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Using simulated satellite images to improve the characterization of Atmospheric Motion Vectors (AMVs) and their errors for Numerical Weather Prediction

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Abstract

Atmospheric Motion Vectors (AMVs) have been derived at CIMSS from synthetic satellite images, simulated from a high-resolution ECMWF model forecast, and the resulting AMVs have been compared to the model wind field used in the simulation. This framework is attractive as the atmospheric truth (including the wind field and cloud distribution) is exactly known, allowing a detailed characterisation of AMVs, their processing, and their interpretation as single-level wind observations. Caveats are that the cloud representation in the forecast model may still differ from reality and that the model resolution used (~10km) still lags behind the resolution of today's satellite imagery used for AMV derivation (typically 3-5 km). The study is primarily intended as a proof-of-concept study.

Comparison statistics for simulated AMVs against the model truth are broadly similar to monitoring statistics commonly observed for real AMVs. In particular, slow speed biases prevail at high levels in the extra tropics, and fast biases in the tropics. An analysis of the CIMSS quality control reveals that the auto editor acts more through data removal than through data adjustments in the simulated dataset. Also, the use of forecast data in the quality control step has a small, but noticeable effect on the final wind dataset, whereas winds before CIMSS quality control show little sensitivity to the forecast data used in the processing. A detailed study of two situations with known problems for real AMVs (low-level inversions and high-level winds) shows rather noisy wind speeds in both situations. Also, for high-level winds, speed biases are still present even in situations when height assignment is less important, and these biases appear to be linked to cloud thickness and evolution over the tracking period. Further studies are suggested to corroborate the current findings and to evaluate the applicability of the findings to real data.

1 Executive summary

Atmospheric Motion Vectors (AMVs) derived from image sequences obtained from geostationary or polar satellite data are an established ingredient to global and regional data assimilation systems. However, the monitoring of AMVs against model short-range forecast (first guess) information that is used in the assimilation or against collocated radiosonde data often shows considerable biases or larger, more random deviations in certain geographical regions. It is generally accepted that a large proportion of these biases or deviations can be attributed to the indirect measurement method of AMVs, i.e. the AMV processing and the interpretation of the AMVs as single-level wind observations. Further analysis of the origin of the problems and improvements in the interpretation of the AMVs are difficult as "ground-truth" data with sufficient coverage and including detailed information on clouds is usually not available. The cross-validation with space-borne observations that observe wind speeds in the troposphere should be considered when these data become available. Cloud-track winds from the MISR (Multiangle Imaging Spectro Radiometer) instrument on-board of Terra or Doppler wind lidar measurements from the Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus) are very good candidates for cross-checking and validation of the passive tracer assumption for AMVs. Instantaneous observation of clouds and their properties are excellent benefits of these missions to prove the concept of AMVs.

The rationale of this study has been to investigate AMVs derived from simulated image sequences covering a 6-hour period by comparing the derived AMVs to the wind field of the atmospheric model underlying the image simulations. Recent studies have shown this to be an effective approach for examining the potential properties of AMVs from future satellites/instruments (Velden et al. 2005, Wanzong et al. 2007, Genkova et al. 2007). In this framework the "true" wind field and the position and vertical extent of the cloud or humidity features are exactly known. This 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. The study also allows us to shed light on height assignment which has long been established as one crucial area for AMV processing.

There are of course some caveats with the approach of this study. Firstly, the chosen 6-hour period is rather short, and the study is primarily intended as a demonstration study. Secondly, the underlying assumption of using simulated imagery for the characterization of AMVs is that the simulation adequately represents reality. While past studies have demonstrated a high degree of realism in cloudy satellite images simulated from ECMWF fields, they also found shortcomings, for instance in the representation of cirrus clouds (e.g., Chevallier and Kelly 2002). Also, the model resolution that is computationally possible for this study is still significantly lower than the 3-5 km resolution of today's geostationary imagers. Therefore, it should be stressed that not all findings of the study will be directly valid for real observations and some care will be needed when interpreting the results.

1.1 Simulated data

An ECMWF model forecast at very high spatial resolution (T2047, ~10 km) was computed to simulate Meteosat-8 infrared imagery (6.2, 7.3 and 10.8 µm) in clear and cloudy conditions. This forecast serves as the "true" atmosphere in our framework. The images were simulated with RTTOV-Cloud (e.g., Chevallier and Kelly 2002) and model fields between the 24 and

30-hour forecast range in 15-minute intervals were used for the simulation (covering 12-18 Z on 2 January 2006). Figure 1.1 (top) shows an example of a simulated and the corresponding observed IR image. While the simulated image appears generally realistic, there is clearly additional structure in the real infrared image. In contrast to the infrared simulation the simulated WV image shows an under-representation of cirrus (e.g., Fig. 1.1, bottom).

