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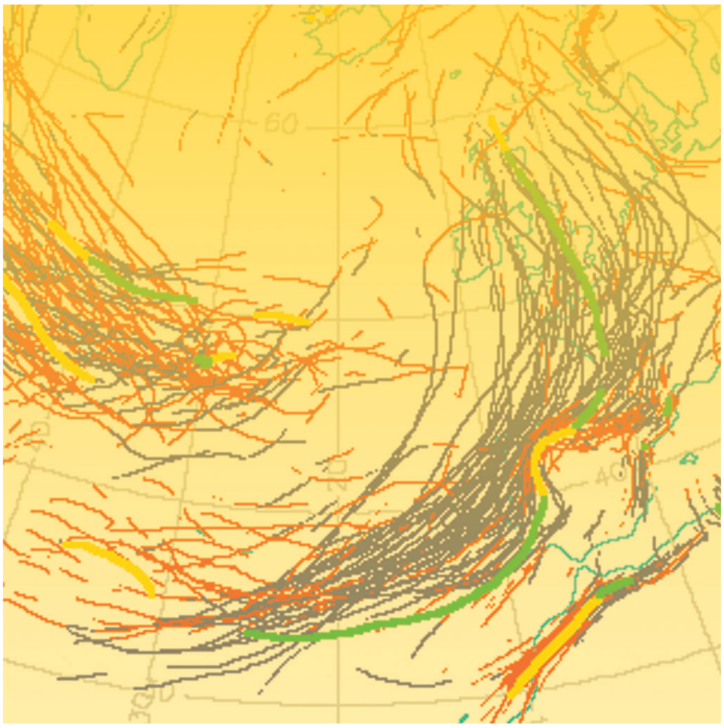

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Evaluation of AMVs derived from ECMWF model simulations

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In a collaborative project between ECMWF and the Cooperative Institute for Meteorological Satellite Studies (CIMSS), Atmospheric Motion Vectors (AMVs) derived from simulated image sequences have been investigated to shed further light on the interpretation of real AMVs used for NWP. This pilot study has demonstrated the potential of the simulation framework to characterize errors in actual AMVs and identified a number of issues that require further investigation. For example, the influence of cloud evolution and thickness on biases in AMVs has been highlighted, an area that has so far received much less attention than height assignment issues.

Improving the characterization and interpretation of AMVs

AMVs are wind observations derived from image sequences obtained from geostationary or polar-orbiting satellite data. They are an established ingredient to global and regional data assimilation systems. The wind information is retrieved by tracking features such as clouds in subsequent images, assuming that the feature acts as a passive tracer of the atmospheric flow. The resulting wind vector is assigned to a pressure level, typically an estimate of the cloud top for higher-level clouds, and the cloud base for lower-level clouds. ECMWF currently assimilates AMVs from five geostationary and two polar-orbiting satellites, with data derived at EUMETSAT, NOAA/NESDIS and JMA.

Monitoring of AMVs against short-range forecast information or against collocated radiosonde observations often shows considerable biases or larger, more random deviations in certain geographical regions. Particular problem areas are slow speed biases for high-level extra-tropical AMVs, and fast biases for mid-level AMVs in the tropics. It is generally accepted that a large proportion of these biases or deviations can be attributed to the indirect measurement method of AMVs. On the one hand, several steps in the AMV processing can introduce such errors, especially the height assignment which tends to rely on information from just a few infrared and water-vapour channels. On the other hand, the interpretation of the AMVs as single-level wind observations can also be prone to errors, for instance because the tracked motions may be more representative of a layer-wind, or because the tracked feature may not strictly be a passive tracer.

The assimilation of observations with systematic biases and geographically varying quality poses particular challenges for data assimilation. As the assimilation system assumes unbiased observations, biases need to be removed before or during the assimilation. This requires a good understanding of the biases and their origin, and an adequate model for the bias characteristics. For AMVs, modelling of biases has so far been unsuccessful, primarily owing to the indirect measurement method used in AMVs. Geographically varying quality of observations can be addressed through varying the observation error or through adequate quality control. Both require a good understanding of the sources of the errors.

