obviously in some cases they are underestimating and in some cases overestimating the errors. To study the impact of using the default values instead of tailored error estimates two two-month long experiments covering a summer period 1.7-31.8.2013 have been performed. The ECMWF IFS cycle 40r1 at T511 resolution, 137 vertical levels and 12-hour 4D-Var has been applied in the experiments. The control experiment (**Ctl**) uses the operationally used height and tracking errors for AMVs while the second experiment (**Default**) uses the default height and tracking error values for all AMVs. In both experiments all operationally assimilated conventional and satellite observations are used.

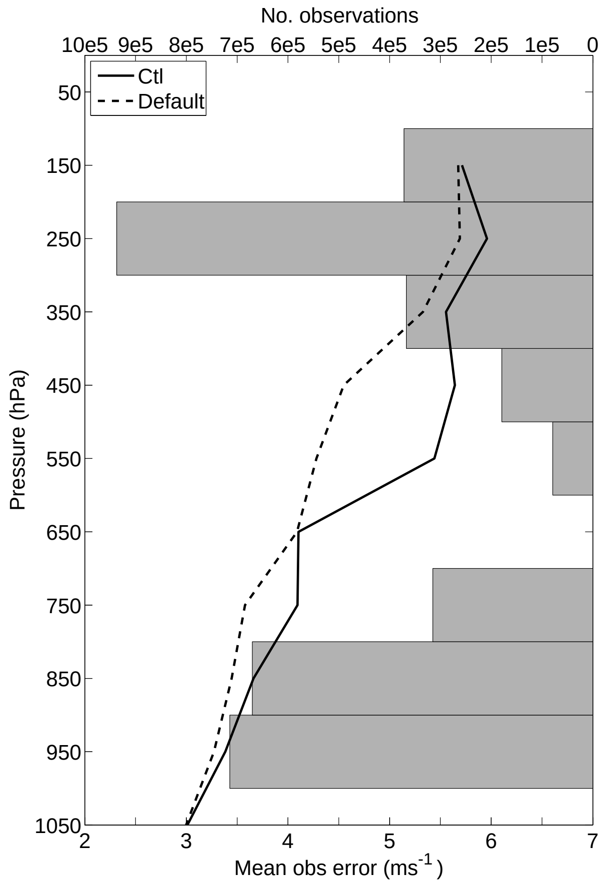

Figure 20: Average observation errors for Meteosat-10 AMVs at different heights. The solid line indicates the **Ctl** *experiment with the tailored height and tracking errors and the dashed line the* **Default** *experiment applying the default error values. The grey bars show the number of observations for the* **Ctl** *experiment.*

Generally, the resulting observation errors for wind components u and v are on average somewhat lower when the default values are applied for the height assignment and tracking errors instead of the tailored error estimates. Figure 20 shows the average observation errors for Meteosat-10 AMVs at different heights as an example. The solid line indicates the **Ctl** experiment with the tailored height and tracking errors and the dashed line the **Default** experiment applying the default error values. The largest differences between the average observation errors are seen at mid levels, where the default value of 80 hPa is an underestimate of the uncertainty in height assignment. However, most of the AMVs originate from high and low levels where the differences in the average observation errors are not very drastic.

The model first guess check compares observations to their model counterparts. If the observation differs from the model counterpart more than a predefined limit, it will be rejected. The first guess check rejections are dependent on the magnitude of the observation and background errors. Due to somewhat higher observation errors in the **Ctl** experiment more AMVs pass the first guess check and are used in the model analyses. Figure 21 shows the change in the number of observations (left) and the actual number of observations (right). In the **Default** experiment 90% - close to 100% observations are used compared to the **Ctl** experiment. The difference is smallest over the northern hemisphere.

To investigate the impact of using the default error values on the short term forecasts, figure 22 shows the normalised change in the OmA (left panel) and OmB (right panel) standard deviation calculated against ra-