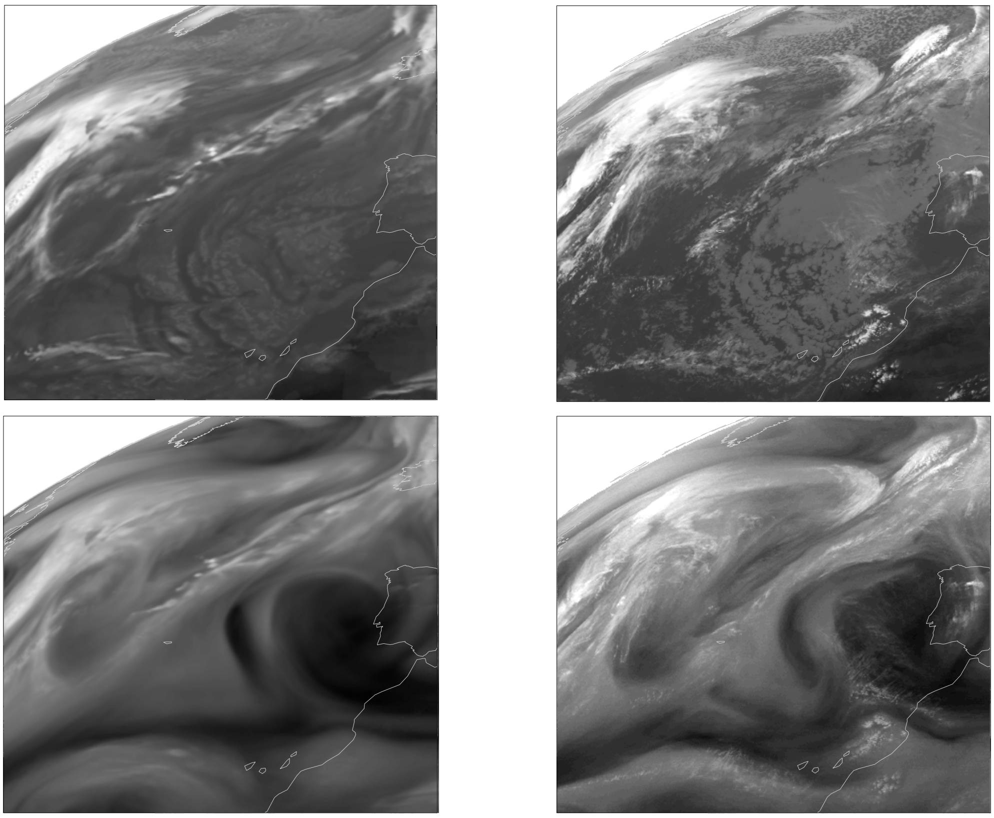


Figure 1.1: Simulated (left) and observed Meteosat-8 (right) IR 10.8µm (top) and 6.2µm (bottom) image (2 Jan 2006, 15.45UTC).

The sequences of images were processed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) to derive AMVs using the standard CIMSS processing (e.g., Velden et al. 1997; Nieman et al. 1997). The CIMSS retrievals were processed with operational NOGAPS forecasts and ECMWF model data from the “truth” forecast, respectively. This allows us to investigate the relative impact on the AMV product. CIMSS made available the winds sets before quality control (“raw”) as well as quality-controlled AMVs; the latter having passed a number of internal quality checks and having been post-processed by a recursive filter (e.g., Hayden and Purser 1995).

1.2 General results

1.2.1 Comparison to monitoring statistics for real AMVs

Difference statistics for simulated AMVs against the truth can be compared to monitoring statistics of real AMVs against a short-term forecast (first guess, FG). The patterns of speed biases and normalized root mean square vector differences (NRMSVD) for simulated and observed AMVs show similarities (e.g., Fig. 1.2, middle and right), with negative speed biases prevailing at high levels in the Extra-tropics and positive biases at mid-levels in the Tropics, especially in the dataset before quality control. The bias in the Northern Extra-tropics for IR high-level AMVs is -1.64 m/s and -0.96 m/s for simulated AMVs (after auto-editing) and real observations, respectively. NRMSVD values are 0.32 and 0.29, respectively. This confirms 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 WV winds. Note, that real AMV-FG statistics include contributions from the forecast errors, whereas for the simulations we compare AMVs to the "truth". Unfortunately, it is not possible to quantify the differences that arise from the different AMV processing in the real observations (EUMETSAT processing) and the simulated AMVs (CIMSS processing). Note also that the study period is rather limited and statistics may change slightly for different time periods.

1.2.2 Influence of CIMSS quality control

For the set of AMVs before quality control, no significant differences could be found between the retrievals based on the ECMWF "truth" and the ones based on NOGAPS forecast data. For the "raw" AMVs, the forecast data is used in the height assignment step only, and it appears that errors in the forecast data are less important in this step in our simulation.

