EUMETSAT/ECMWF Fellowship Programme
Research Report No. 32

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

K. Salonen and N. Bormann

November 2013

Series: EUMETSAT/ECMWF Fellowship Programme Research Reports

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

Contents

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 five polar orbiting (Aqua, NOAA-15, NOAA-16, NOAA-18, NOAA-19) satellites. In addition, AMVs from five other satellites (FY-2D, FY-2E, Terra, METOP-A, METOP-B) are currently passively monitored. Table 1 summarises the monitored and used AMVs. The main results from research work and the changes in the operational use of the AMVs in the ECMWF system during 2013 are discussed in this report.

The work on situation dependent observation errors and revising the quality control has reached maturity for operational implementation. The changes are included to the ECMWF integrated forecasting system (IFS) cycle 40r1 which has been the operational ECMWF system since 19th November 2013. 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. A summary of the changes is presented in Section 2.

For situation dependent observation errors, the height errors have been estimated based on model best-fit pressure statistics. The benefit of the model best-fit pressure is that under certain constraints it allows to estimate uncertainties in the height assignment everywhere where AMVs are available. The model best-fit pressure includes contributions from the errors in the model background wind field. The impact of these errors has been estimated based on ensemble of data assimilations (EDA) experiment, and the results are discussed in Section 3.

The operational changes include changeover from Meteosat-9 to Meteosat-10. The parallel monitoring period covered nearly three months. The monitoring statistics were very similar for both satellites and the changeover in the operational system was done without further experimentation. A short summary of the monitoring is presented in Section 4.

EUMETSAT changed their AMV processing in September 2012. The introduction of the Cross-Correlation Contribution (CCC) method improved the AMV quality at high and mid levels but some degradation was seen for low level IR and VIS AMVs. After further investigations, EUMETSAT re-introduced the pre-CCC inversion correction to improve the quality of the low level AMVs. Section 5 discusses

Table 1: Overview of the use of AMV data in the ECMWF system in November 2013.

	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 (31 October - 19 December 2013 replaced by MTSAT-1R)	used	used	monitored	used
CMA FY-2D	monitored	monitored	monitored	-
CMA FY-2E	monitored	monitored	monitored	-
MODIS AMVs from Aqua	used	used	used	-
MODIS AMVs from Terra	monitored	monitored	monitored	-
AVHRR AMVs from NOAA-15, -16, -18 and -19	used	-	-	-
AVHRR AMVs from METOP-A and METOP-B	monitored	-	-	-

briefly the experimentation with the Meteosat-10 AMVs after the fix.

NESDIS is going to disseminate hourly AMVs from GOES-13 and GOES-15 satellites in the near future. Currently 3-hourly AMVs are disseminated. The hourly wind product contains also some algorithm improvements related to low level winds. The ECMWF system is prepared for the change. Experimentation with the hourly winds is discussed in Section 6. The results indicate improved AMV quality at mid and low levels which leads to some positive impacts over using the current operational GOES AMVs particularly over the tropical east Pacific where mixed impacts of AMVs were previously observed. However, using the new data 3-hourly instead of hourly seems to be more beneficial in the current ECMWF system.

The status of the use of polar AMVs in the ECMWF system is discussed in Section 7. Activation of the AVHRR AMVs from NOAA satellites has increased the use of polar winds by ca. 75% in the ECMWF system. Experimentation with the AVHRR and MODIS AMVs reveals that the positive impact obtained by using AVHRR AMVs alone is rather similar to that from the use of MODIS AMVs. This is encouraging as at some point the AVHRR AMVs will be the main source of polar AMVs. METOP-A and METOP-B AMVs are currently monitored in the ECMWF system. The monitoring statistics show some improvements in the high level AMV quality after the latest improvements in the EUMETSAT polar AMV processing. Further investigations are ongoing.

Work on alternative interpretations of AMVs is also ongoing. A typical interpretation for an AMV is a single-level point estimate of wind at the assigned height. Comparison to radiosonde and lidar observations as well as investigations in a simulation framework indicate some benefits from interpreting AMVs as layer averages, or as single-level wind estimates but within the cloud instead of cloud-top or cloud base which are typically assumed to be representative heights for high and mid level clouds and for low level clouds, respectively. The status of the work is presented in section 8.

Finally, in Section 9 some additional ongoing activities are shortly listed.

2 General revision of the AMV usage

The use of AMVs in the ECMWF system has been revised. 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 a notable simplifications to the AMV quality control. The modifications are operational in the ECMWF IFS cycle 40r1. In the following a summary of the changes is given, more details can be found from Salonen and Bormann (2013).

2.1 Situation dependent observation errors and revised quality control

Errors in AMVs originate mainly from two sources. Namely, errors in the height assignment and errors in the wind vector tracking. The impact of errors in height assignment is highly situation dependent. It can be very significant in areas where wind shear is strong but on the other hand it is less relevant in areas where there is not much variation in wind speed with height. Forsythe and Saunders (2008a) have introduced an approach to estimate situation dependent observation errors for AMVs and this method has been investigated in the ECMWF system.

In practice, the observation errors are estimated in two parts. In the ECMWF system the height errors have been estimated based on model best-fit pressure statistics. Model best-fit pressure is the height where the observed wind agrees best with the model wind. The height errors have been estimated separately for all satellites, channels and height assignment methods. Comparison of the best-fit pressure statistics with Met Office has shown that the statistics are very similar for both systems and it was concluded that the best-fit pressure can be considered as a reliable method to estimate the height errors (Salonen et al., 2012b). Typically the height error estimates vary from around 70 hPa at high levels to 100 - 120 hPa at mid and low levels over areas where AMVs are operationally used. The height error is converted to wind error following the Forsythe and Saunders (2008a) approach.

The tracking errors have been estimated from observation minus background (OmB) statistics from cases where the wind error due to error in height assignment is small. The tracking errors have been estimated separately for geostationary and for polar winds and they vary from 2 to 3.2 ms^{-1} depending on height. Finally, the error due to error in the height assignment and the tracking error are combined to form a highly situation dependent observation error for each AMV.

Introduction of the situation dependent observation errors gives an opportunity to re-evaluate also the quality control for AMVs. The quality control consists of blacklisting where observations are rejected based on information from long-term monitoring of the quality of the data. This part of the quality control process has not been modified at this point. The second quality control step is to compare the observation to the model counterpart and if the observation deviates more than a predefined limit the observation will be rejected. Traditionally the first guess check has been very strict for AMVs. For example if the observed wind has been slower than the model wind the observation has been rejected more easily. This feature has been implemented to avoid that AMVs slow down extra tropical jets. The situation dependent observation errors allow a reduction in the weight given to observations where wind shear is strong, and the error in height assignment can have a drastic impact such as the extra tropical jets. The revised first guess check is symmetric and the same rejection limits are applied everywhere. It allows more observations to enter the model analysis. Depending on height and location up to 10%, and on average 4%, more observations are accepted in the revised first guess check.

A new quality control criterion has been investigated as well. The criterion limits the magnitude of the observation error due to error in height assignment to be smaller than four times the tracking error. The value four is based on trial and error. The new quality control criterion is motivated by the fact that the height assignment errors are likely to be more correlated spatially and such correlations are currently neglected in assimilations. The criterion rejects on average 1% of the AMVs on top of the revised first guess check.

2.2 Impact assessment

The impact of using the situation dependent AMV observation errors and the revised quality control described above has been investigated for two 3-month periods. The winter period covers 1st January to 31st March 2012, and the summer period 1st June to 31st August 2012. The ECMWF IFS cycle 38r2 at a T511 resolution, 137 levels, and 12-hour 4D-Var has been applied in the experiments. All operationally assimilated conventional and satellite observations are used. In the control experiments AMVs are treated as in the operational system prior to the IFS cycle 40r1, and in the test experiments the revised system is used.

The revised assimilation of AMVs leads to a significant positive forecast impact below 500 hPa especially in the tropics but also at higher latitudes. Figure 1 shows zonal plots of the normalised difference

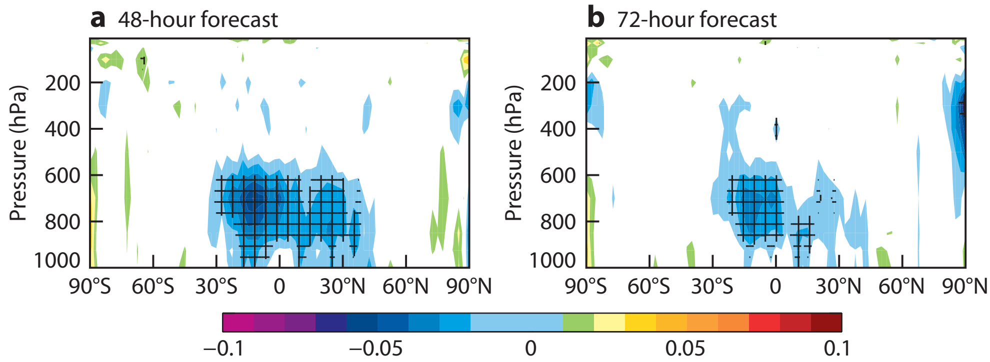


Figure 1: Zonal plot of the normalized difference (test experiment - control) in RMS error for 48-hour (left) and 72-hour (right) wind forecasts. Verification is done against each experiments own analysis. The period is 1.6 31.8.2012.

in the RMS error for 48- and 72-hour wind forecasts for the summer period. The difference is calculated as test experiment minus the control experiment, i.e blue shades indicate positive impact and green and red shades negative impact. The verification has been done against each experiments own analysis. The results are similar for the winter period. Verification against observations also shows positive impact especially over the northern hemisphere extra-tropics (not shown). Overall the use of the situation dependent observation errors and the revised first guess check clearly improves the use of AMVs in the ECMWF system with a positive impact on the model forecasts.

3 Impact of short-term forecast errors on the best-fit pressure statistics

In the context of the situation dependent observation errors, the height errors have been estimated based on the best-fit pressure statistics as described in Section 2 and in more details in Salonen et al. (2012). The model best-fit pressure allows us to study the uncertainties in the AMV height assignment comprehensively in space and in time. However, care must be taken when the results are interpreted. It is not always possible to define an unambiguous best-fit pressure, and the model best-fit pressure includes also contributions from the errors in the model background wind field, i.e. in the short-term forecast.

The impact of short-term forecast errors on the best-fit pressure statistics has been estimated based on a 25 member ensemble of data assimilations (EDA; Bonavita et al., 2012) experiment performed with the ECMWF IFS cycle 38r2 at a T511 resolution, 91 levels, and 12-hour 4D-Var. In an EDA experiment an ensemble of independent 4D-Var data assimilations is performed. The main analysis error sources are represented by perturbing observations, the forecast model and sea surface temperature according to their estimated accuracy. The performed EDA experiment provides 26 estimates, including the control run, of the best-fit pressure for each AMV. In the operational ECMWF system an EDA is used to estimate background errors, based on the spread of the ensemble.

Figure 2 shows the mean standard deviation of the best-fit pressure estimates resulting from the spread of the enseble as a function of pressure for the southern hemisphere extratropics (left panel), tropics (middle panel), and northern hemisphere extratropics (right panel). The grey bars indicate the number of cases at each level. The spread of the best-fit pressures is of the order of 15 hPa throughout the troposphere. Calibration of the EDA suggests that it is usually underdispersive in the extratropics typically by a factor of 1.5-2. This suggests that the uncertainty in the best-fit pressure due to errors in the short-term forecasts

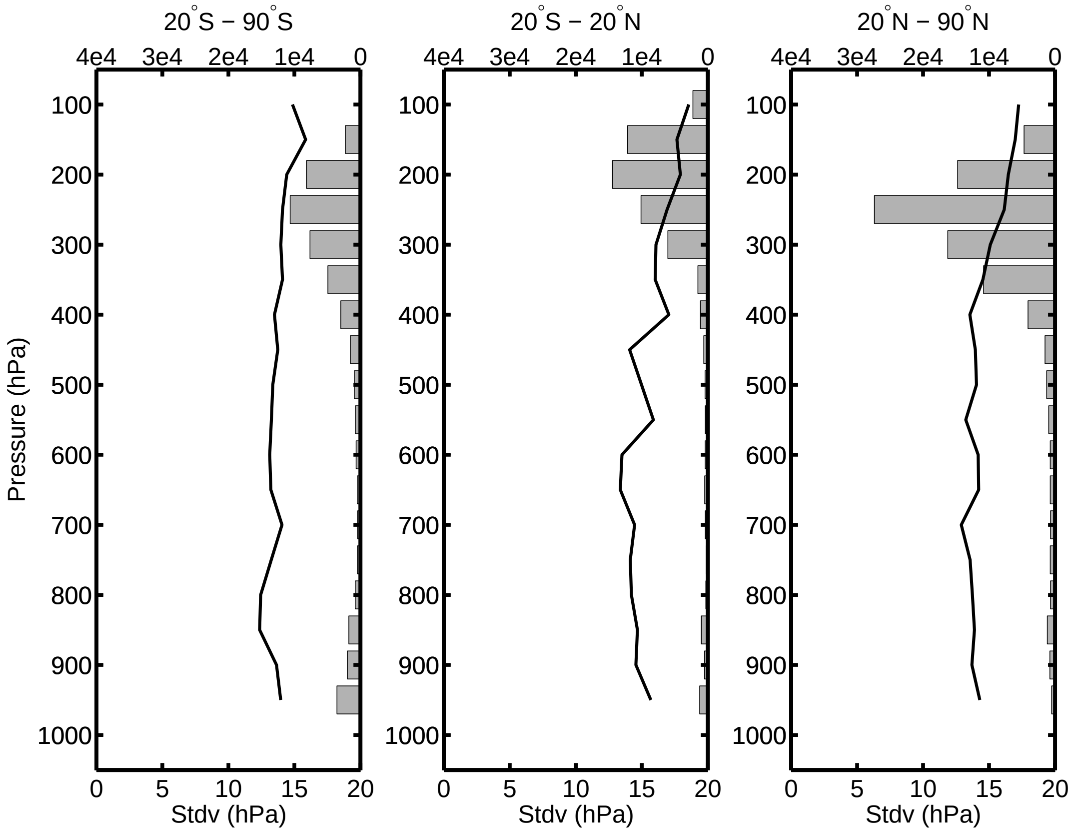


Figure 2: The mean standard deviation of the best-fit pressure estimates from the 25 member EDA experiment as a function of pressure for the southern hemisphere extratropics (left panel), tropics (middle panel), and northern hemisphere extratropics (right panel). The grey bars indicate the number of cases at each level.

is of the order of 20-30 hPa. A typical value for standard deviation of the assigned observation height and best-fit pressure difference is around 70 hPa at high levels, increasing to 100 - 120 hPa or slightly larger at mid and low levels over areas where AMVs are operationally used in NWP.