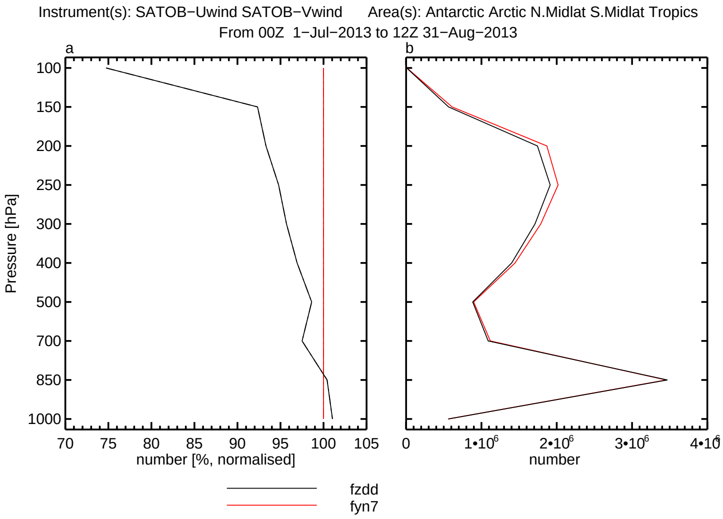

Figure 21: The change in the number of observations compared to **Ctl** *experiment (left) and the actual number of observations (right). Black line indicates the* **Default** *experiment and red line the* **Ctl** *experiment.*

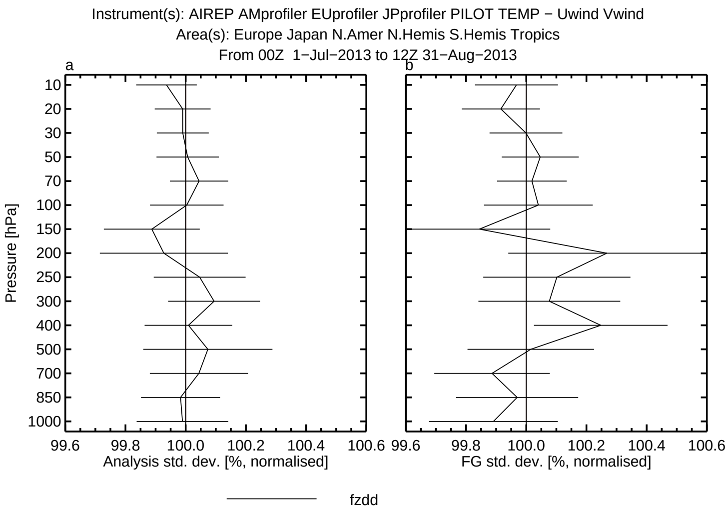

Figure 22: The normalised change in the OmA (left panel) and OmB (right panel) standard deviation calculated against radiosondes, pilot, aircraft and wind profiler observations. The horizontal bars indicate 90% confidence range.

diosondes, pilot, aircraft and wind profiler observations. The horizontal bars indicate the 90% confidence range. The changes both in the OmB and OmA statistics are mainly statistically insignificant. However, between 400 and 200 hPa the OmB statistics show negative impact and for the southern hemisphere (not shown separately) the impact is also statistically significant. This indicates that the other wind observations fit slightly worse the model first guess when the default values for the height assignment and tracking errors are used.

Figure 23 shows the zonal plots of the normalised difference (**Default** - **Ctl**) of the RMS wind error for 24-hour and 48-hour forecast lengths. The impact of using the default values for the height assignment and tracking errors is neutral compared to using the tailored values.

Based on the results it can be concluded that using the default height assignment and tracking error values

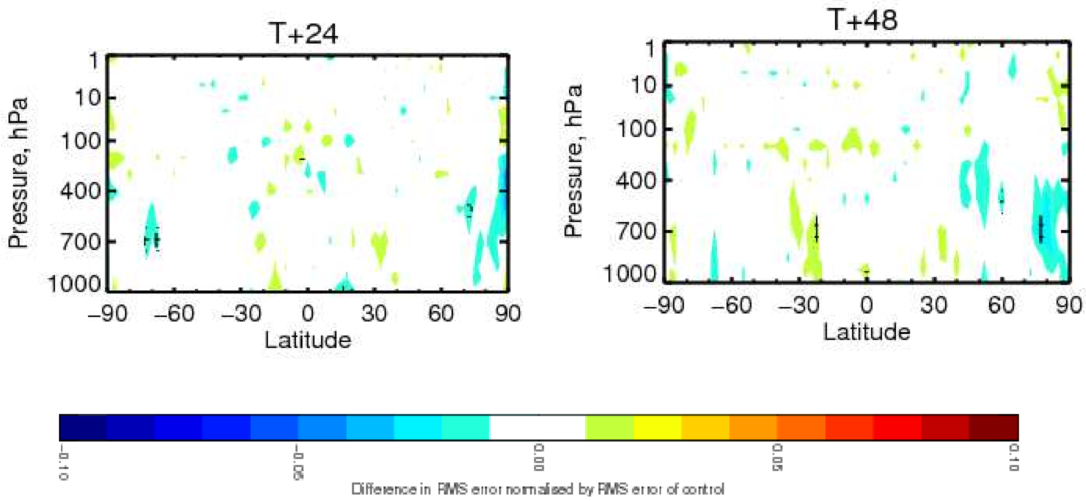

*Figure 23: Zonal plots of the normalised difference (**Default** - **Ctl**) of the RMS wind error for 24-hour and 48-hour forecasts. Blue shades indicate positive impact from using the default error values and red shades negative impact. The cross-hatching indicates statistical significance at 95%. The considered period is 1st July - 31st August 2013.*