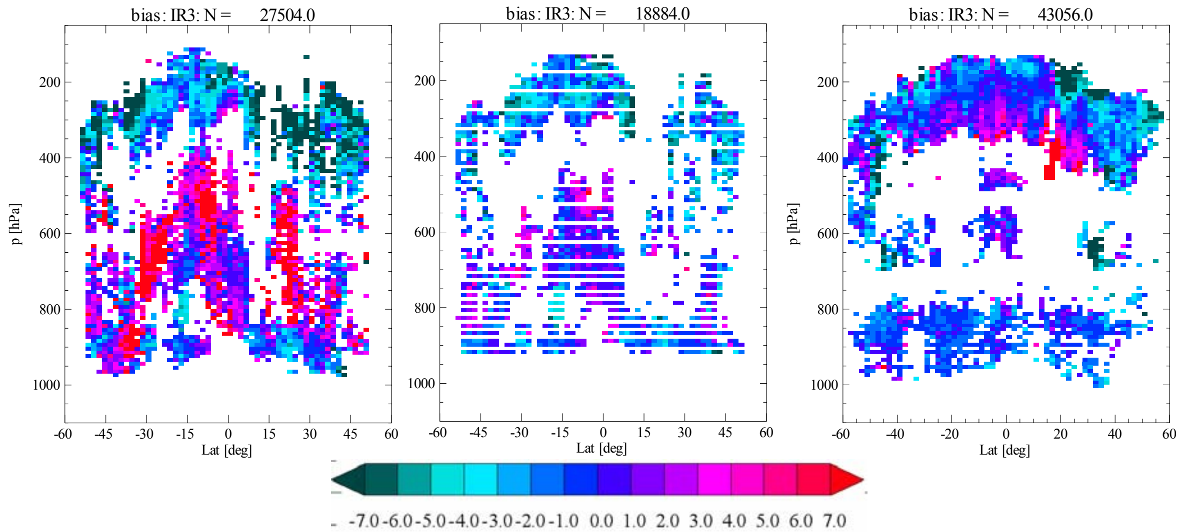


Figure 1.2: Zonal mean speed bias (AMV-truth, m/s) for simulated IR AMVs (left before auto-editing, middle after auto-editing) derived with the NOGAPS background. Also shown is the equivalent zonal mean speed bias for real Meteosat-8 AMVs (Jan 2006 12-18UTC). Quality indicator>60. Numbers at the top indicate the number of winds in the sample.

Application of the "auto-editor" and other quality-control measures improve the comparison statistics considerably, but mainly through data removal rather than correction. Figure 1.2 (left) is for IR "raw" AMVs and the bias and NRMSVD (not shown) are very large (-5.89 m/s and 0.60, respectively). In the post-processing about 9000 AMVs were excluded.

After the CIMSS quality control, AMVs derived and post-processed with ECMWF fields compare better with the "true" winds than those derived with NOGAPS fields. 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 the dominant error source.

In the CIMSS processing, the auto-editor also increases the wind speed for certain high-level winds, and it allows adjustments to the assigned heights. The latter is based on deriving a "best fit" pressure relative to an analysis of the 3-dimensional AMV wind field, with NWP model data as a background constraint.

A detailed analysis of the auto-editor changes reveals that the modifications are relatively small for the simulated dataset. For IR high-level winds (H_2O intercept method used for height assignment) the speed-up is, on average, from 12.1 m/s to 12.35 m/s and the auto-edited winds are assigned, on average, only 3 hPa lower in the atmosphere. This height difference corresponds to a mean model speed change from 14.26 to 14.10 m/s. The AMV-minus-truth bias is therefore only reduced from -2.16 to -1.75 m/s. NRMSVD drops from 0.43 to 0.4, only. WV winds are comparable. The findings are somewhat in contrast to the experience from NWP SAF AMV monitoring statistics (http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/index.html) where considerable differences are found between raw and auto-edited winds. This may be due to the under-representation of high cirrus clouds in the simulated images as noted earlier.

The most significant and positive changes due to the auto-editor can be reported for mid-level IR winds (with IR window channel method used for the height assignment). The auto-editor assigns winds about 26 hPa higher, which corresponds to a model speed increase of 0.65 m/s. The positive bias is reduced from 0.70 m/s to 0.17 m/s.

1.3 Analysis of two situations with known problems for real AMVs

Two case studies focus on situations in which AMV retrievals generally exhibit systematic problems, namely lower level temperature inversions with clouds near the top of the planetary boundary layer and cirrus clouds. For both case studies only situations with idealistic atmospheric conditions are extracted.