4 Changeover from Meteosat-9 to Meteosat-10

Parallel monitoring of Meteosat-10 AMVs began at ECMWF on 30th October 2012, while the Meteosat-9 AMVs were used actively in the operational system. Monitoring statistics for observation minus model background (OmB) bias and root mean square vector difference (RMSVD) indicated that Meteosat-9 and Meteosat-10 AMVs were generally consistent with each other.

Figure 3 shows the timeseries for OmB bias (upper panel), RMSVD (middle panel), and the number of observations (lower panel) for WV 7.3μm AMVs at high levels in the tropics as an example of the results. The black line indicates Meteosat-9 AMVs and the red line Meteosat-10 AMVs respectively. Some small differences were seen for high level IR AMVs in the Southern hemisphere midlatitudes where the negative bias was slightly smaller for the Meteosat-10 AMVs (not shown). For mid and low level AMVs the statistics were very similar for both satellites.

Based on the monitoring statistics it was decided to switch Meteosat-9 AMVs to Meteosat-10 AMVs in

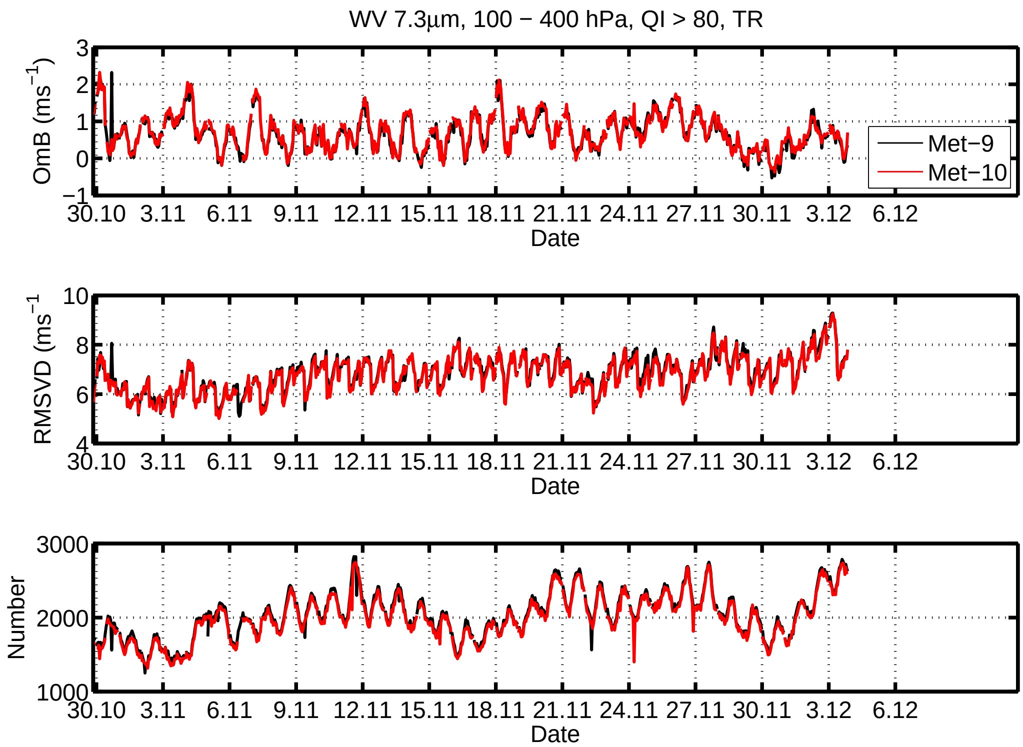


Figure 3: Timeseries of the OmB bias (upper panel), RMSVD (middle panel), and number of observations (lower panel) for WV 7.3 µm Meteosat-9 (black), and Meteosat-10 (red) AMVs in the tropics between 100 and 400 hPa. The considered time period is 30st October - 3rd December 2012.

the ECMWF system on 24 January 2013 without further experimentation.

5 Meteosat-10 low level AMVs

EUMETSAT upgraded their AMV processing algorithm to use the Cross-Correlation Contribution (CCC) method on 5th September 2012. The new data were tested in the ECMWF system and the results are reported in Salonen and Bormann (2012). The quality of the high and mid level AMVs was clearly improved but for low level IR and VIS AMVs the quality was somewhat degraded when compared to the model background. The investigations showed that with the pre-CCC algorithm the low level AMVs were in general assigned to lower heights than with the CCC algorithm.

The changes in the low level AMV heights mainly appear in regions where the atmospheric temperature profile has an inversion (Doutriaux Boucher and Carranza, 2013). In the pre-CCC algorithm, an inversion correction was applied over these areas. The CCC algorithm uses direct outputs from the EUMETSAT Cloud Analysis (CLA) product to get the height of the individual selected pixels. The CLA applies an inversion correction, and to avoid double correction it was originally decided not to do the inversion correction in the CCC algorithm. However, the way the inversion correction is applied differs between CLA and pre-CCC algorithms, and the differences explain why the AMVs are assigned to lower levels with the pre-CCC than with the CCC algorithm.

On 16th April 2013 EUMETSAT re-introduced the pre-CCC inversion correction as a solution to the

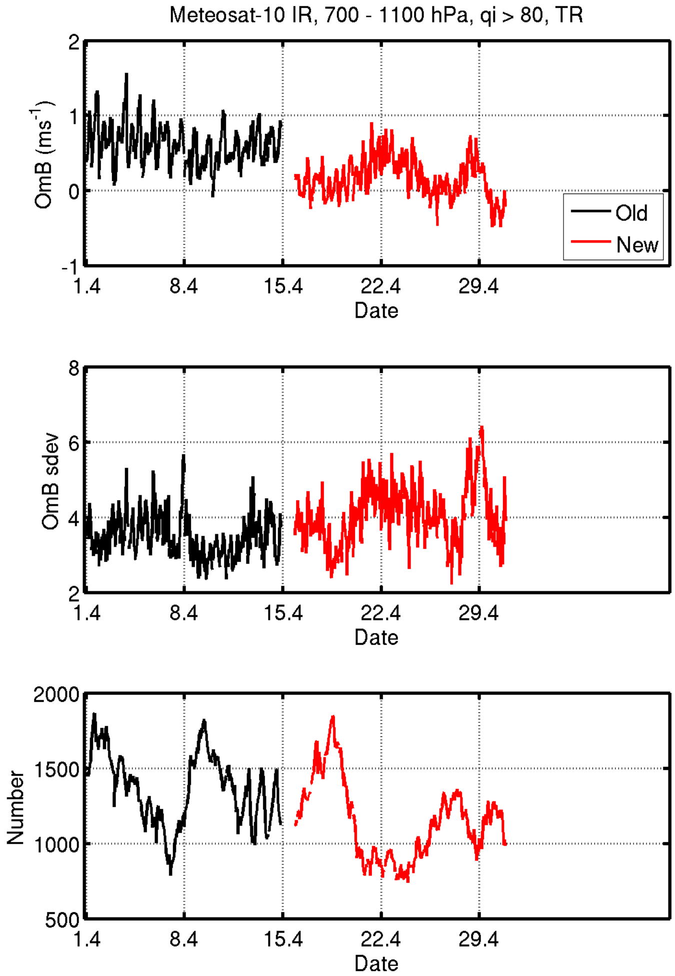


Figure 4: Timeseries of the OmB bias (upper panel), RMSVD (middle panel), and number of observations (lower panel) for IR Meteosat-10 AMVs before the low level fix (black), and and after the low level fix (red) in the tropics between 700 and 1100 hPa. The considered time period is April 2013.

degraded low level IR and VIS AMV quality. After the fix, an averaged equivalent black body temperature (EBBT) is computed for the pixels selected by the CCC algorithm if an atmospheric temperature inversion occurs in the forecast background profile. In the case where the calculated EBBT temperature is warmer than the forecast temperature at the base of the inversion, the assigned height for the AMV will be the level of best agreement between the EBBT temperature and the forecast temperature. If the EBBT temperature is colder than the forecast temperature at the base of the inversion, the assigned AMV height will be the height of the base of the inversion (Doutriaux Boucher and Carranza, 2013).

Figure 4 shows the timeseries for OmB bias (upper panel), OmB standard deviation (middle panel), and the number of observations (lower panel) for low level IR AMVs in the tropics during April 2013. After the re-introduction of the inversion correction there is a clear drop in the magnitude of the OmB bias. In the extra tropics the time series show similar statistics before and after the change (not shown).

5.1 Impact assessment

When the CCC method was introduced, Meteosat-9 low level IR and VIS AMVs were blacklisted in the ECMWF system. To investigate what is the impact of the low level AMVs on model analysis and forecasts after the inversion correction has been re-introduced two sets of data assimilation experiments have been performed over a four-month long period 17.4-16.8.2013. In the first pair, the ECMWF IFS cycle 38r2 at a T511 resolution, 137 vertical levels, and 12-hour 4D-Var has been applied in the experiments. In the second pair the IFS cycle 38r2 but with situation dependent observation errors and a revised quality control for AMVs have been used, for details see Section 2. All operationally assimilated conventional and satellite observations are used. The experiment pairs are:

- **Control**: Low level Meteosat-10 AMVs not used
- **Experiment**: Low level Meteosat-10 AMVs used

In the following we focus on the experiment pair with situation dependent observation errors and the revised quality control. Figure 5 shows the normalised change in the OmB and observation minus analysis (OmA) standard deviation calculated against radiosondes, pilot, aircraft and wind profiler observations in the tropics. The reference is the control run where low level Meteosat-10 AMVs are not used. Thus, values below 100% indicate improvements in the observation fit statistics while values above 100% indicate degradation. The horizontal bars indicate 90% confidence range. At 700 hPa level and below some improvements in the OmB statistics can be seen. This indicates that the other wind observations fit better the model first guess when the low level AMVs are used. However, the improvements are not statistically significant within the 90% confidence range. In the experiment pair where the situation dependent observation errors are not used, the results are more neutral (not shown).

Scatterometer winds allow an independent cross-validation of the changes to the mean wind analysis at low levels over sea. First guess departures for the scatterometer winds indicate that over the Meteosat-10 coverage area there are areas where the magnitude of the first guess departures has decreased but also areas where the magnitude has increased when the low level AMVs are used. On average the impact is neutral. This is the case in both experiment pairs.

Verification against each experiment's own analysis indicate also rather neutral impact. Figure 6 shows a map of the normalised RMS difference between the experiment and the control for 48-hour wind forecast at 850 hPa level. Blue shades indicate positive impact and green and red shades negative impact from using the low level IR and VIS AMVs. When all forecast lengths are considered, the impact over the tropics is on average neutral to slightly positive when the situation dependent observation errors and revised quality contol are used. For the clean 38r2 experiment pair the impact is neutral to slightly negative.

Based on the results it can be concluded that there is no reason to blacklist the low level IR and VIS AMVs, and their use has mainly a neutral impact on model analyses and forecasts. The Meteosat-10 low level AMVs are currently active in the ECMWF system.

6 Experimentation with GOES hourly AMVs

NESDIS is making preparations to disseminate hourly AMVs from GOES-13 and GOES-15 satellites. Currently 3-hourly AMVs are disseminated. The new hourly GOES wind product contains an additional

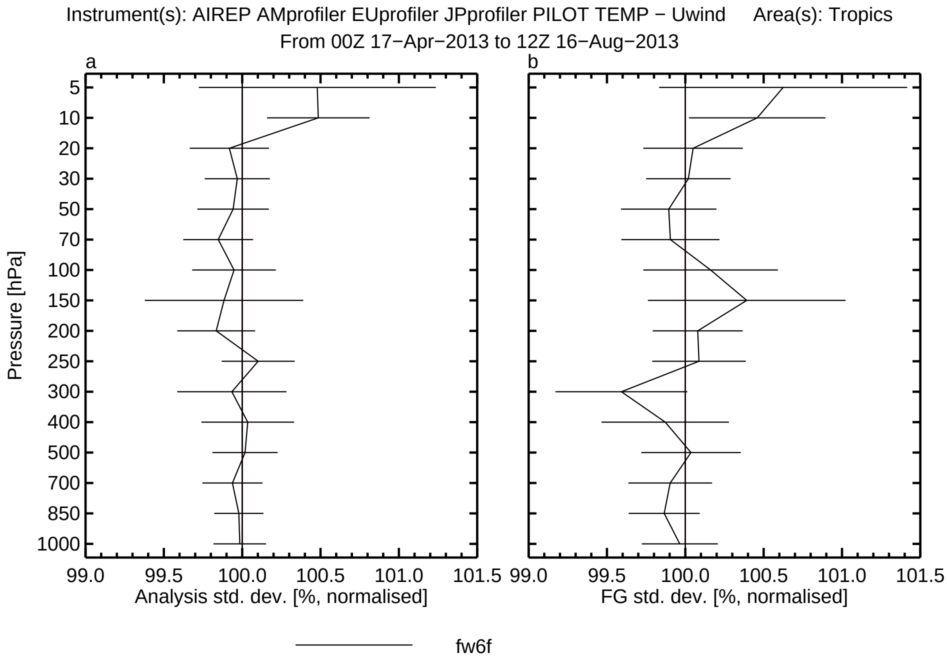


Figure 5: The normalised change in standard deviation of analysis (left panel) and background (right panel) differences from radiosonde, pilot, aircraft and wind profiler u-component wind observations with respect to the control experiment in the tropics. Values less than 100% indicate beneficial impacts from the use of low level IR and VIS Meteosat-10 AMVs. The horizontal bars indicate 90% confidence range.