Improvements in the characterization and interpretation of AMVs are therefore required for a better assimilation of AMVs in the ECMWF system. Further analysis of the origin of the errors and improvements in the interpretation of the AMVs are difficult as other correlative observations with sufficient coverage and including detailed information on winds and clouds are not usually available.

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A simulation framework has now been used in a pilot study to improve our understanding of AMVs and their interpretation. Image sequences were simulated from high-resolution ECMWF forecast fields over a 6-hour period (at T2047, ~10 km spatial resolution). AMVs were subsequently derived from these images at CIMSS. The derived AMVs, in turn, were compared back to the wind field of the atmospheric model underlying the image simulations. In this framework the 'true' wind field and the position and vertical extent of the cloud or humidity features are exactly known – they are given by the values from the high-resolution ECMWF forecast fields.

The simulation provides the opportunity to characterize in detail the errors that have arisen in the AMV processing and/or arise from the assumption that clouds are near-perfect passive tracers of the ambient wind at a single level and location. The study also allows us to shed light on height assignment which has long been established as one crucial area for AMV processing. The aim is to provide further characterization of AMVs which will lead to an enhanced assimilation of the data, for instance, through improvements in the interpretation of AMVs ('observation operator'), developments for a bias correction, or revisions to the quality control. The study was based on Meteosat-8 imagery (6.2, 7.3 and 10.8 µm channels), and the images were simulated every 15 minutes for clear and cloudy conditions using RTTOV-Cloud, a radiative transfer model.

An example of simulated and observed images from two channels is shown in Figure 1. For our purposes, an exact correspondence between the simulated and observed images is of secondary importance; more important is that the general structure and spatial details of the simulated images adequately resemble the observed ones. Generally speaking, this is the case – the simulated images indeed appear realistic. However, it is also clear from just this one example that there is additional small-scale structure in the real infrared image, for example around the frontal band in the upper half of the images (Figure 1a). This is not too surprising, as the model resolution that is currently possible with the Integrated Forecast System (IFS) used for this study is still significantly lower than the 3–5 km resolution of today's geostationary imagers. Also, in contrast to the infrared simulation, the simulated water-vapour image shows an under-representation of cirrus (Figure 1b). Such shortcomings in the simulation approach have to be kept in mind when interpreting the results, as the underlying assumption of using simulated imagery for the characterization of AMVs is that the simulation adequately represents reality.

The winds derivation for this study was performed by CIMSS, using an algorithm that is similar to that used by NOAA/NESDIS for the operational derivation of GOES AMVs. The processing requires as input atmospheric background information which is used in the quality control of the data as well as in the height assignment. Two AMV datasets were provided by CIMSS, one using the operational forecasts from NOGAPS (Navy Operational Global Atmospheric Prediction System) as background and one in which ECMWF model data from the 'truth' forecast was used as background information. Comparison of the two sets allows us to investigate the relative impact of the model data on the AMV product. CIMSS made winds available in two forms: before quality control ('raw') as well as quality-controlled AMVs. The latter passed a number of internal quality checks and were post-processed by a recursive filter, the so-called auto-editor.

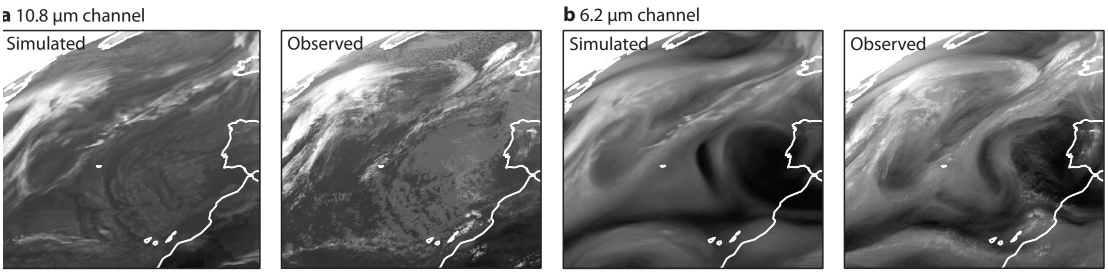

Figure 1 Detail of simulated (left) and observed Meteosat-8 (right) images for (a) infrared 10.8 µm and (b) 6.2 µm channels at 15.45 UTC on 2 January 2006.