in the reanalyses framework for AMVs prior to the situation dependent observation errors were implemented to the operational ECMWF system is an acceptable compromise. Salonen and Bormann (2013b) have shown clear improvements in the forecast quality from using the situation dependent observation errors and the revised quality control. Most of these benefits can be expected to be gained also by using the default error estimates as the comparison between **Default** and **Ctl** experiments shows mainly neutral impact. A caveat of using the default values is that today's quality of the height assignment is assumed.

5 Status update for the work on alternative interpretations of AMVs

The traditional interpretation of an AMV is a single-level point estimate of wind at the assigned height. Recent studies (e.g. Hernandez-Carrascal and Bormann, 2014; Folger and Weissmann, 2014; Weissmann et al., 2013; Velden and Bedka, 2009) indicate some benefits from interpreting AMVs as layer averages, or as single-level wind estimates but for a level within the cloud instead of the cloud-top or cloud base.

In Salonen and Bormann (2013a) preliminary results on investigating alternative interpretations of AMVs in the ECMWF system were discussed. The impact of applying a layer-averaging observation operator on the innovation statistics indicated some benefits from using a layer averaging observation operator compared to the single-level observation operator. Centred averaging around the assigned height gives generally best results in situations where the best-fit pressure statistics indicate little bias in the AMV height assignment, with benefits of 5-10 % in terms of the RMSVD. Averaging below the assigned AMV height shows significant improvements when the best-fit pressure statistics indicate that the assigned AMV height is, on average, too high in the atmosphere, with reductions of up to 30% in the RMSVD.

The investigations have been continued by performing a set of data assimilation experiments and the results are reported here. Observation operators under consideration include the traditional single-level observation operator, boxcar layer averaging centred at the AMV height and below the AMV height. Also, re-assigning the AMV height based on model best-fit pressure statistics is considered.

The model best-fit pressure statistics give valuable information about the height assignment error characteristics for AMVs (Salonen et al., 2015). Best-fit pressure statistics have been successfully applied to define realistic observation errors for AMVs by estimating the uncertainty in the height assignment (Forsythe and Saunders, 2008; Salonen and Bormann, 2013b). Here, the best-fit pressure statistics are used to estimate systematic height assignment errors. The main advantage of the best-fit pressure is that it can be defined for each AMV observation. Thus, systematic height errors can be easily investigated for each satellite, channel and height assignment method, at all locations where AMVs are available. Comparison of the best-fit pressure statistics from Met Office and ECMWF systems have shown that the statistics are very similar for the two systems. Currently there is ongoing work to compare the best-fit pressure bias statistics with lidar height corrections (Folger and Weissmann, 2014) in co-operation with Hans-Ertel-Centre for Weather Research. The aim is to investigate similarities and explain differences in the results from the two approaches to estimate systematic AMV height assignment errors.

As a first trial to take into account the systematic height biases for AMVs in data assimilation, the height errors have been estimated separately for all satellites, channels and height assignment methods at different pressure levels but there is no separation by geographical regions. Figure 24 shows the bias estimates as an example for Meteosat-10 AMVs utilising Cross Correlation Contribution (CCC) height assignment and for GOES-15 and MTSAT-2 AMVs with equivalent black-body temperature (EBBT) height assignment. Typically the bias varies between ± 50 hPa.

The bias information is used to re-assign the AMVs to more representative level: each AMV height is re-assigned based on the bias statistics before calculating the model counterpart for the observation. The systematic height errors are estimated for 200 hPa deep layers. This is a practical choice for the first trial as the height error estimates used for the situation dependent observation errors are defined in a similar way.