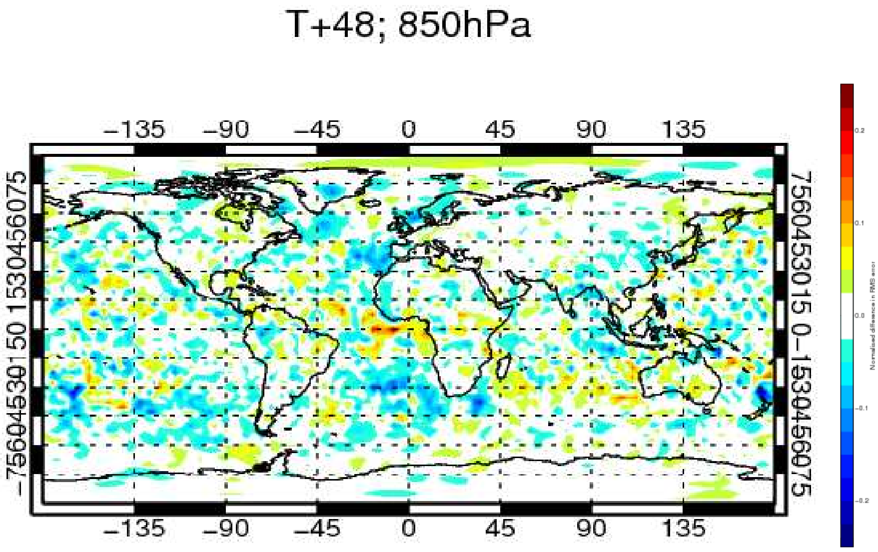


Figure 6: Map of the normalised RMS difference between the experiment and control for 48-hour wind forecast at 850 hPa level. Blue shades indicate positive impact and green and red shades negative impact from using the low level IR and VIS Meteosat-10 AMVs. In the experiment pair situation dependent observation errors and revised quality control has been used.

quality indicator the Expected Error (EE), and the actual scan line time to each satellite wind observation. In addition, a correction to the low level heights in areas over ocean where a low level temperature inversion exists has been implemented. This includes using increased number of vertical levels for temperature obtained from the GFS (The Global Forecast System) NWP model.

The hourly wind product is available for testing. Santek (2011) studied the monitoring statistics for the ECMWF system from experiments where GOES AMVs are not used actively, i.e. the current operational GOES AMVs and the new hourly AMVs have been evaluated against the same short-term forecast. The overall conclusion from the study was that at high and mid levels the departure statistics for the two GOES AMV datasets are fairly similar, except for a marked increase in the number of available winds. In low-level inversion regions considerable improvements were seen for the quality of the hourly GOES AMVs.

The new hourly wind data has been processed operationally at ECMWF since 23rd May 2012. In this study, four experiments covering 23rd May - 22nd July 2012 have been performed to study the impact of the new hourly AMVs compared to the current operational 3-hourly winds. The ECMWF IFS cycle 38r1 at a T511 resolution, 91 vertical levels, and 12-hour 4D-Var has been applied in the experiments. All operationally assimilated conventional and satellite observations are used. The following experiments have been performed:

- **No GOES** No AMVs from GOES-13/15.
- **GOES operational** Current operational GOES-13/15 3-hourly AMVs used.
- **GOES new hourly** The new hourly GOES-13/15 AMVs used.
- **GOES new 3-hourly** The new GOES-13/15 AMVs used 3-hourly.

6.1 Monitoring statistics

The monitoring statistics shown here are from the **GOES operational** and the **GOES new hourly** experiments, i.e. GOES AMVs have been used in the analysis. Thus, the evaluation of the data sets is not done against the same short-term forecast like it was done in Santek (2011).

6.1.1 IR and VIS

Figures 7 and 8 show the zonal plots of the number of observations (upper panel), OmB speed bias (middle panel) and RMSVD (lower panel) for the operational IR AMVs (left panels) and the new hourly IR AMVs (right panels). The number of available AMVs is tripled for the hourly AMVs, as can be expected. In terms of wind speed bias and RMSVD some improvements are seen for mid and low level winds. The positive wind speed bias seen in the tropics below 450 hPa is decreased for the new wind product. Also the negative speed bias in the extratropics has decreased over the Northern hemisphere. Over the Southern hemisphere extratropics the magnitude of the bias is slightly increased between 600 and 750 hPa. The magnitude of the RMSVD is generally slightly decreased. Conclusions are valid both for GOES-13 and GOES-15 AMVs.

Figure 9 shows the OmB speed bias maps for the low level IR operational AMVs (left panel) and the new hourly AMVs (right panel), GOES-13 is shown in the upper panel, and GOES-15 in the lower panel, respectively. For the operational AMVs a positive speed bias is seen over sea off the west coast of South

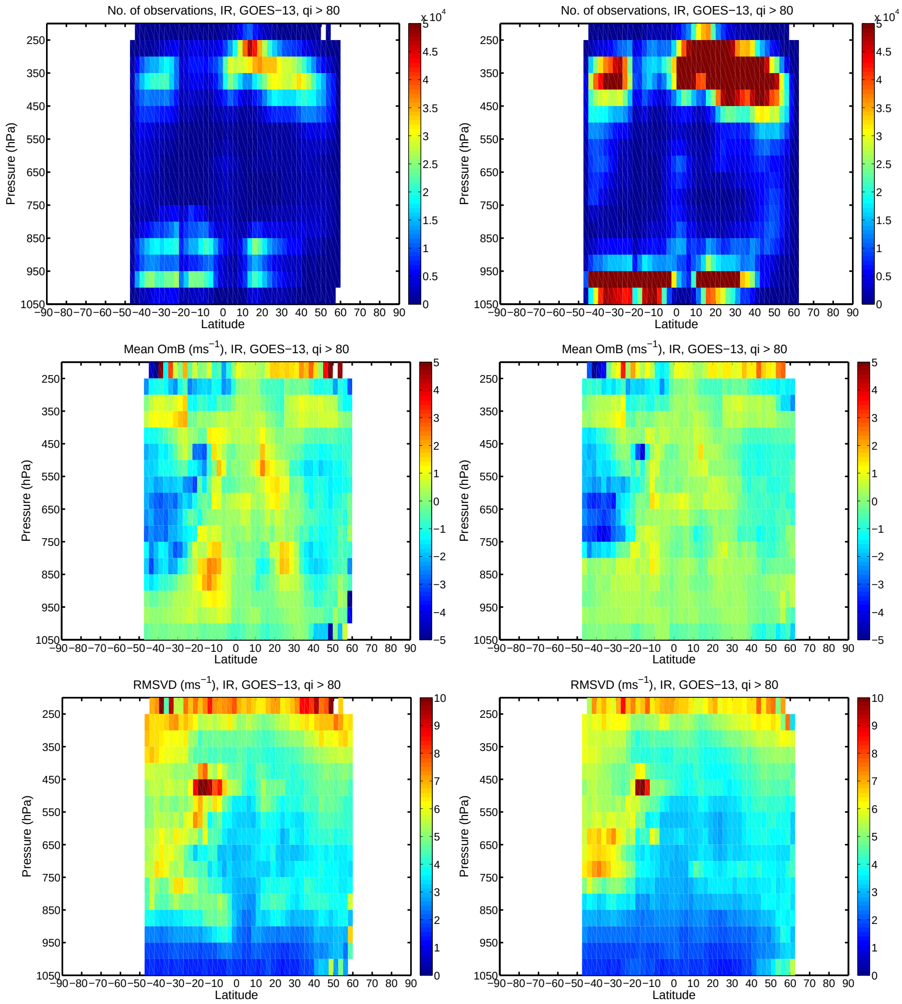


Figure 7: Zonal plots of the number of observations (upper panel), speed bias (middle panel) and RMSVD (lower panel) for the operational GOES-13 AMVs (left panels) and the new hourly GOES-13 AMVs (right panels). AMVs have forecast dependent QI > 80.

America (GOES-13) and over the Eastern Pacific Ocean near California and Mexico (GOES-15). This fast bias has been reported in the NWP SAF monitoring reports, and it has been noted that GOES AMVs in these stratocumulus inversion regions are being assigned heights much higher in the atmosphere than the model preferred position (e.g Forsythe and Saunders, 2008b; Cotton, 2012). This could be due to lack of vertical resolution in the temperature profile used in the height assignment process, meaning that the true depth of the inversion is not properly represented. For the new hourly wind product, a correction to the low level heights in areas over ocean where a low level temperature inversion exists has been implemented. Left panels of Fig. 9 clearly indicate that the magnitude of the fast bias has decreased. Also the slow bias seen north of 30° over the North Pacific Ocean has notably decreased.

Low level VIS AMVs share similar characteristics with the IR AMVs (not shown). Also for the hourly VIS AMVs the magnitude of the bias and RMSVD is decreased compared to the current operational AMVs. Implementation of the correction to the low level heights in areas over ocean with a low level temperature inversion has improved the observation quality significantly.

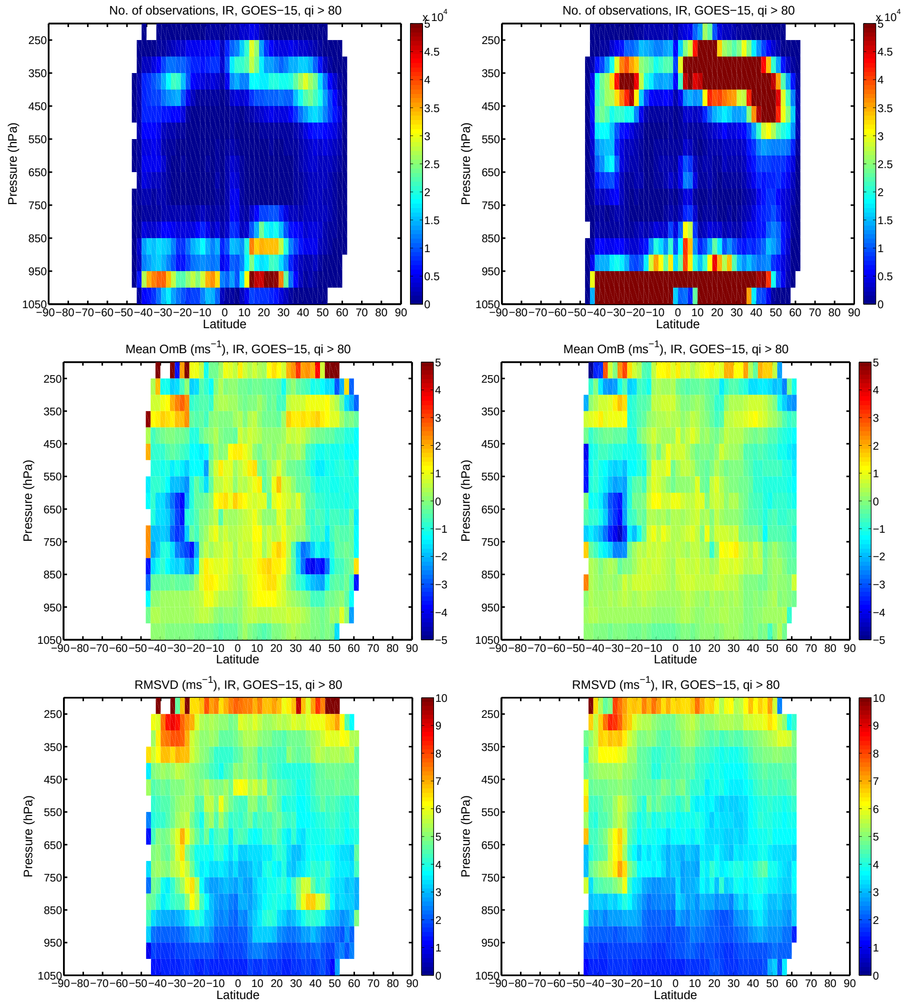


Figure 8: Same as Fig. 7 but for GOES-15 AMVs.

6.1.2 *Cloudy WV*

For WV AMVs the zonal plots do not reveal any drastic changes between operational AMVs and the new hourly AMVs except in the number of available observations. The magnitude of the bias and RMSVD seems to be slightly decreased for the new wind product above 400 hPa. The decrease is consistent in time as seen in Fig. 10 which shows the timeseries for number of observations (upper panel), OmB speed bias (middle panel), and RMSVD (lower panel) for the operational GOES-15 WV AMVs (blue) and the new hourly AMVs (red) at high levels at the Northern hemisphere midlatitudes. Similar improvements but smaller in magnitude are seen also for the statistics in the Southern hemisphere midlatitudes and in the Tropics (not shown).