Comparison to monitoring statistics for real AMVs

As a first step, difference statistics for the simulated AMVs against the model truth can be compared to monitoring statistics of real AMVs against a short-term forecast (first guess). The patterns of speed biases and normalized root mean square vector differences (NRMSVD) for simulated and observed AMVs show several similarities. For example, compare the zonal mean speed bias (AMV minus 'truth') for simulated infrared AMVs before auto-editing (Figure 2a) and after auto-editing (Figure 2b) with the equivalent bias for real Meteostat-8 AMVs (Figure 2c). For the three datasets, negative speed biases prevail at high levels in the extra-tropics and positive biases at mid-levels in the tropics, especially in the simulated AMVs before quality control.

Overall, it appears that a simulation study of this type can adequately represent true observation statistics. Nevertheless, some differences exist, for instance in terms of the coverage in the vertical of water-vapour winds (not shown) or the zonal mean bias characteristics for low-level AMVs. Note, that real AMV first-guess statistics include contributions from the forecast errors, whereas for the simulations we compare AMVs to the 'truth'. Also, the real Meteosat-8 AMVs were derived with the EUMETSAT processing rather than the CIMSS processing; however, differences in monitoring characteristics for EUMETSAT and CIMSS-derived AMVs are usually reduced when CIMSS winds before auto-editing are considered (e.g. http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/index.html).

Next, the influence of the atmospheric background information can be studied. This background information is used in the derivation of the winds for the initial height assignment and in complex quality control procedures. Considering the AMVs before the quality control, it was found that the influence of the background data on the height assignment has little impact on the AMV quality in our simulations. AMVs derived with the NOGAPS background compared similarly well to the truth from the forecast simulation as AMVs derived with knowledge of this truth. It appears that the height assignment has relatively small sensitivity to the background used in the processing, at least within current short-term forecast errors. This is an important finding for NWP, as it is easier to assimilate observations that are independent of short-term forecast errors.

Though the height allocation appears relatively insensitive to the background, the quality control introduces a noticeable dependence on the background information used in the processing. After the CIMSS quality control, AMVs derived and post-processed with ECMWF fields compare better with the 'true' winds than those derived and quality-controlled with NOGAPS fields (e.g. bias and NRMSVD for high-level cloudy water-vapour AMVs over the southern hemisphere are –1.5 ms–1 and 0.38 for NOGAPS AMVs, and –0.6 ms–1 and 0.35 for ECMWF AMVs). The ECMWF fields used represent the truth in this study, so that the processing with the ECMWF fields eliminates forecast errors otherwise present in the NWP data. The finding that winds processed with the NOGAPS forecasts compare more poorly to the truth suggests that the CIMSS quality control shows some sensitivity to forecast errors. However, NWP errors are also clearly not a dominant error source.

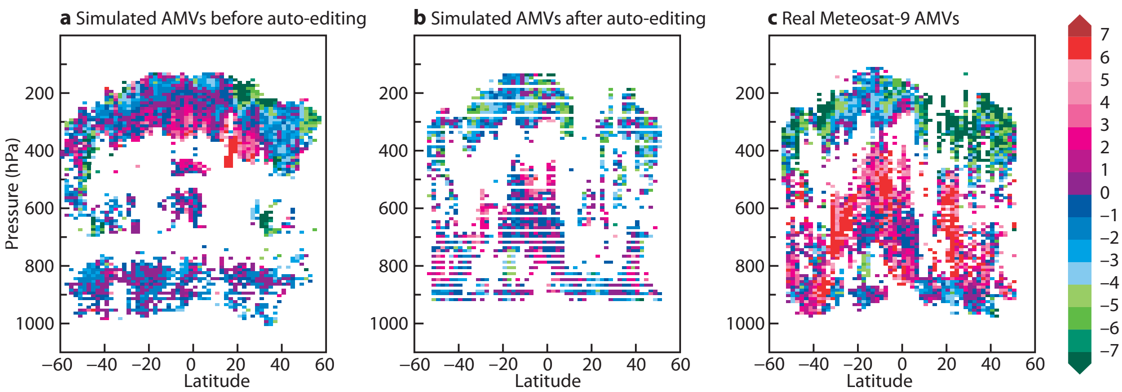

Figure 2 Zonal mean speed bias (AMV minus 'truth', ms–1) for simulated infrared AMVs (a) before auto-editing and (b) after auto-editing derived with the NOGAPS background for 12–18 UTC on 2 January 2006 (the stripes are due to the discretization of the background data). (c) The equivalent zonal mean speed bias for real Meteosat-8 AMVs. Quality Indicator > 60% – this is a measure of the AMV's consistency within the derived wind field. The numbers of winds used in the three sets of results are 27,504, 18,884 and 43,056.