1.3.1 Low-level temperature inversions

Low-level temperature inversions in tropical regions are areas in which GOES AMVs typically exhibit considerable positive biases, for instance over the eastern Pacific. Investigations at ECMWF and the Met.Office (Forsythe, pers. communication) suggest that GOES low-level winds tend to be assigned too high in the atmosphere in these conditions. The origin of the problem is unlikely to be linked to the GOES imager, but rather to the AMV processing, and it is therefore studied here with the Meteosat-8 data. CIMSS/NESDIS employs a "cloud base" reassignment method to most low-level marine tracers, based on a histogram method (LeMarshall et al. 1993). The approach lowers height assignments from the IR-W cloud top to an estimated cloud base.

To investigate AMVs in low-level temperature inversion regions, we extracted only those AMVs for which a low-level temperature inversion could be detected in the ECMWF model truth. The simulation framework allows us to compare the simulated AMVs with the true model wind at the inversion cloud as inferred from the model cloud cover field. Only IR AMVs are investigated here. The main findings for simulated AMVs are:

i) Assigned AMV heights are too low in the atmosphere (~20 hPa), i.e. below the detected model cloud base. This finding is in contrast to the experience with real AMV retrievals.

ii) The correlation between model wind speeds at the assigned height and at the cloud base height is very high (Fig. 1.3, left). It can be concluded that exact height assignment is of minor importance.

iii) The correlation between observed AMV speeds and model speeds (at cloud base height or assigned height) is poor (Fig. 1.3, right). It can be concluded that the derived speeds are very noisy. This may be due to the lower wind speeds and the spatial resolution of the model simulation (~10 km) which is still considerably poorer than that of today's geostationary imagers (3-5 km).

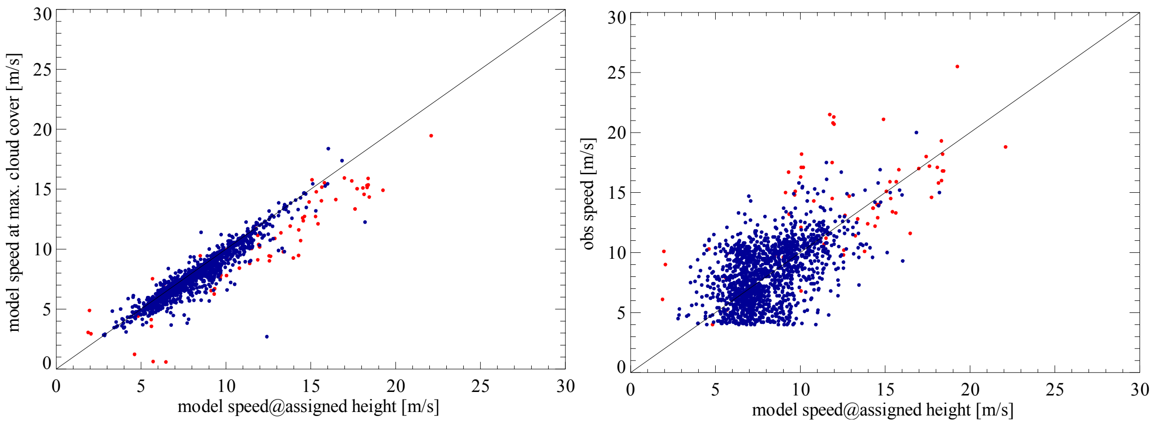


Figure 1.3: Extracted cases with low inversion clouds. Model speed at inversion cloud base (left) and observed AMV speed (right), respectively versus model speed at originally assigned AMV height (after auto-editing and QI>60).

1.3.2 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 further.

The negative speed bias is commonly attributed to height assignment problems (e.g., Bormann et al. 2002). 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 (selection being based on the model data). The limitation to situations in which height assignment should be of lesser importance does not mean that height assignment does not provide another additional source of bias in the general case.

In the following, only high-level IR and WV winds with the H_2O intercept method have been investigated, and we restrict our sample to situations with little vertical wind shear and without multi-layer clouds. Only "raw" winds are considered. The main findings are:

i) Strong negative speed biases are still present in situations with little vertical wind shear and no multi-layer clouds.

ii) Model wind speeds at assigned heights agree well with linear averages of model speeds in the cirrus cloud (Fig. 1.4, left). 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 (Fig. 1.4, right) arise from uncertainties in the tracked speed

iii) The negative bias is larger for thin cirrus. IR AMVs have larger bias than cloudy WV AMVs (-3.7 and -3.0 m/s, respectively).

iv) The bias appears to be linked to changes in the evolution of the clouds: Situations with a change in the tendency of the cloud evolution during the tracking (e.g., cloud decay followed by cloud growth) show the highest bias in the AMVs. The effect of cloud evolution was studied using the model cloud data associated with the images used in the tracking.