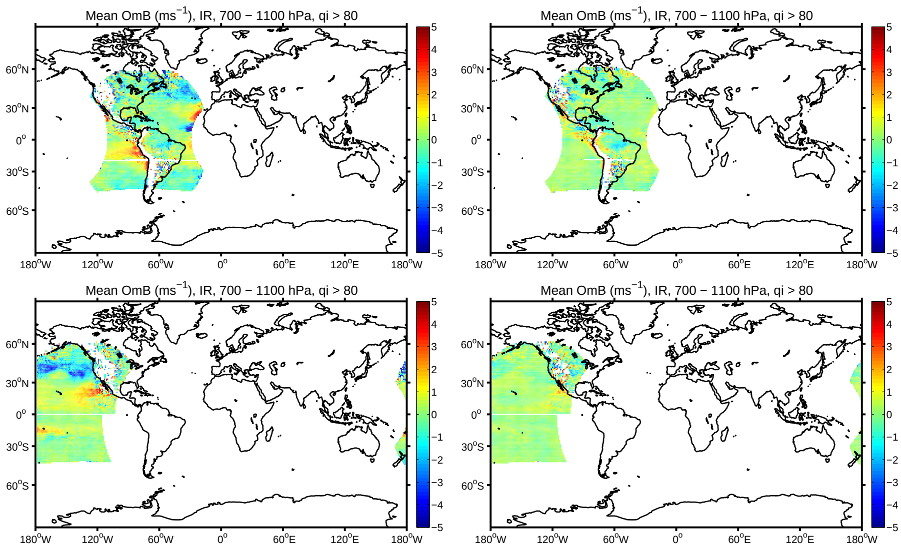


Figure 9: *The OmB speed bias maps for the low level IR operational AMVs (left panel) and the new hourly AMVs (right panel), GOES-13 is shown in the upper panel, and GOES-15 in the lower panel, respectively. AMVs have forecast dependent QI > 80.*

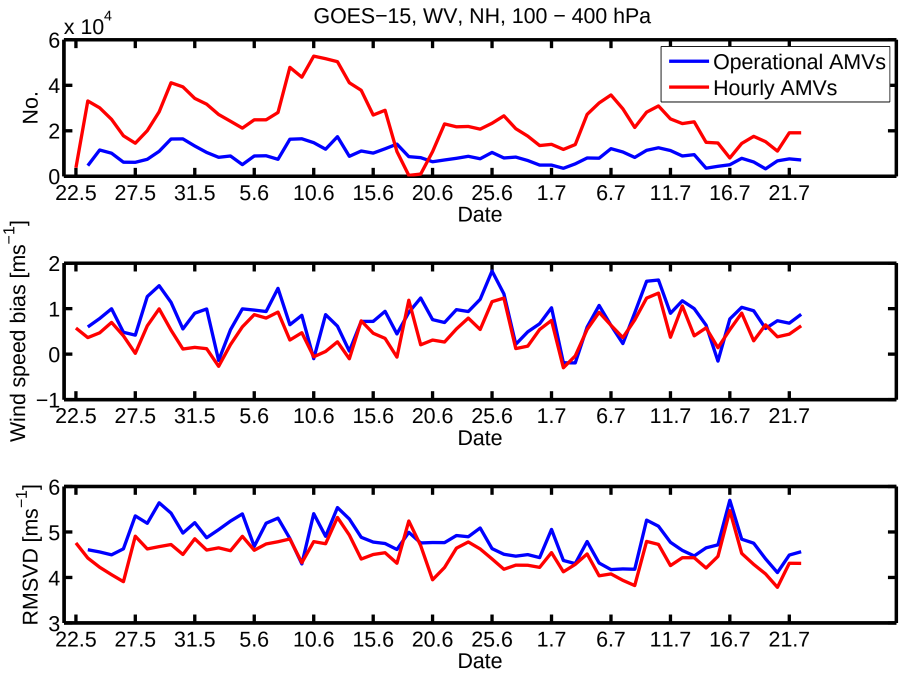


Figure 10: *Timeseries for number of observations (upper panel), OmB speed bias (middle panel), and RMSVD (lower panel) for the operational GOES-15 WV AMVs (blue) and the new hourly AMVs (red) at high levels at the Northern hemisphere midlatitudes. AMVs have forecast dependent QI > 80.*

6.2 Impact assessment

6.2.1 Impact on the mean wind analysis

Using AMVs from GOES satellites has a significant impact on the mean wind analysis over their coverage area. Figure 11 shows the mean wind analysis at 200 hPa (upper panel) and 850 hPa (lower panel) levels for the **No GOES** experiment, whereas Fig. 12 shows the vector difference of the mean wind analysis between the **GOES operational** and **No GOES** experiments. At 200 hPa level the use of the GOES AMVs tends to weaken the mean wind and at 850 hPa level the mean wind is stregthened. Similar features are seen also for the **GOES new hourly** and **GOES new 3-hourly** experiments. Bechtold et al. (2012) have investigated the impact of GOES-13 AMVs over East Pacific for the period September - November 2011, and concluded that the use of the AMVs amplify the low-level convergence across the Equator. This is the case also for this studied period 23 May - 22 July 2012 (lower panel of Fig. 12).

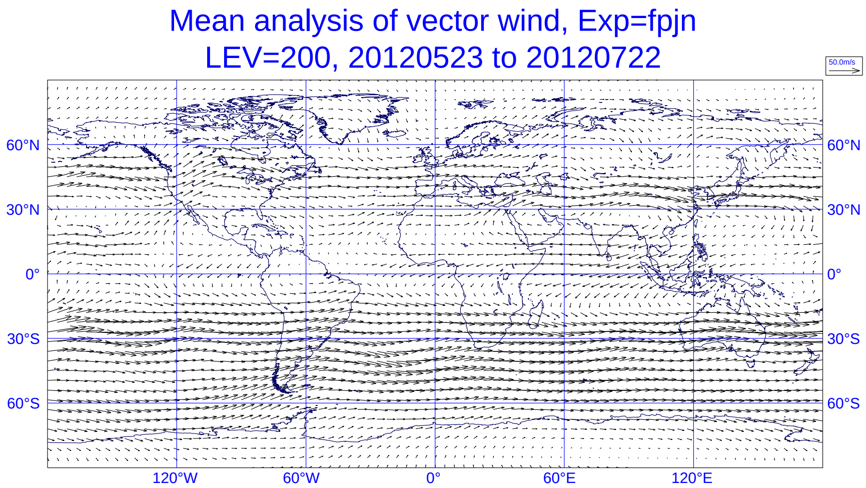
To investigate how the mean wind analysis changes when the new hourly wind product is used, Fig. 13 shows the same as Fig. 12 but between the **GOES new hourly** and the **GOES operational** experiments. The differences in the mean wind analysis are seen mainly in areas where the bias characteristics have changed (e.g. Fig. 9). The changes indicate that the amplification of the low level convergence across the Equator is not as strong when the new hourly AMVs are used compared to the operational GOES AMVs. The **GOES new 3-hourly** experiment shows similar differences in the same regions but the magnitude of the changes is slightly smaller than for the **GOES new hourly** experiment (not shown).

In Bechtold et al. (2012) it is discussed that at low levels the model overshoots in response to the large analysis increments caused by assimilation of AMVs, and the forecast adjustment processes produce a temporary flow reversal up to 3-day forecasts. A similar kind of flow reversal is seen also in the **GOES operational** experiment. The new hourly AMVs agree better with the model first guess and consequently in the **GOES new hourly** and the **GOES new 3-hourly** experiments the analysis increments are smaller. As a result also the flow reversal is somewhat smaller in magnitude.

Scatterometer winds allow a validation of the changes to the mean wind analysis at low levels over sea. The upper panel of Fig. 14 shows a map of the mean first guess departure for used scatterometer winds in the **GOES operational** experiment. The largest departures are seen over the same areas as for the low level AMVs (left panels of Fig. 9). The lower panel of Fig. 14 shows the first guess departure difference between the **GOES operational** and the **GOES new hourly** experiments. The first guess departures are smaller in magnitude in the **GOES new hourly** experiment North from the Equator. Thus, the scatterometer winds agree better with the model first guess when the new hourly AMVs are used. However, over the South Pacific near Ecuador and Peru the scatterometer wind first guess departures are increased when the new wind product is used.

6.2.2 Observation fit statistics

Departure statistics from radiosonde winds suggest a degradation of the short-range forecasts when the new GOES winds are used hourly. Figure 15 shows the normalised change in standard deviation (left panels) and the OmB and OmA bias (right panels) for radiosonde wind u-component observations over the GOES area. For the **GOES new hourly** experiment the OmB and OmA standard deviation, as well as the bias, are larger than for the **No GOES** experiment. They are also larger than for the **GOES operational** and the **GOES new 3-hourly** experiments indicating that the radiosonde wind observations have better agreement with the model background in the experiments where GOES AMVs are used 3-hourly, or not used at all. Similar features are seen also for OmB and OmA statistics against pilot wind



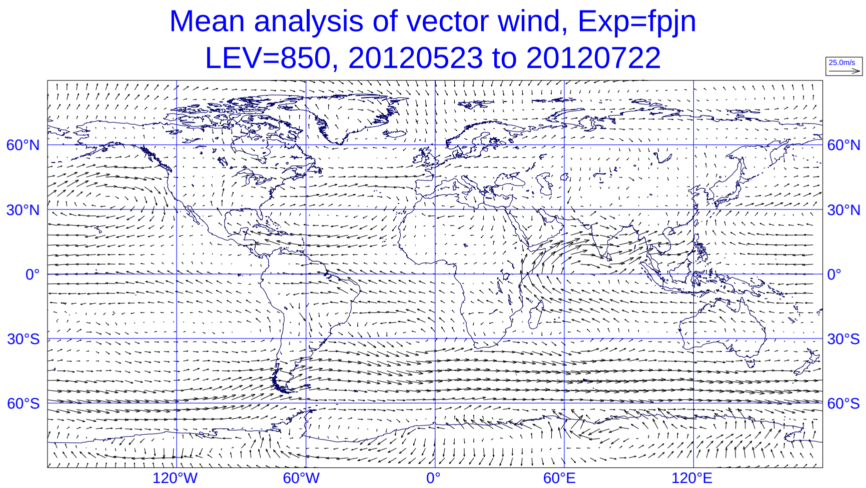


Figure 11: The mean wind analysis for the **No GOES** *experiment at 200 hPa (upper panel) and 850 hPa (lower panel).*

observations (not shown).

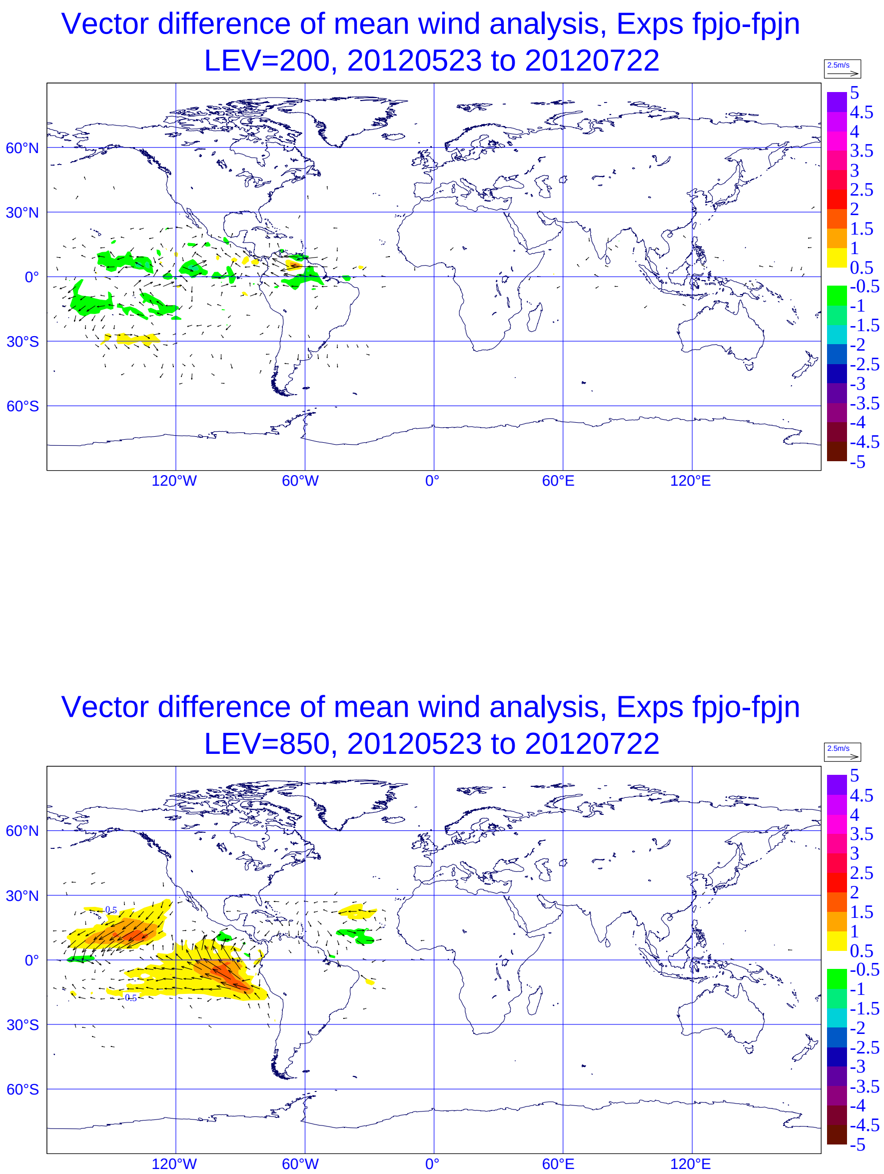
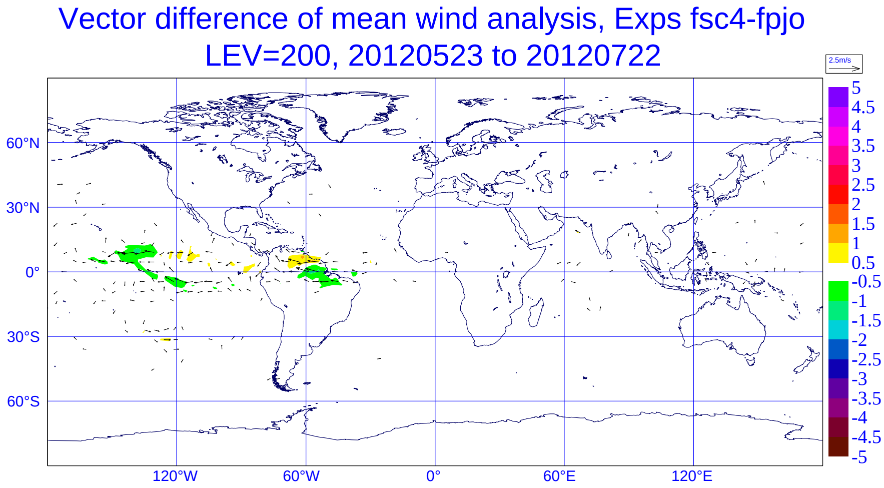


Figure 12: The vector difference of the mean wind analysis between the **GOES operational** *and* **No GOES** *experiments at 200 hPa (upper panel) and 850 hPa (lower panel).*

6.2.3 Forecast verification

Forecast verification has been done against observations and against each experiment's own analysis. The general impression of the results is that using GOES AMVs has mainly a positive or neutral impact on the forecasts. Here the focus is on what is the impact of using the new hourly wind product compared to using the current operational AMVs.