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The quality control and auto-editing step is an important and complex part of the AMV derivation in the CIMSS processing. It excludes winds based on various consistency checks, and also includes adjustments to the wind speed and possibly the assigned height. The latter is performed as part of the recursive filter analysis and also involves the model background. For the simulated dataset, we found that the main effect of the step is the removal of poorer winds, whereas the adjustments to the wind speed or the assigned pressure were overall relatively small. One exception is mid-tropospheric winds from the infrared channel, for which an average raising of the AMVs by 26 hPa helped to reduce a fast bias versus the true wind field. The findings are in contrast to the monitoring statistics for the AMVs from the NWP Satellite Applications Facility (http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/index.html). Those statistics indicate considerable differences between raw and auto-edited winds resulting from speed adjustments.

Investigation of a problem area: high-level cirrus clouds

Monitoring of real extra-tropical high-level AMVs (especially in higher wind-speed regimes) typically shows negative speed biases against both other observations and model data. Such biases were also found in the simulated data, and it was therefore decided to investigate these in further detail.

The negative speed bias is commonly attributed to height assignment problems. However, during the course of the present study it was found that height assignment alone cannot explain all biases found in the simulated dataset. In the following, we will therefore characterise the negative bias only for situations in which height assignment can be ruled out as primary error source, i.e. situations with little vertical wind shear and no multi-layer clouds (with the selection based on the high-resolution ECMWF forecast, i.e. the true atmosphere for our study setup). The limitation to situations in which height assignment should be of lesser importance simplifies our analysis; of course for the general case the height assignment provides an additional source of bias.

Strong negative speed biases in the AMVs are still present in situations with little vertical wind shear and no multi-layer clouds. This can be seen in Figure 3b which shows that for many simulated AMVs the wind speed is considerably lower than the average model speed within the cloud used for tracking. In contrast, the model wind speeds at the assigned heights agree well with the average model speed within the cirrus cloud as indicated in Figure 3a); this is as expected for cases with little wind shear. This confirms that height assignment is a minor error source for the selected cases, as intended by our selection. The main deviations between AMVs and the truth must therefore arise from uncertainties in the tracked speed.