Data assimilation experiments have been performed with ECMWF IFS cycle 40r1 at a T511 resolution, 137 levels, and 12-hour 4D-Var. The experiments cover 1st December 2013 - 28th February 2014. All operationally used conventional and satellite observations have been used. Results from the following experiments are considered:

- **Control**: Single-level observation operator with AMVs at originally assigned height
- **Exp 1**: Single-level observation operator with AMV height re-assignment

In addition, two experiments use a layer averaging observation operator at the original height:

- **Exp 2**: Boxcar centred averaging 120 hPa
- **Exp 3**: Boxcar averaging 40 hPa below

The most promising results are seen for the **Exp 1** where a traditional single-level observation operator is used together with the height re-assignment. Figure 25 shows the normalised change in the standard deviation of background differences for radiosonde, pilot, aircraft and wind profiler observations. The observation fit is improved at almost all levels indicating that the observations agree better with the model first guess.

Figure 26 shows the normalised difference in vector wind RMS error for 48-hour forecasts for **Exp 1** (upper panel), **Exp 2** (middle panel) and **Exp 3** (lower panel). The verification has been done against each experiment's own analysis. In general, taking into account the systematic height errors for AMVs has a positive impact on the forecasts, especially in the tropics. The experimentation with layer averaging gives more mixed results. For both experiments using the layer averaging observation operator a statistically significant negative impact is seen between 30°S and 30°N above 400 hPa. Figure 27 shows the zonal plots of OmB wind speed bias for the **Control** (upper panel), **Exp 1** (middle panel) and **Exp 2** (lower panel). Generally there is a positive speed bias in the tropics at mid and high levels, i.e. the observed wind is on average stronger than the model counterpart. Using the layer averaging observation operator increases the magnitude of this bias. The Met Office has seen similar issues in their preliminary work (Mary Forsythe, personal communication). For **Exp 2** where layer averaging is done 40 hPa below the assigned AMV pressure indications of positive impact are seen at low levels (Fig. 26). Single observation experiments have confirmed that averaging below the assigned AMV pressure shifts the maximum analysis increment downwards and thus has an effect similar to re-assigning the AMV pressure lower in the atmosphere than the assigned pressure.

It can be concluded that the results from the first experiments indicate clear benefits from taking into account the systematic height errors. The impact of using layer averaging observation operator is more mixed. Further investigations are ongoing.

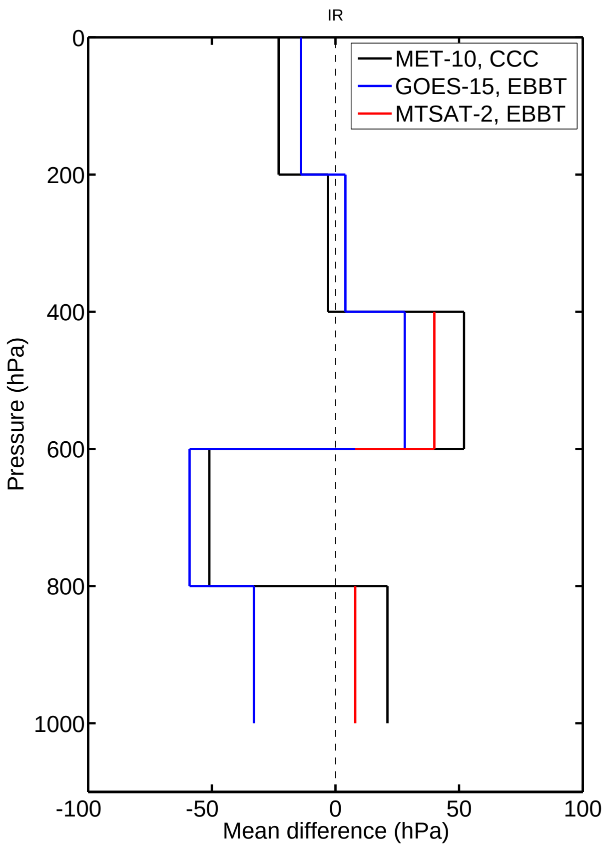

Figure 24: Mean difference of assigned AMV pressure minus model best-fit pressure at different pressure levels for Meteosat-10 AMVs utilising Cross Correlation Contribution (CCC) height assignment (black line) and for GOES-15 (blue line) and MTSAT-2 (red line) AMVs with equivalent black-body temperature (EBBT) height assignment.