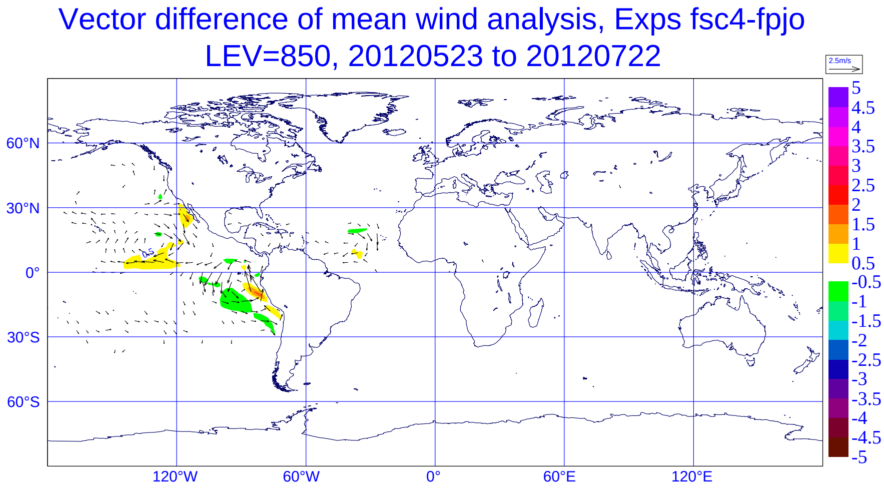


Figure 13: The same as Fig. 12 but between the **GOES new hourly** *and the* **GOES operational** *experiments.*

Figures 16 and 17 show the normalised difference of the wind forecast RMS error as a function of the forecast range at 200 hPa and 850 hPa levels, respectively. The verification has been done against observations, and the difference is calculated as **GOES operational** minus **GOES new hourly** (left panel) and **GOES operational** minus **GOES new 3-hourly** (right panel), i.e. positive values indicate positive impact from using the new wind product. Both the **GOES new hourly** and the **GOES new 3-hourly** experiments show mainly neutral impact within the 95% confidence intervals compared to the

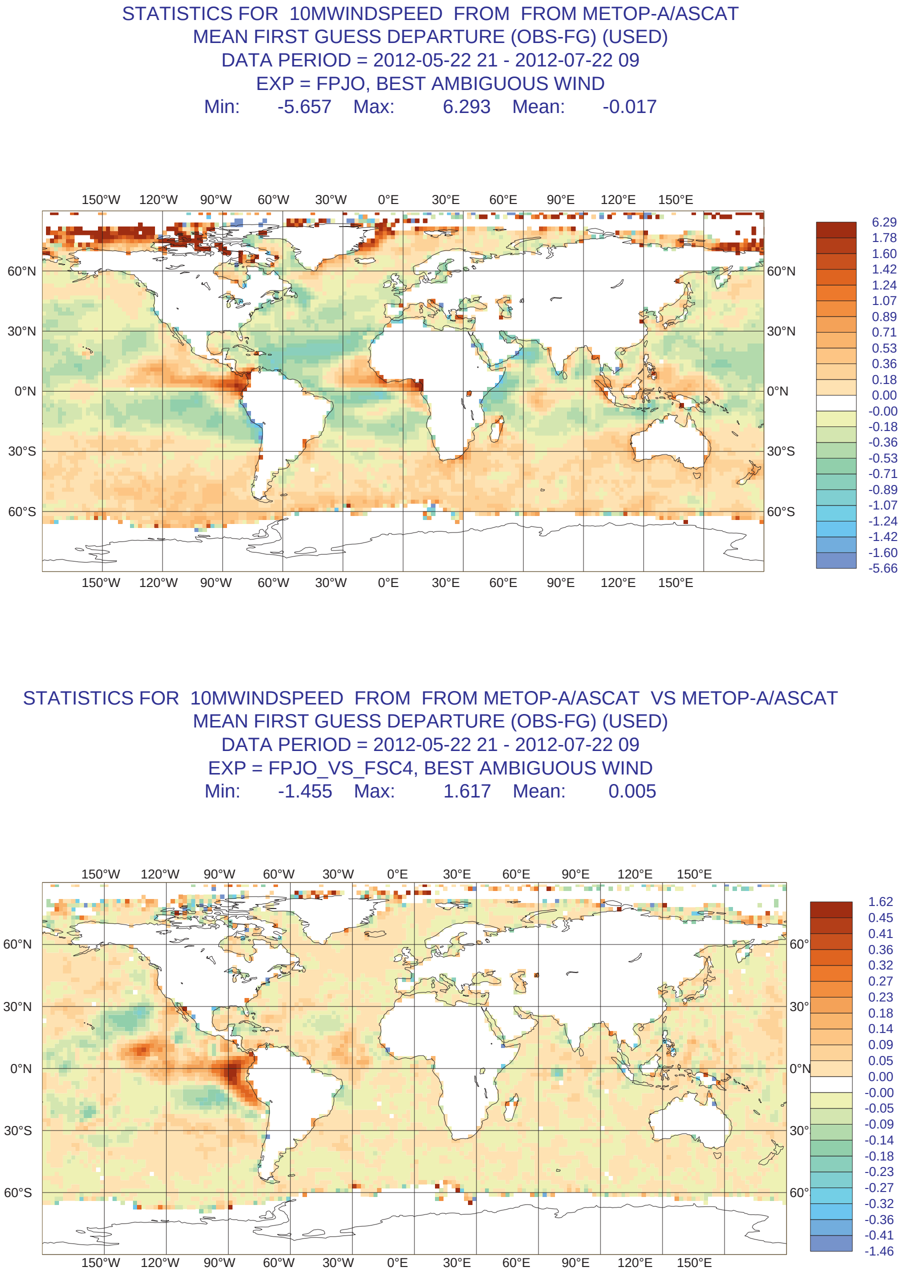


Figure 14: A map of the mean first guess departure for used scatterometer winds in the **GOES operational** *experiment (upper panel), and the first guess departure difference between the* **GOES operational** *and the* **GOES new hourly** *experiments (lower panel).*

GOES operational experiment. However, the **GOES new 3-hourly** experiment has some indications of positive impact whereas the **GOES new hourly** experiment is more on the negative side.

Verification against each experiment's own analysis support the results seen in the observation verification. Results indicate mainly neutral impact within the 95% confidence intervals from using the new

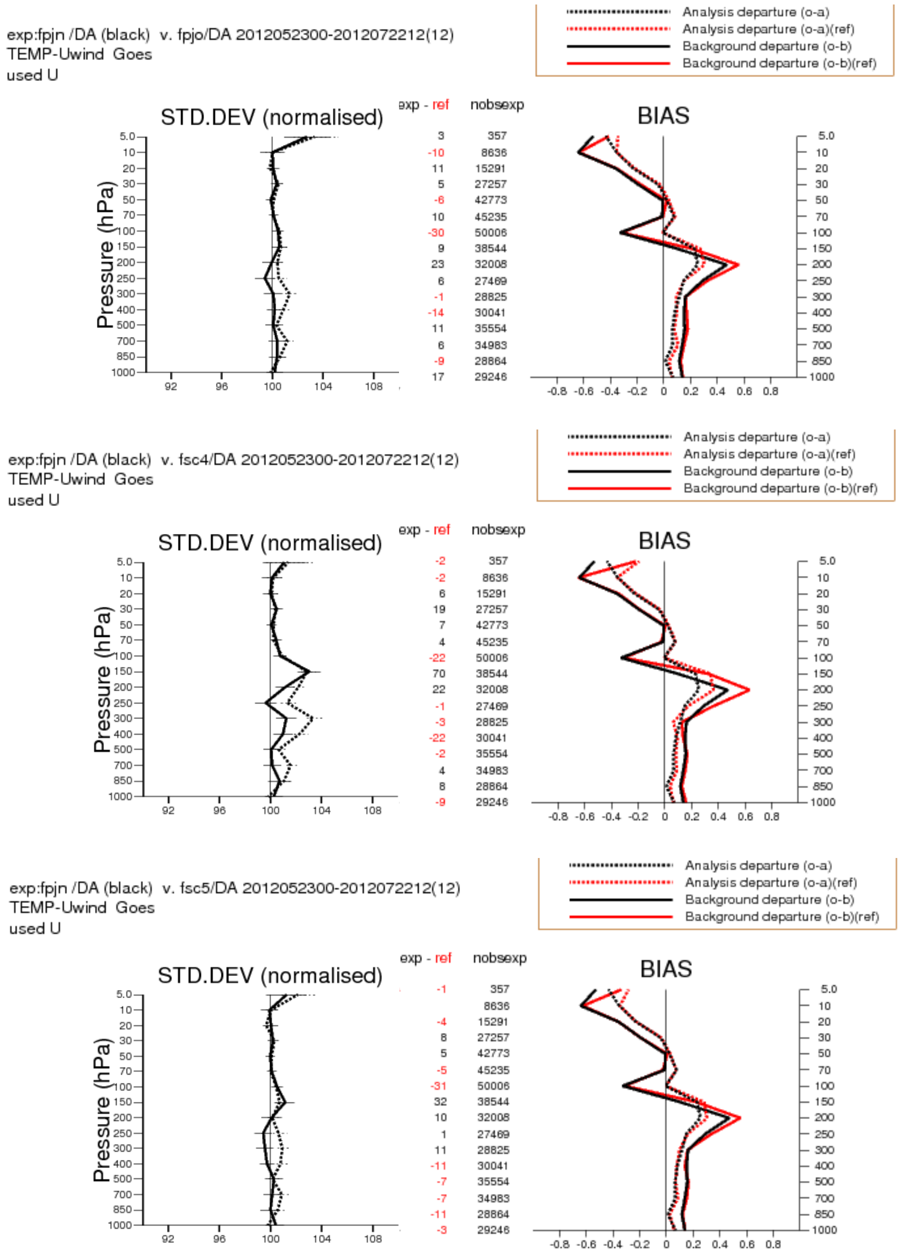


Figure 15: Left panels: The normalised change in standard deviation of the background (solid line) and analysis (dashed line) differences for radiosonde wind observations (u-component) for **GOES operational** *(upper panel), the* **GOES new hourly** *(middle panel), and the* **GOES new 3-hourly** *(lower panel) experiments with respect to the* **No GOES** *experiment over the GOES area. Values less than 100% indicate beneficial impacts from using the GOES AMVs. Right panels: The OmB (solid line) and OmA (dashed line) bias. The black line indicates the* **No GOES** *experiment and the red line the* **GOES operational** *(upper panel), the* **GOES new hourly** *(middle panel), and the* **GOES new 3-hourly** *(lower panel) experiments, respectively.*

wind product compared to the current operational AMVs but the **GOES new 3-hourly** experiment has systematically better scores than the **GOES new hourly** experiment. Figure 18 shows maps of the normalised difference of the 72-h wind forecast RMS error at 850 hPa level as an example of the results.

The **GOES new 3-hourly** experiment shows positive impact over the GOES coverage area, especially over locations where the bias characteristics of the AMVs have changed. For the **GOES new hourly** experiment the impact is more mixed.

The main findings from the impact assessment are:

- Verification against own analysis indicates postivive impact from using the new GOES AMVs 3-hourly at low levels.
- For hourly winds the impact is more mixed.
- Verification against radiosonde observations shows neutral impact.

As discussed in e.g. Hernandez-Carrascal et al. (2012) and Bormann et al. (2012) assimilation of more frequent AMVs is not necessarily beneficial. This is because errors in AMVs are likely to be correlated in time, and these error correlations are currently neglected in the ECMWF data assimilation system. Neglecting the error correlations can lead to overfitting of certain aspects of the AMVs, and hence to a degradation compared to using the data less frequently.

6.3 Conclusions

NESDIS is making preparations to disseminate hourly AMVs from GOES-13 and GOES-15 satellites. The new wind product contains some improvements, one of the most important ones being a correction to the low level heights in areas over ocean where a low level temperature inversion exists.