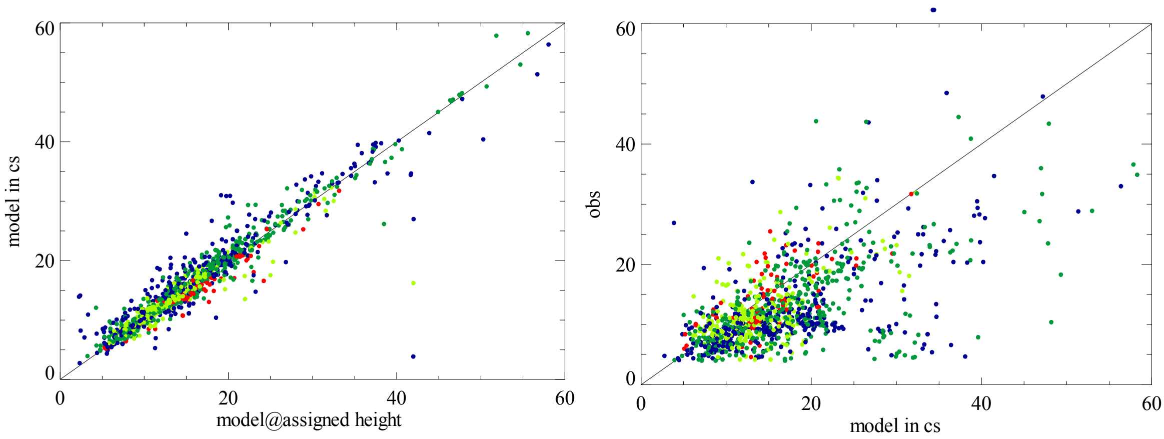


Figure 1.4: Mean model wind speed [m/s] in the cirrus cloud versus model speed at the originally assigned height for IR AMVs (left). On the right the observed AMV speed [m/s] is plotted versus the mean model wind speed in the cirrus cloud. The colour coding corresponds to the thickness of the cirrus cloud in terms of numbers of model levels. Blue, dark green, bright green, red is from thin to thick cirrus. ("raw" AMVs, i.e. before autoediting, QI>60).

1.4 Results and recommendations

In this study we used AMVs derived from images simulated from a high-resolution ECMWF forecast to investigate characteristics of AMV data. The main findings are:

- The simulated AMVs exhibit broadly similar characteristics against the model truth as are commonly observed in monitoring statistics of real AMVs against short-range forecasts. This indicates that, overall, the simulation is adequately representing the characteristics of the real data.
- Before the CIMSS quality control, the simulated AMVs show relatively little sensitivity to the source of forecast data used in the AMV processing. However, quality control in the CIMSS processing (including the auto-editor) is sensitive to the choice of forecast data. For the given dataset, the CIMSS quality control acted primarily through removal of poorer data, rather than through adjustments to the assigned height in the auto-editor.
- At least some of the negative bias observed at high levels in the extra-tropics appears to be due to the fact that clouds do not act as passive tracers and their motions do not

fully represent the ambient wind. Biases are still present in situations in which height assignment is of less importance, and the largest biases are observed for thin cirrus clouds with considerable evolution between the images used in the tracking.

- Characteristics for AMVs in low-level inversion regions point to tracking problems in the simulated dataset. The characteristics for the simulated data agree less with experience from real AMVs in these situations.

The above findings for the simulated AMVs provide a number of interesting insights into AMVs and their interpretation. The interpretation of the results for real AMVs is 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 completely eliminate 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 whether stronger biases in real data can be related to very thin cirrus clouds and situations with a certain cloud evolution over the tracking period. If the current findings apply to real data, a quality flag that indicates cloud thickness could prove a useful addition to the AMV product.

There is also still scope for further investigations based on the current dataset. Comparisons to EUMETSAT-derived AMVs will further highlight the differences in the AMV processing and quality control used at CIMSS and at EUMETSAT. EUMETSAT-derived winds were not yet available for the present study, but should be available in due course. Furthermore, the aspect of interpreting AMVs as layer or horizontal averages rather than single-level point observations could be studied in more detail. Also, the simulation framework lends itself well to the study of spatial error correlations in AMVs (e.g., Bormann et al. 2003).

For future simulations, we recommend a higher model resolution and a longer study period.

2 Introduction

AMVs derived from image sequences from geostationary or polar satellite data are an established ingredient to global and regional data assimilation systems. However, monitoring of observed AMVs against short-range forecast information used as a first guess in the analysis often shows considerable biases or larger, more random deviations in certain geographical regions. It is generally accepted that a large proportion of these biases or deviations can be attributed to the indirect measurement method of AMVs, i.e. the AMV processing and the interpretation of the AMVs as single-level wind observations. This can be concluded from the fact that similar monitoring pattern have been found in several NWP systems. Similar features are also found in studies in which AMVs from different sources are collocated between each other and collocated with other observations. Further analysis of the origin of the underlying problems and improvements in the interpretation of the AMVs are difficult as “ground-truth” data with sufficient coverage is usually not available.