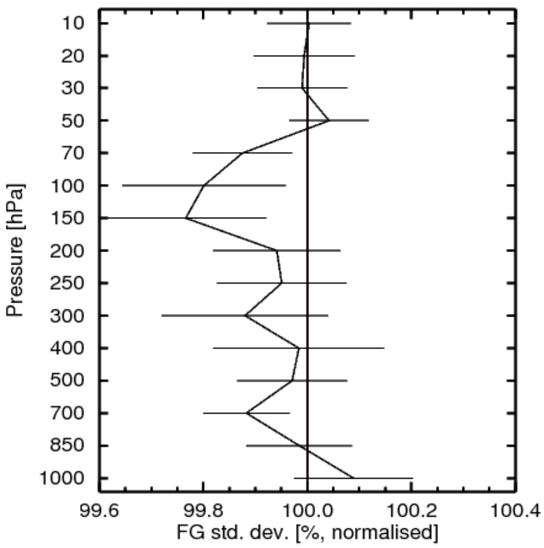

Figure 25: The normalised change in the standard deviation of observation minus background differences for radiosonde, pilot, aircraft and wind profiler observations for experiment **Exp 1** *applying the single-level observation operator with AMV height re-assignment. Reference is the* **Control** *experiment.*

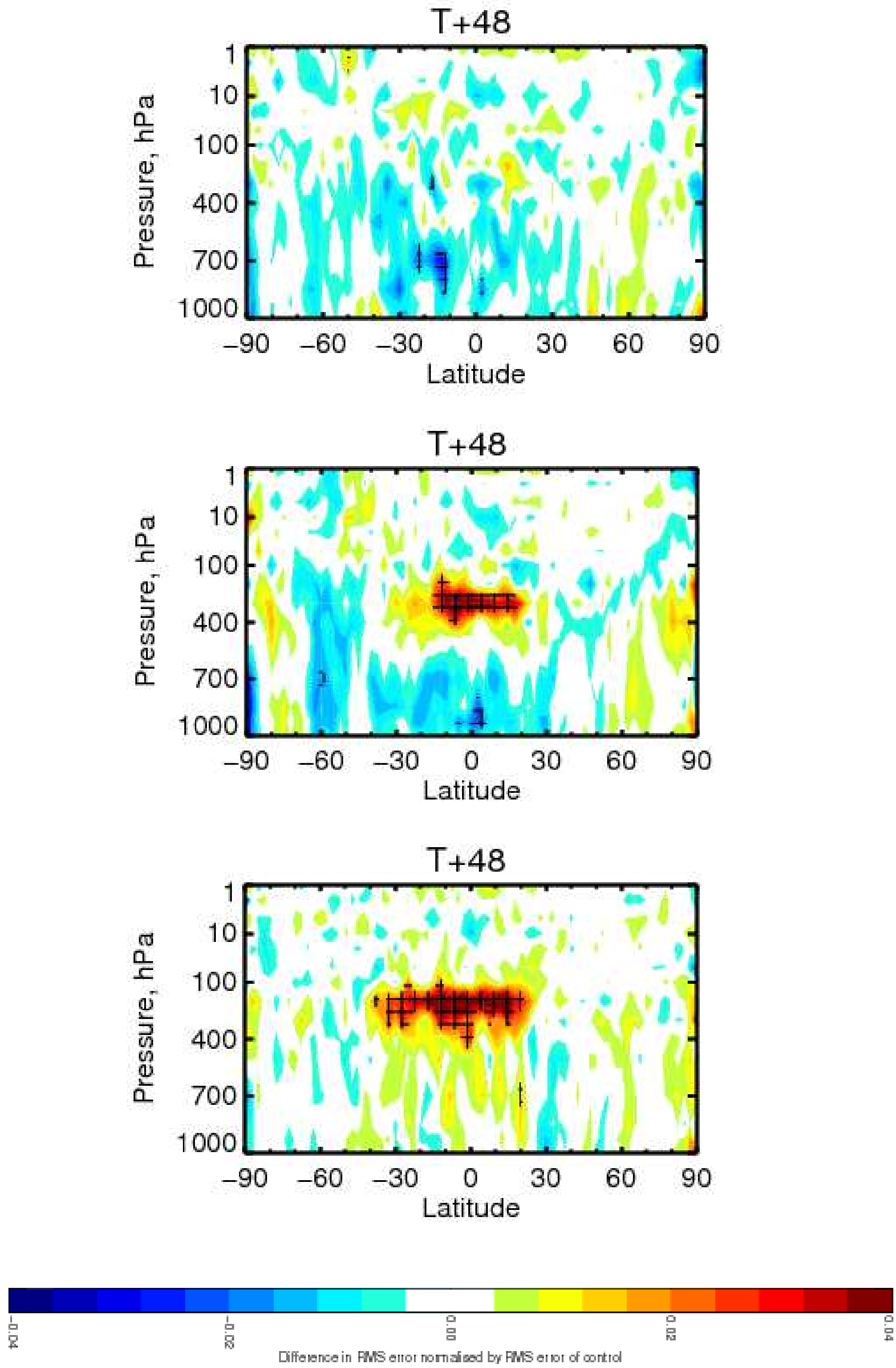

Figure 26: Zonal plots of the normalised difference (experiment minus control) of the RMS wind error for the 48-hour forecasts for the experiment applying the single-level observation operator with AMV height