The number of available AMVs is tripled for the hourly AMVs, as can be expected. Monitoring statistics indicate improvements in the data quality, especially for mid and low level winds. Data assimilation experiments show that using GOES-13/15 AMVs (current operational AMVs or the new hourly wind product) has in general a neutral to positive impact on the forecast quality. Data assimilation experiments also reveal that using the new wind product has some positive impacts over using the current operational GOES AMVs. However, it seems that with the current system using the new wind product 3-hourly is more beneficial than 1-hourly. This is in contrast to the experience with MTSAT AMVs, and the reasons for that are not clear.

7 Latest activities with polar AMVs

Polar AMVs are derived from the MODIS instrument on-board the Aqua and Terra satellites and from the AVHRR instrument on-board the NOAA-15, -16, -18, -19, METOP-A, and METOP-B satellites. Visible Infrared Imaging Radiometer Suite (VIIRS) AMVs from the Suomi NPP satellite are expected to be available in late 2013. In July 2013 NESDIS decided to suspend operational production of MODIS Terra WV AMVs until further notice due to increased striping seen on water vapor channels. In the ECMWF system also Terra IR AMVs were blacklisted as a precaution as the problems may affect the height assignment of the IR AMVs. It is a known fact that the lifetime of MODIS AMVs is approaching to its end. Thus, the use of AVHRR AMVs in operations is becoming more and more important.

Results from experiments using AVHRR AMVs from NOAA-15, -16, and -18 in the ECMWF system are discussed in Salonen and Bormann (2012). The conslusions are that the data has mainly a neutral impact on model analysis and forecasts when used on top of the MODIS AMVs. AVHRR AMVs from

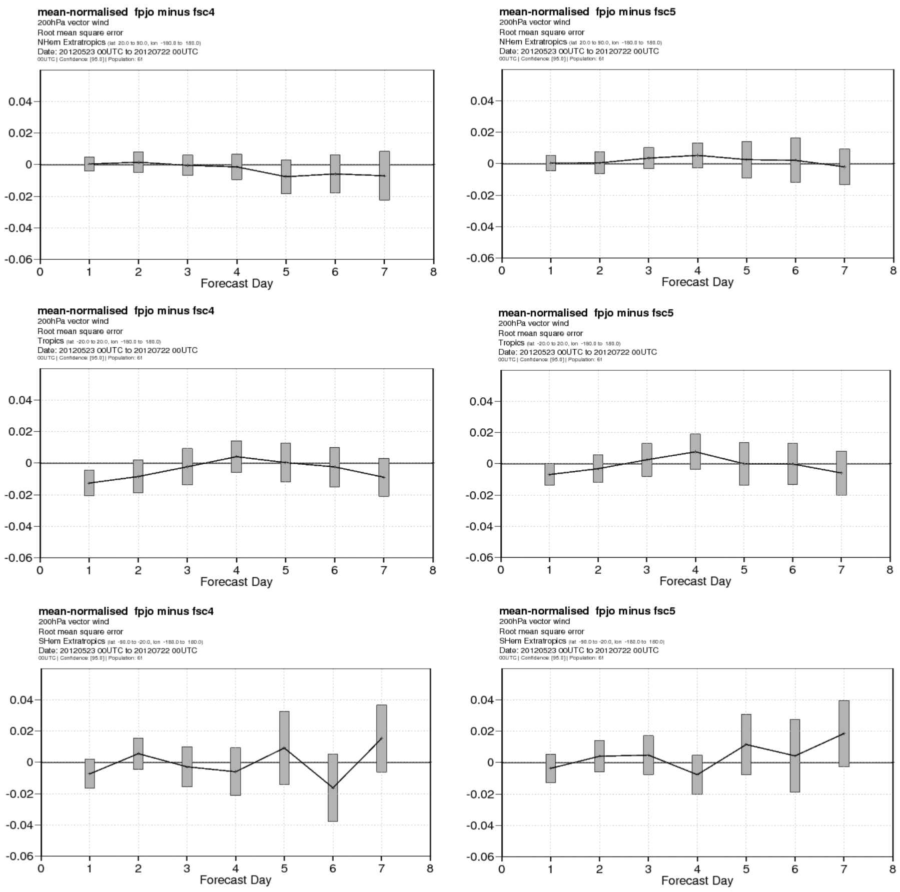


Figure 16: Normalised difference of the 200 hPa RMS wind forecast error as a function of the forecast range for the Northern hemisphere extra tropics (upper panel), tropics (middle panel), and the Southern hemisphere extra tropics (lower panel). Verification has been done against observations, and the difference is calculated as **GOES operational** *minus* **GOES new hourly** *(left panel) and* **GOES operational** *minus* **GOES new 3-hourly** *(right panel).*

NOAA-15, -16, and -18 have been used in active mode in the ECMWF system since 19th November 2012, and they increased the number of used polar winds by ca 60%. Complementary experiments have been performed to assess the impact of AVHRR AMVs when MODIS AMVs are absent. The results are summarised in subsection 7.1.

AMVs from NOAA-19 have been added to operational monitoring in passive mode at 20th March 2013. The monitoring statistics indicate that the quality is similar to other NOAA AVHRR AMVs. Experiments to investigate the impact of using the data have been performed and the results are presented in section 7.2.

METOP-B was launched 17th September 2012, and the first AMV test data set was provided by Eumetsat for the second half of January. METOP-B AVHRR AMVs have been added to the operational monitoring in passive mode at 14th May 2013. Section 7.3 gives a summary of the monitoring results so far.

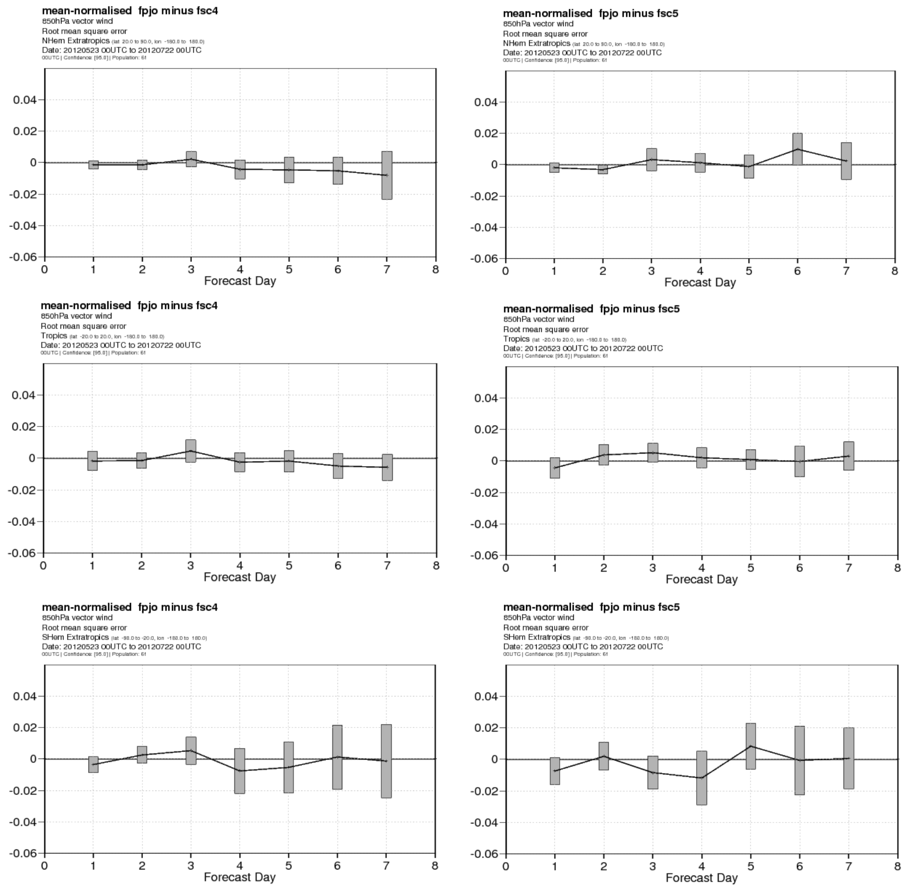


Figure 17: The same as Fig. 16 but for the 850 hPa wind forecasts.

7.1 Impact of the AVHRR AMVs in the absence of MODIS AMVs

The summer (1st June - 31st July 2011) and winter (1st December 2011 - 31st January 2012) season experiments investigating the impact of using NOAA-16, -18, and -19 AVHRR AMVs on top of the MODIS AMVs (Salonen and Bormann, 2012) have been complemented by additional experiments where polar AMVs are not used at all, or AVHRR AMVs are used without the MODIS AMVs. The ECMWF IFS cycle 38r1 at a T511 resolution, 91 vertical levels, and 12-hour 4D-Var has been applied in the experiments. All operationally assimilated conventional and satellite observations are used. Next results from the following experiments are compared:

- **Control**: No polar AMVs used.
- **MODIS**: MODIS AMVs used, AVHRR AMVs not.
- **AVHRR**: AVHRR AMVs used, MODIS AMVs not.
- **MODIS + AVHRR**: AVHRR and MODIS AMVs used.

AVHRR and MODIS winds are thinned together, when they are both actively used. The blacklist applied for the AVHRR AMVs is similar to the MODIS IR AMV blacklisting in the ECMWF system and excludes the following observations:

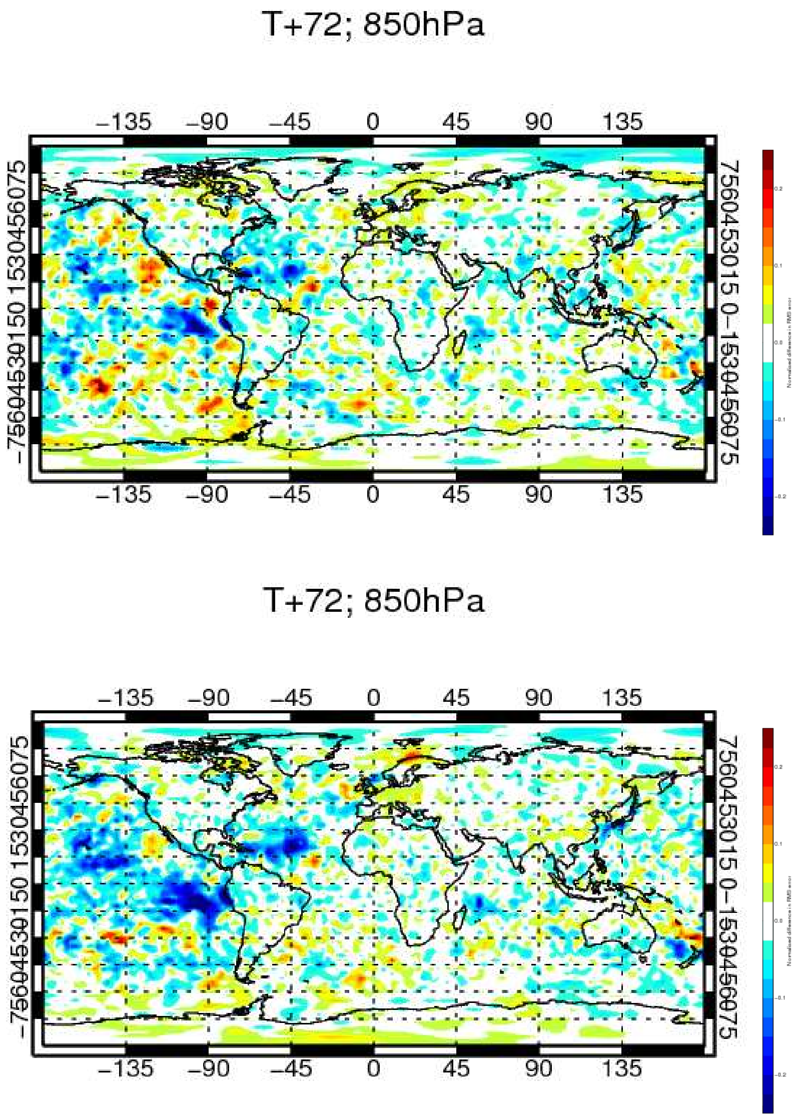


Figure 18: Map of the normalised RMS difference between the **GOES new hourly** *and* **GOES operational** *experiments (upper panel) and the* **GOES new 3-hourly** *and* **GOES operational** *experiments (lower panel) for 72-hour wind forecast at 850 hPa level. Blue shades indicate positive impact and green and red shades negative impact from using the new wind product.*

- All winds equatorwards of 60° latitude
- All winds over land below 400 hPa.
- All winds over sea or sea-ice below 700 hPa.
- All winds below 1000 hPa or above 100 hPa.

All experiments indicate positive impact from using polar AMVs, especially at high latitudes, as seen in Fig. 19 which shows zonal plots of the normalised difference (experiment minus control) of the RMS wind error for the 48-hour (left panel) and 72-hour (right panel) forecasts for the MODIS (upper panel), MODIS+AVHRR (middle panel), and AVHRR experiments (lower panel). Comparison of the upper and middle panel shows that using AVHRR AMVs on top of the MODIS AMVs has mainly a neutral impact, as was concluded also in Salonen and Bormann (2012). However, the positive impact gained from using only the AVHRR AMVs (lower panel) is very similar to the positive impact obtained from using the MODIS AMVs. Results are similar for both considered seasons. The result is very encouraging as at some point the AVHRR AMVs will be the main source for polar AMVs.

7.2 Experimentation with NOAA-19 AVHRR AMVs

NOAA-19 AVHRR AMVs have been added to the operational monitoring in passive mode at 20th March 2013. The monitoring statistics indicate that the quality of NOAA-19 AVHRR AMVs is very similar to the quality of actively used NOAA AVHRR AMVs. Figure 20 shows a timeseries of the OmB bias, RMSVD, and the number of available observations as an example of the monitoring statistics for NOAA-15, -16, -18, and -19 AVHRR AMVs at the Northern hemisphere between 100 and 400 hPa.