The rationale of this study is to investigate AMVs derived from simulated image sequences by comparing the derived AMVs to the model wind field 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. This provides a unique opportunity to characterize in detail the errors that have arisen in the AMV processing or the interpretation of AMVs as single-level data. Liaison with the winds producers makes it possible to attribute errors to various aspects of the processing, such as tracking, height assignment, or other ad-hoc adjustments. Using AMV data, extracted at different stages of quality control, allows specific aspects to be studied in greater detail. This is the first time that such AMV simulations in clear and cloudy conditions have been performed with ECMWF forecast data.

There are of course some caveats with the approach of this study. Firstly, the study period of 6-hours is rather short, and it is primarily intended as a demonstration study. Secondly, the underlying assumption of using simulated imagery for the characterization of AMVs is that the simulation adequately represents reality. While past studies have demonstrated a high degree of realism in cloudy satellite images simulated from ECMWF fields, they also found shortcomings, for instance in the representation of cirrus clouds (e.g., Chevallier and Kelly 2002). Also, while the model resolution of 10 km was the highest resolution computationally possible with the ECMWF model at the time, it still falls short of the 3-5 km resolution of today’s geostationary imagers. Therefore, it should be stressed that not necessarily all findings of this study will be directly valid for real observations and some care will be needed when interpreting the results.

Section 3 of this report describes the setup and data available to this study. In Section 2 the delivered AMV data sets from CIMSS are investigated. Special focus is given to the quality improvement during the post-processing. The following two sections describe two case studies that have an idealistic setup, i.e. the reason for deviations between observation and truth is pinpointed to one single aspect. Other aspects (error sources) are assumed to be excluded. Here, low level winds derived from infrared channel data in case of temperature inversion clouds are chosen as well as high-level winds related to isolated cirrus clouds that are obtained from infrared and water vapor channel data.

3 Set-up and data

3.1 Forecast model and satellite image simulation

The image sequences for this project were simulated by ECMWF using data from a high-resolution global model run of the ECMWF forecast model. The resolution corresponds to a wave-number cut-off of T2047 which translates to about 10km horizontal resolution. The vertical resolution was 60 levels. The model was initialized on 1 January 2006 with the operational ECMWF analysis and ran up to lead-time +30h. In the time interval +24h to +30h the model output was archived every 15 minutes and was subsequently used as input to RTTOV_CLD (e.g., Chevallier and Kelly 2002) to simulate Meteosat-8 images. Images for the 12, 13.4 and 10.8 micron (infrared), and the 7.3, 6.2 micron (water vapor) channels of SEVIRI have been computed at these 25 time steps for the Meteosat-8 (MSG-1) target area. The image sequences for the 7.3, 10.8 and 6.2 micron channels have been made available to the University of Wisconsin (CIMSS), and all simulated channels were given to EUMETSAT in order to derive AMVs. Note that we did not add measurement noise to the simulated images, as the focus of this study is to characterize the errors in the AMV processing and the AMV interpretation.

Figure 3.1 (top) shows an example of a simulated and the corresponding observed infrared (IR) image. While the simulated image appears generally realistic, there is clearly additional structure in the real IR image. In contrast to the infrared simulation the simulated water vapour (WV) image (Fig. 3.1, bottom) clearly shows an underrepresentation of cirrus.

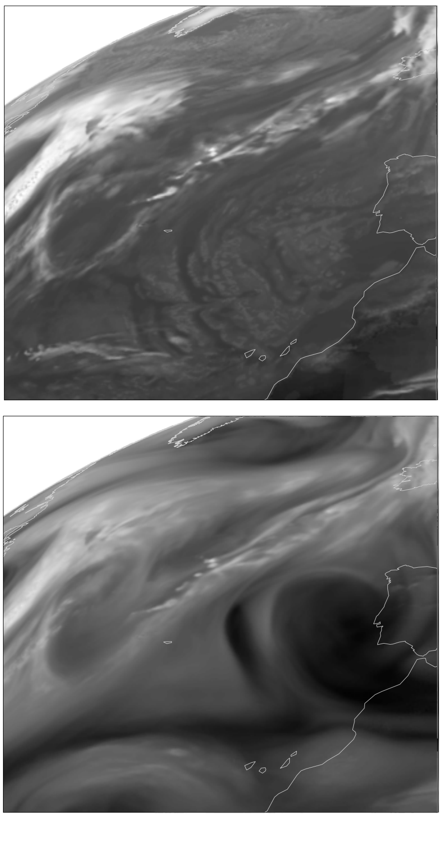


Figure 3.1: Simulated (left) and observed Meteosat-8 (right) IR 10.8µm (top) and 6.2µm (bottom) image (2 Jan 2006, 15.45UTC).