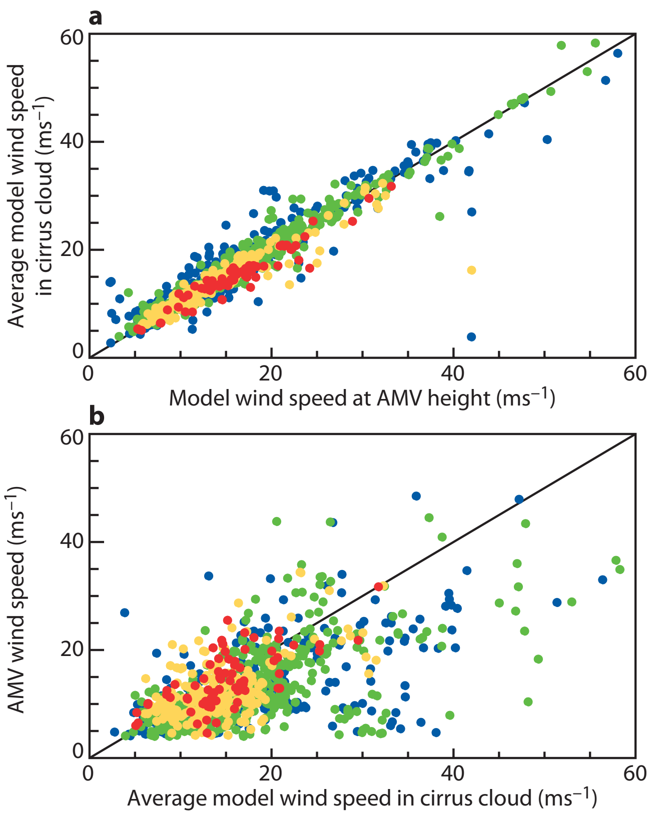

Figure 3 (a) Scatter diagram of the layer-mean model wind speed (ms–1) in the selected cirrus cloud versus the single-level model speed at the originally assigned height for simulated infrared AMVs. See the main text for further details on the selection. (b) Scatter diagram of the speed of the simulated AMV (ms–1) versus the mean model wind speed in the cirrus cloud for the selected cases. For both panels, the colour coding corresponds to the thickness of the cirrus cloud in terms of numbers of model levels. Blue, green, yellow, red is from thin to thick cirrus. These results are based on ‘raw’ AMVs, i.e. before auto-editing, with Quality Indicator > 60%.

The systematic biases for the selected cases were further characterized as a function of the thickness of the cirrus clouds and its temporal evolution. Such detailed information is readily available in the simulation framework, as the true cloud fields that led to the simulated image sequences are known at their full resolution. Investigations of this kind explore the full potential of the simulation framework.

The investigations showed that the speed bias is stronger for thinner cirrus clouds, whereas thicker cirrus clouds show less bias. This can be seen in Figure 3b, where simulated AMVs derived from thin cirrus clouds (blue and dark green dots) show a particular tendency to have winds speeds lower than their model counterparts. However, simulated AMVs derived from thick cirrus (red dots) are much more symmetrically distributed around the diagonal. A similar analysis showed that clouds exhibiting more temporal evolution within the image-sequence used for the winds derivation also showed larger biases. It is apparent that such situations will pose a challenge to any winds derivation, and it is interesting that the simulation framework can be used to highlight such cases.

Further studies required

The pilot study to use simulations to characterize errors in current AMVs has shown that this method provides a framework with great potential for a better understanding and interpretation of AMVs. The study already provides a number of interesting insights. The interpretation of the results for real AMVs is, however, not straightforward, not least due to the limited study period of 6-hours and the still considerable differences between the nominal model resolution of 10 km and that of today's geostationary imagers (3–5 km). Nevertheless, the study poses some important questions that deserve further attention.

Especially intriguing is the finding that cloud evolution contributes to the bias seen for high-level winds in the simulated dataset. While physically very plausible, this is an aspect that has received much less attention over the years compared to, for instance, the issue of height assignment for AMVs. Height assignment is doubtlessly a crucial issue for AMVs, but the assumption that clouds are passive tracers is equally fundamental in the interpretation of AMVs. Further studies are needed to determine to what extent clouds can be treated as passive tracers. One possibility would be to use the simulation framework, but to derive AMVs directly from model cloud fields on model or isentropic levels, in order to further simplify the height assignment aspect. A cloud-resolving model may be more suited for this purpose than the global ECMWF model. Another possibility would be to investigate with real AMVs whether situations with thin cirrus clouds and a certain cloud evolution over the tracking period can be linked to stronger biases in the AMVs. If the current findings apply to real data, a quality flag that indicates cloud thickness could prove a useful addition to the AMV product. Further insights are also expected when AMVs can be compared to data from ESA's future ADM-Aeolus wind lidar.

There is clearly scope for further investigations with the simulation framework, and such studies have been recommended by various international bodies, such as the International Winds Working Group. The aspect of interpreting AMVs as layer or horizontal averages rather than single-level point observations could be studied in more detail. This may lead to a reduction in the bias in the interpretation of AMVs. Also, the simulation framework lends itself well to the study of spatial or temporal error correlations in AMVs. Accounting for such error correlations in the assimilation is currently under investigation at ECMWF. At the same time, further work is required to further establish the realism of the simulations and their shortcomings, for example, due to the model resolution, the model cloud parametrization, or the radiative transfer modelling.

It is planned that further simulation studies will be performed in the future, in collaboration with European and American satellite agencies and partners, with the aim of optimizing the processing and interpretation of AMVs and their use in today's assimilation systems.

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