It is not always evident that adding new data similar to what is already actively used in the system will result in a positive or even neutral impact. Thus, the impact of using NOAA-19 AVHRR AMVs on model analysis and forecasts has been investigated. ECMWF IFS cycle 38r2 at a T511 resolution, 137 vertical levels, and 12-hour 4D-Var has been applied in the experiments. All operationally assimilated conventional and satellite observations are used. The following four experiments covering 17th April - 16th June 2013 have been performed:

- **Control, operational**: AMV usage similar to the IFS cycle 38r2 operational setup.
- **NOAA-19, operational**: Like related control but NOAA-19 AVHRR AMVs are used.
- **Control, revised AMV usage**: Situation dependent observation errors and revised quality control used for AMVs (operational in IFS cycle 40r1 onwards).
- **NOAA-19, revised AMV usage**: Like related Control but NOAA-19 AVHRR AMVs are used.

In the first pair of the experiments AMVs are used like in the IFS cycle 38r2 operational setup. In the second pair of the experiments situation dependent observation errors and a revised quality control are applied for AMVs. These improvements in the AMV usage are operational from cycle 40r1 onwards (Salonen and Bormann, 2013). Conclusions from both experiment pairs are similar and thus in the following only results from the revised AMV usage are shown.

The observation fit statistics against radiosonde and pilot wind observations are very similar between the Control and the NOAA-19 experiments at Northern and Southern hemisphere midlatitudes and in particular over the polar regions as shown in Figure 21 for the Northern hemisphere polar cap. This indicates overall consistency between NOAA-19 AVHRR AMVs and the other wind observations.

The impact of using NOAA-19 AVHRR AMVs in addition to the already used AVHRR AMVs is neutral as seen in Fig. 22 which shows zonal plots of the normalised difference (NOAA-19 experiment minus Control) of the RMS wind error for the 48-hour (left panel) and 72-hour (right panel) forecasts. Verification has been done against each experiment's own analysis. Verification against observations shows also neutral impact (not shown). Based on the results it was decided to activate NOAA-19 AVHRR AMVs in the ECMWF system on 27th August 2013. This increased the number of used polar AMVs by further 10%.

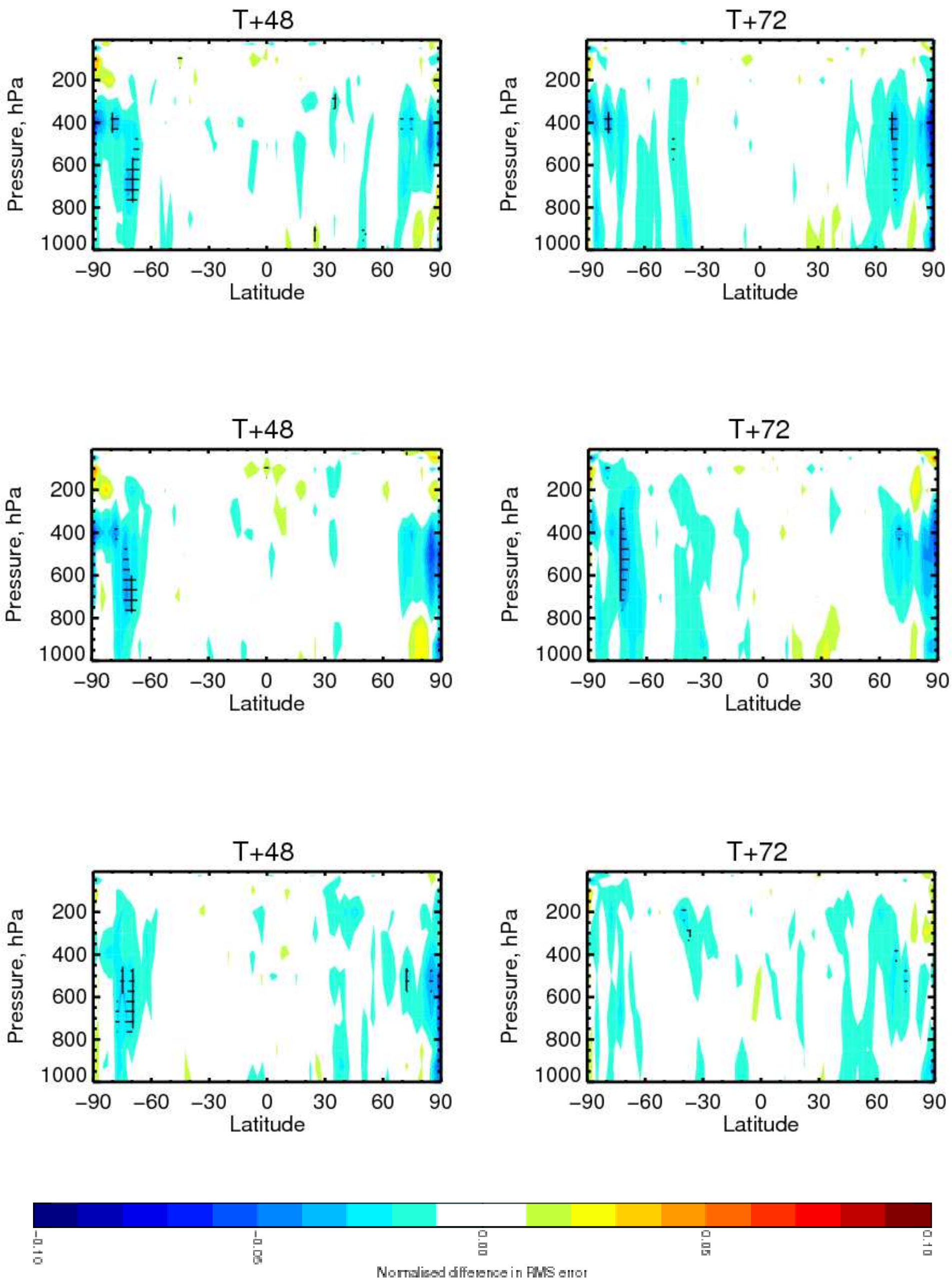


Figure 19: Zonal plots of the normalised difference (experiment minus control) of the RMS wind error for the 48-hour (left panel) and 72-hour (right panel) forecasts for the MODIS (upper panel), MODIS+AVHRR (middle panel), and AVHRR experiments (lower panel).

7.3 Monitoring of METOP-B AMVs

METOP-A AVHRR AMVs produced by EUMETSAT have been passively monitored in the ECMWF system for several years. The monitoring statistics have shown larger values for bias and RMSVD for METOP-A AMVs than for the NOAA AVHRR AMVs. This is the result of different processing algorithms used at EUMETSAT and NOAA/NESDIS. Thus, the METOP-A data were not included in the

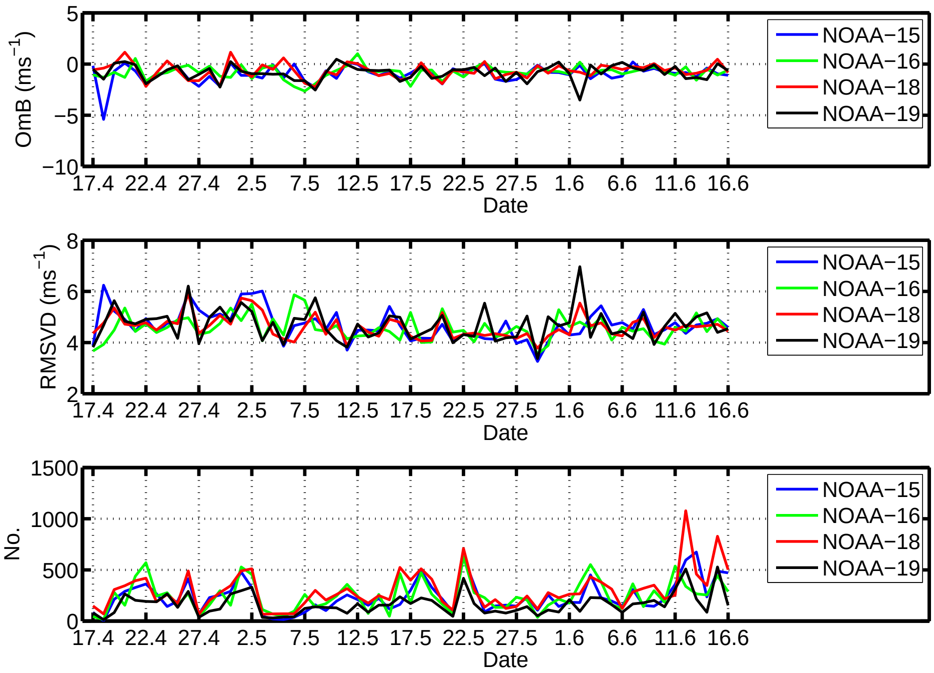


Figure 20: Timeseries of the OmB bias (upper panel), RMSVD (middle panel), and number of observations (lower panel) for NOAA-15 (blue), NOAA-16 (green), NOAA-18 (red), and NOAA-19 (black) AVHRR AMVs for Northern hemisphere between 100 and 400 hPa. The considered time period is 17th April - 16th June 2013. All data after blacklisting is shown.

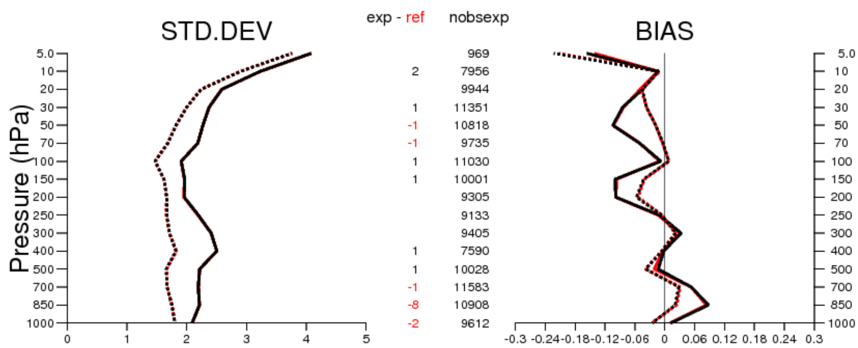


Figure 21: OmB (solid line) and OmA (dashed line) standard deviation (left panel) and bias (right panel) for radiosonde wind observation u-component over the Northern hemisphere polar cap. The Control run is indicated with black and the NOAA-19 experiment with red. The considered period is 17th April - 16th June 2013.

study discussed above.

METOP-B was launched 17th September 2012, and the first test data set was provided by EUMETSAT for the second half of January. Monitoring statistics for the test data indicate that METOP-A and METOP-B share similar characteristics, small or zero OmB bias at high levels but increased positive bias below 450 hPa over Southern hemisphere and below 650 hPa over Northern hemisphere. The METOP-A test data have been compared also to the METOP-A AMVs from the operational stream. The quality of the test data was slightly better compared to the operational stream. This is due to changes introduced to

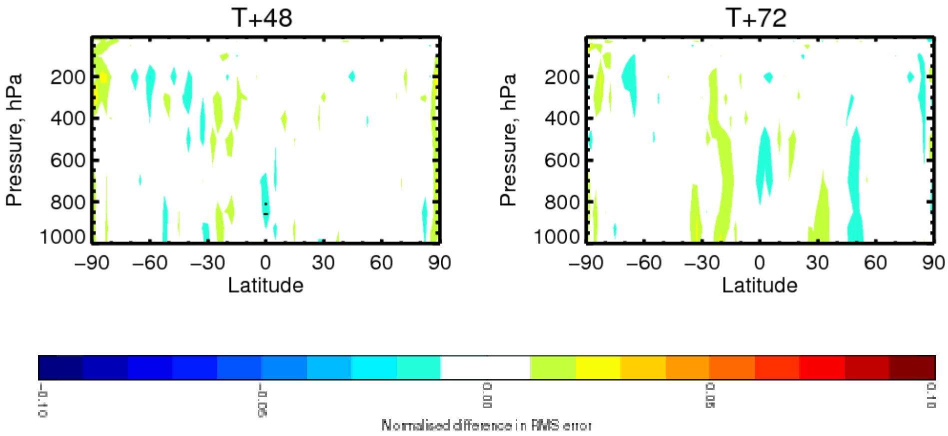


Figure 22: OmB (solid line) and OmA (dashed line) standard deviation (left panel) and bias (right panel) for radiosonde wind observation u-component over the Northern hemisphere polar cap. The Control run is indicated with black and the NOAA-19 experiment with red. The considered period is 17th April - 16th June 2013.

the polar AMV processing.

METOP-B AMVs became available operationally in spring 2013 and have been added to the ECMWF operational monitoring in May 2013. On 25th June 2013 some further improvements and changes were introduced to the EUMETSAT polar wind processing. The changes included

- Tropopause determination
- Temperature inversion determination
- Coverage extended from 55° to 50° latitude
- Stronger test to use IASI CTH to set the altitude

Figure 23 shows timeseries of the OmB bias, RMSVD and number of observations for METOP-A (solid line) and METOP-B (dashed line) AMVs over Northern hemisphere at high levels (100 - 400 hPa) for June - July 2013. A decrease in the magnitude of the bias is seen at high levels after the changes were implemented on 25th June. At mid and low levels the positive bias of one to two meters is still present (not shown).

The investigations are now continuing with more detailed studies where the improvements in the bias take place, and by performing impact studies with the high level METOP AVHRR AMVs.