3.2 Derived AMV data sets

For this visiting scientist project only AMV datasets from CIMSS were available, i.e. the findings in this report focus on aspects of the CIMSS AMV derivation chain (auto editor, post-processing, Velden et al. 1997) and on two more generic case studies.

The AMV derivation procedure used at CIMSS requires NWP model data for the height assignment step and for quality control. Therefore all required model data of this forecast simulation, including zonal and meridional (u,v) wind components, temperature, and humidity were given to CIMSS with a degraded horizontal resolution (1 degree x 1 degree) at standard pressure levels. In order to compare the dependency of the AMV quality on the used NWP model, CIMSS prepared a second AMV data set that used NOGAPS forecasts instead. This also allows the characterization of how errors in the NWP model fields influence the derived AMVs.
CIMSS uses 3 subsequent images in the derivation process to compute AMVs for the middle image. This results in a half-hourly resolution of the AMV data sets that were delivered in 12 time slots along the investigated period.
CIMSS has compiled 5 data sets for each NWP background field, i.e. AMVs are removed from the original data set and/or AMVs are changed in an automated process by the so-called autoeditor in four steps. The following data sets are available:

i) all: all winds derived, relaxed check against NWP model background (50 m/s).
ii) raw: winds from step i) with tighter check against background (usually referred to as "raw" winds by CIMSS (pre-Quality Control, pre QC).
iii) check: as ii) with three different checks applied:
   (1) cirrus check modifies the heights of the wind vectors in multi-deck cloud scenes with cirrus present. Heights are adjusted upwards in the atmosphere.
   (2) IR wind check removes low to mid-level IR winds that differ significantly from the model backgrounds speed and direction.
   (3) slow check removes mid-level winds with large speed differences from the model ground whose height assignment was determined by the H_2O intercept method (Bowen and Saunders, 1984).
iv) autoe: as iii) and application of the auto-editor (speedup in extra-Tropics and height reassignment).
v) final: as iv) with re-evaluation of winds in strong high-level jet regions that have been rejected in the previous step (post-QC).

As an example, the quality of the different IR data sets is discussed in Section 4.2 in terms of observation-minus-first guess (obs-fg) biases.

3.3 Model equivalent winds

The quality of the simulated AMVs is checked and expressed as deviation from the ECMWF model background (first guess, fg) which provides the true wind field in this study. To provide model equivalent fields, the ECMWF fields were horizontally and vertically interpolated to the locations provided in the AMV dataset. The horizontal interpolation was performed on a reduced Gaussian grid using 4-point bilinear interpolation and the full model resolution data. In a second step, the vertical interpolation of the wind components was performed with pressure coordinates to the assigned AMV height (pressure), and wind speed and direction was computed.

Throughout the whole study it must be kept in mind that the model equivalent wind is a point value while a derived AMV depends on a large-scale cloud field in the simulated images. However, we assume that the derived AMVs are assigned to the centre of the cloud feature and that, apart from horizontal smearing, obs-fg statistics are meaningful.
The used error (deviation) metrics are systematic error (speed bias), mean vector difference (MVD), normalized root mean square vector difference NRMSVD (normalized with model speed). The deviation is defined as obs-fg.

4 Characterization of simulated AMVs

In this section the quality of different derived CIMSS AMV data sets is compared to the wind from the ECMWF simulation experiments that is considered the ‘truth’ in our study.

4.1 Comparison of final product with real Meteosat-8 observation

It is very important to be confident that the obs-fg statistics in the simulated AMV data set are within the range of observed AMV obs-fg differences, as otherwise each result from this study is debatable and no general conclusions are possible.
In the following, we will compare obs-fg statistics for the CIMSS-simulated Meteosat-8 AMVs with obs-fg statistics from the operational monitoring of EUMETSAT-derived Meteosat-8 AMVs for the same period. Note that for the simulated dataset, the comparison between AMVs and ECMWF model fields gives the true error in the AMVs, as the ECMWF fields provide the truth in this framework. For the obs-fg statistics for the real data, the differences are made up of errors in the AMVs as well as errors in the model’s first guess. Note also, that there are some differences between the CIMSS and EUMETSAT AMV processing, leading to different AMV characteristics. For real data, the differences in the AMV characteristics are usually smallest when CIMSS pre-QC winds are considered (http://www.metoffice.gov.uk/ research/interproj/nwpsaf/satwind_report/index.html).