re-assignment (left panel), 40 hPa bocxcar averaging below the assigned height (middle panel) and 120 hPa centred averaging (right panel). The control experiment uses the traditional single-level observation operator. The considered period is 1st December 2013 - 28th February 2014.

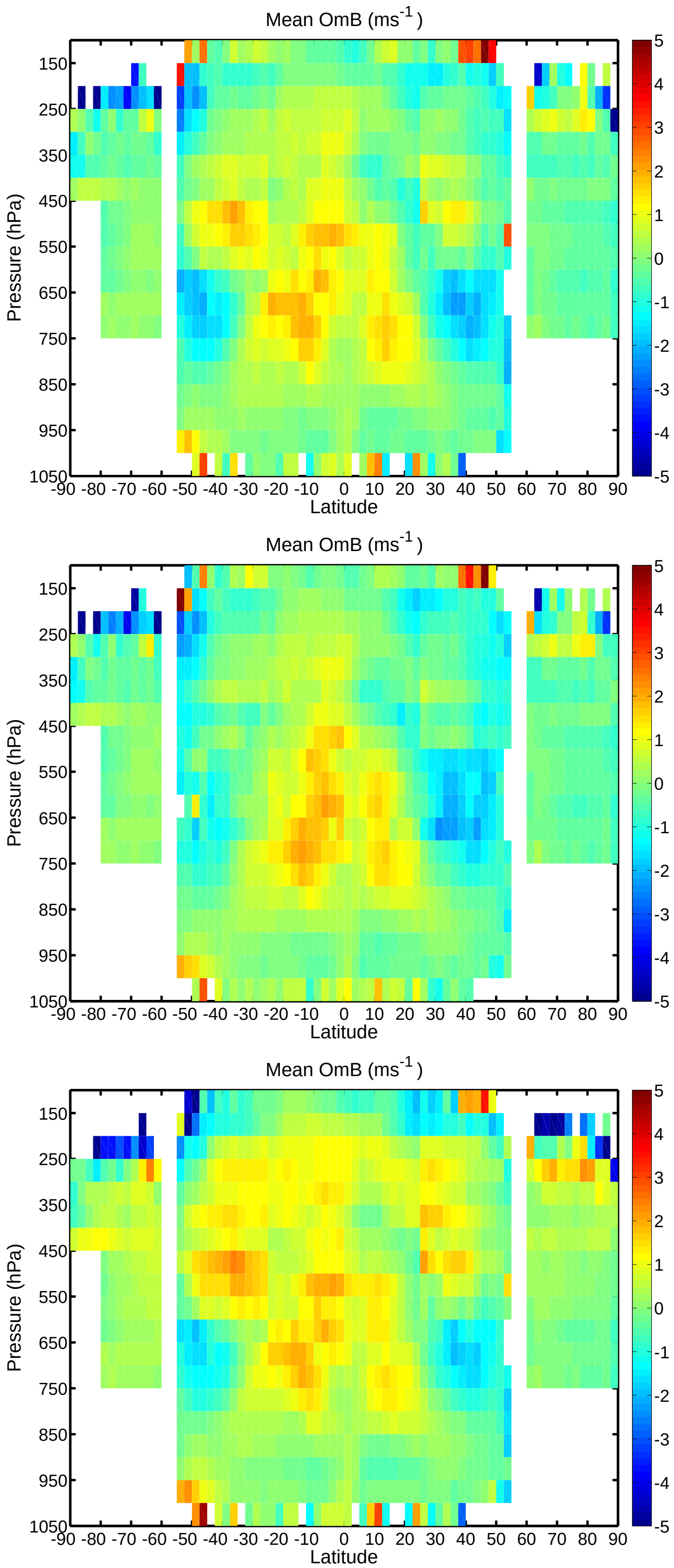

Figure 27: Zonal plots of the OmB bias for the **Control** *(upper panel),* **Exp 1** *(middle panel) and* **Exp 3** *(lower panel) experiments. The considered period is 1st December 2013 - 28th February 2014.*

Acknowledgements

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