8 Alternative interpretations of AMVs

Work on alternative interpretations of AMVs has recently started. In this section some very preliminary results are discussed. Typically, AMVs are interpreted as single-layer observations even though it is evident that clouds that are used in the AMV tracking have vertical extent, or in the case of tracking clear sky features the radiances represent contribution of deep vertical layer. Comparison to sonde observations (e.g. Velden and Bedka, 2009; Weissmann et al., 2013), and results from a simulation framework

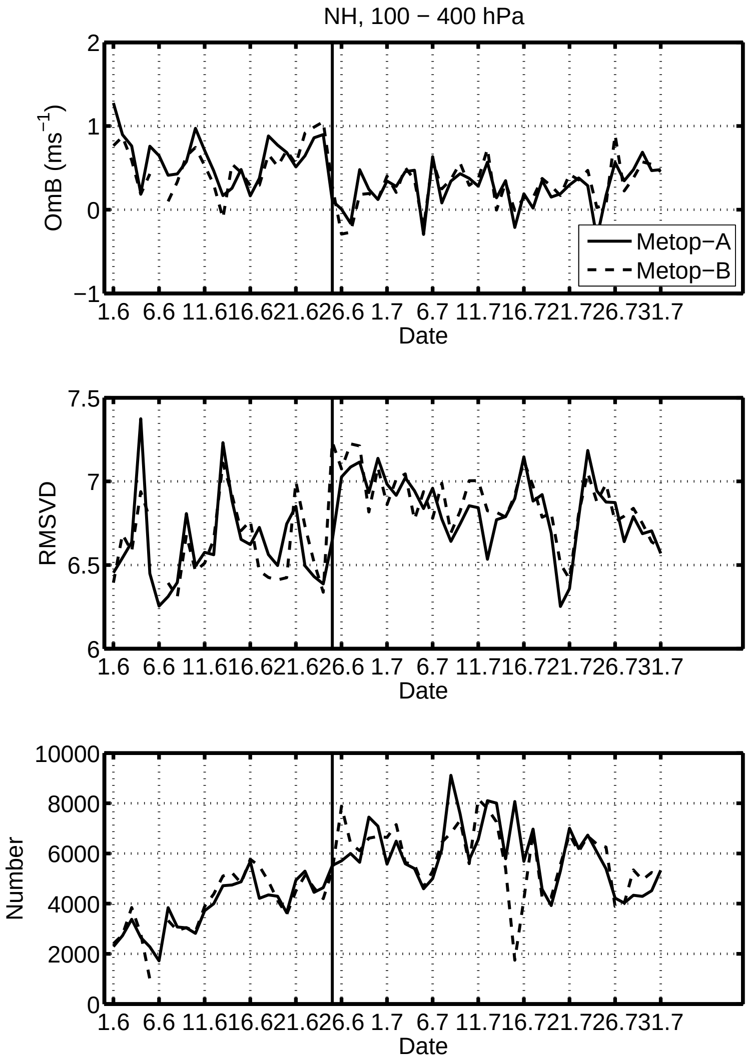


Figure 23: Timeseries of the OmB bias (upper panel), RMSVD (middle panel) and number of observations (lower panel) for METOP-A (solid line) and METOP-B (dashed line) AMVs over Northern hemisphere at high levels (100 - 400 hPa) for June - July 2013.

(e.g. Hernandez-Carrascal and Bormann, 2012) suggest some benefits from layer averaging in terms of departure statistics.

In the following, three types of observation operators are considered:

- Single-level observation operator
- Boxcar layer averaging, layer below the observation height
- Boxcar layer averaging, layer centered at the observation height

A single-level observation operator is used in the ECMWF operational system, and it is the most commonly used approach also in other NWP systems. Layer averaging below the assigned AMV height

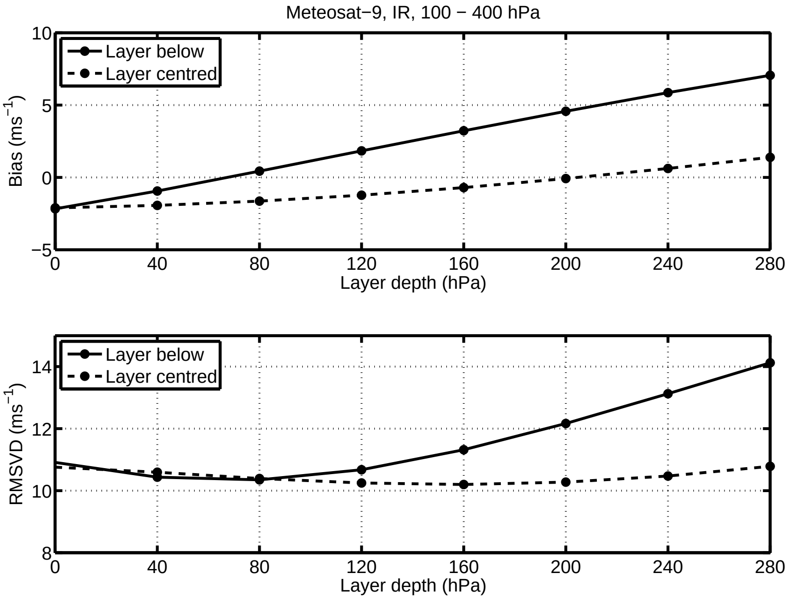


Figure 24: The OmB wind speed bias (upper panel) and RMSVD (lower panel) with varying layer depths for Meteosat-9 IR AMVs after blacklisting at high levels. Solid line indicates observation operator with layer averaging below the assigned observation height, and dashed line layer averaging centered at the assigned observation height.

is a realistic approach if the assigned height represents the cloud top height. On the other hand, if the assigned height is interpreted as a representative level, centered averaging would be more justifiable.

To begin with, the OmB statistics have been studied for layer averaging observation operators with different layer depths. The passive monitoring experiments have been done with IFS cycle 38r1, T511, and 91 levels. The studied period covers 1 January - 29 February 2012. Figure 24 shows the OmB wind speed bias and RMSVD for Meteosat-9 IR AMVs after blacklisting at high levels. The solid line indicates observation operator with layer averaging below the assigned observation height, and dashed line shows layer averaging centered at the assigned observation height, respectively. The minimum bias is seen with 80 hPa layer depth below and 200 hPa centered, and the minimum RMSVD with 80 hPa layer depth below and 160 hPa centered. Thus, there is some indication that layer averaging could have some benefit over the single-level observation operator. However, it is yet unclear if similar benefits could be obtained by re-assigning the observation heights. Model best-fit pressure bias statistics could provide some information for re-assignment or positioning of the layer used in the observation operator. Also, the characteristics differ between different satellites and processing algorithms. These issues are under investigations and at this point it is too early to draw any conclusions.

Layer averaging will affect how the AMV information is spread in vertical during the assimilation. At the same time, the background error covariances also define how the information from observations is spread in the model analysis. To investigate these aspects four single observation experiments have been performed with the ECMWF IFS cycle 40r1 at a T511 resolution, 137 levels, and 12-hour 4D-Var. In the experiments four different versions of the observation operator have been used:

- Single-level observation operator
- Boxcar layer averaging, 80 hPa layer centered at the observation height

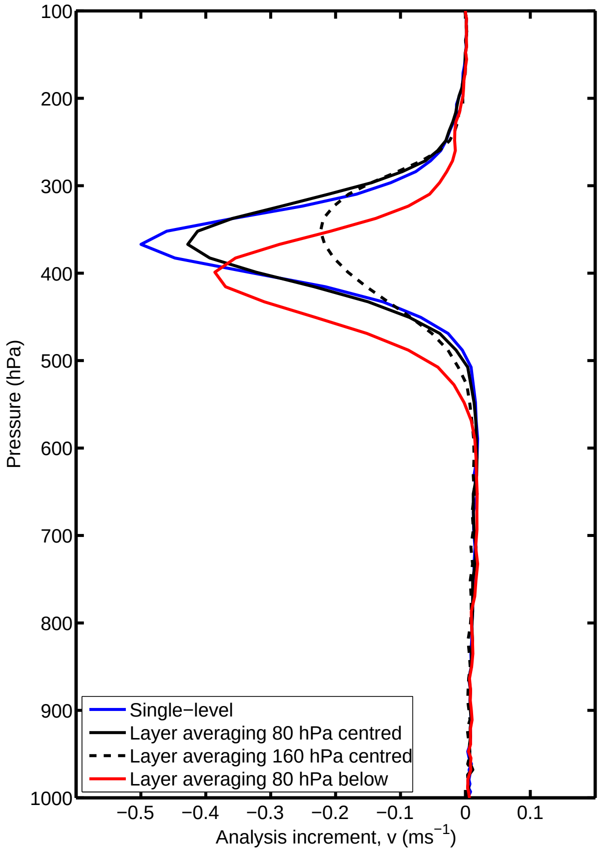


Figure 25: Vertical analysis increment for the single-layer observation operator (blue line), boxcar layer averaging 80 hPa centerd at the observation height (black solid line), boxcar layer averaging 160 hPa centerd at the observation height (black dashed line), and boxcar layer averaging 80 hPa below the observation height (red line), respectively. The observation height is 370 hPa. The first guess departure is the same in all three cases.

- Boxcar layer averaging, 160 hPa layer centered at the observation height

- Boxcar layer averaging, 80 hPa layer below the observation height

In each experiment only one AMV observation enters the system. The experiments have been designed so that the first guess departure is the same in all four cases. The assigned observation height is 370 hPa.

Figure 25 shows the vertical analysis increment for the four observation operators. Using the centered averaging instead of single-level interpretation spreads the observation information slightly more in vertical and the magnitude of the maximum analysis increment at the assigned observation height decreases, the more the greater is the layer depth. Layer averaging below the assigned observation height also shifts the level of the maximum analysis increment lower in the atmosphere. Thus, it is evident that the choice of the observation operator will have an impact on the resulting analysis and consequently on the forecasts in addition to changes to the innovation statistics. Investigations on these issues continue.

9 Other ongoing activities

The next significant change in the operational use of AMVs will be the dissemination of the hourly GOES AMVs. The ECMWF system is prepared for the change. We are also expecting the first test data from Suomi NPP VIIRS and from METOP-A/B tandem AMVs in the near future to investigate the data quality and impact on model analyses and forecasts. Investigations with the METOP-A and METOP-B AMVs are also ongoing as discussed in Section 7.3.

The use of AMVs in the ECMWF system has changed significantly in the IFS cycle 40r1. In the light of all the changes it is justified to carefully revise the geographical and QI-dependent blacklisting for AMVs aiming possibly to increase the use of AMVs in the system.

Introduction of the situation dependent observation errors to the ECMWF system will have an impact on reanalysis activities as well. Height errors have been defined for the satellites that are currently in use but not for satellite, channel, and height assignment combinations prior to 2006. Currently, a default value of 80 hPa is used in all cases where the height error estimate has not been defined. Experimentation is ongoing to investigate how much impact the use of the default value instead of the more sophisticated height error estimates will have on the analyses and forecasts. If the impacts are significant, one possibility would be to define different default values for different heights.

Acknowledgements

Kirsti Salonen is funded by the EUMETSAT fellowship programme.

References

Bechtold, P., Bauer, P., Berrisford, P., Bidlot, J., Cardinali, C., Haiden, T., Janousek, M., Klocke, D., Magnusson, L., McNally, A., Prates, F., Rodwell, M., Vitart, F., 2012. Progress in predicting tropical systems: The role of convection. ECMWF Technical Memorandum No.686.

Bonavita, M., Isaksen, L., Holm, E., 2012. On the use of EDA background error variances in the ECMWF 4D-Var. QJRMS 138 (667), 1540–1559.

Bormann, N., Salonen, K., Peubey, C., McNally, T., Lupu, C., 2012. An overview of the status of the operational assimilation of AMVs at ECMWF. Proceedings of the 11th International Wind Workshop, Auckland, New Zealand, 20-24 February 2012.

Cotton, J., 2012. Fifth analysis of the data displayed on the NWP SAF AMV monitoring website. Available online at http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/.

Doutriaux Boucher, M., Carranza, M., 2013. Low level AMVs improvement following the introduction of the new AMV-CCC scheme in MSG-MPEF facility. EUMETSAT document.

Forsythe, M., Saunders, R., 2008a. AMV errors: a new approach in NWP. Proceedings of the 9th International Wind Workshop, Annapolis, Maryland, USA, 14-18 April 2008 EUMETSAT P.51.

Forsythe, M., Saunders, R., 2008b. Third analysis of the data displayed on the NWP SAF AMV monitoring website. Available online at http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/.

Hernandez-Carrascal, A., Bormann, N., 2012. Atmospheric Motion Vectors from model simulations. Part II: Interpretation as spatial and vertical averages of wind and role of clouds. ECMWF Technical Memorandum No.678.

Hernandez-Carrascal, A., Bormann, N., Borde, R., Lutz, H.-J., Wanzong, S., 2012. Using model simulations to improved the characterisation of current atmospheric motion vectors. Proceedings of the 11th International Wind Workshop, Auckland, New Zealand, 20-24 February 2012.

Salonen, K., Bormann, N., 2012. Atmospheric Motion Vector observations in the ECMWF system: Second year report. EUMETSAT/ECMWF Felloship Programme Research Report No.28.

Salonen, K., Bormann, N., 2013. Winds of change in the use of Atmospheric Motion Vectors in the ECMWF system. ECMWF Newsletter 136, 23–27.

Salonen, K., Cotton, J., Bormann, N., Forsythe, M., 2012. Characterising AMV height assignment error by comparing best-fit pressure statistics from the Met Office and ECMWF system. Proceedings of the 11th International Wind Workshop, Auckland, New Zealand, 20-24 February 2012.

Santek, D., 2011. Evaluation of new hourly GOES AMVs with Expected Error. Visiting Scientist mission report, Document NWPSAF-EC-VS-019.

Velden, C., S., Bedka, K., M., 2009. Identifying the uncertainty in determining satellite-derived atmospheric motion vector height attribution. J. Applied Meteorology and Climatology 2, 380–392.

Weissmann, M., Folger, K., Lange, H., 2013. Height correction of atmospheric motion vectors using lidar observations. JAMC 58, 1868–1877.