Figure 4.1 shows a geographical map of obs-fg departures of cloudy WV AMVs in the range 200-300 hPa for the time period 2 Jan 2006 12-18UTC. It can be seen that much fewer AMVs have been derived in the simulation (Fig. 4.1, top left) compared to real Meteosat observations (Fig. 4.1, top right). This is probably a result of the lower resolution of the simulated images and the already mentioned underrepresentation of cirrus clouds in the forecast model (Fig 3.1, bottom). However, simulated AMV target areas coincide with real observations. Quantitatively, areas east of South Brazil and in the west North-Atlantic show good correspondence in terms of obs-fg, i.e. the derived AMVs are too low. Fig. 4.1 bottom shows the mean vector difference (MVD) between observation and first guess. The range for MVD is between 2 and 8 m/s. Some extreme deviations occur for the real Meteosat-8 AMVs (up to 13 m/s).
It must be noted that the atmospheric situation for the real Meteosat-8 AMVs is the real atmosphere that may deviate slightly from the high resolution model run. Although it is believed that this impact is minor and does not contribute to the obs-fg deviation very much.

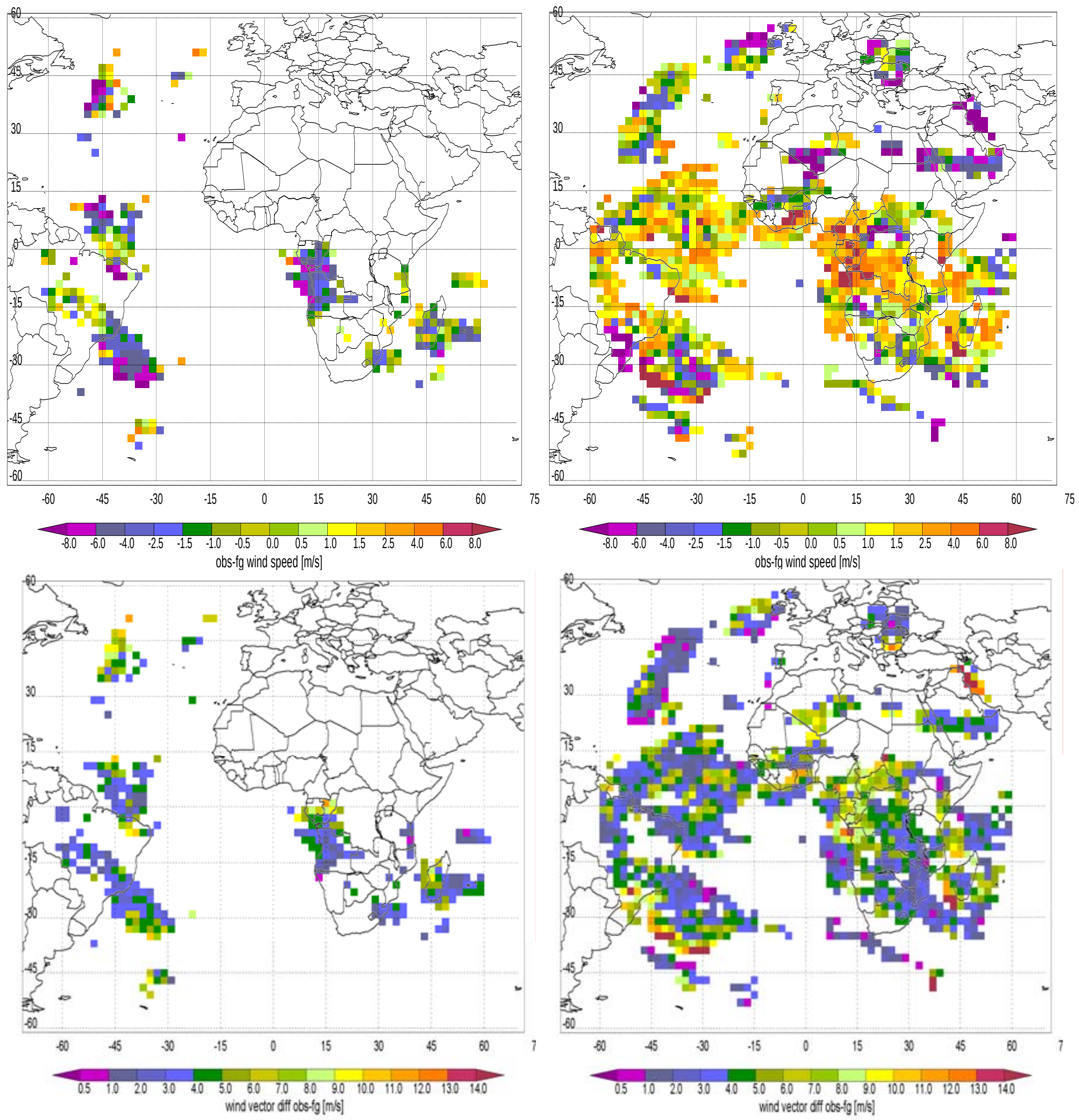


Figure 4.1: Bias (top) (obs-fg) and mean vector difference (bottom) of (final quality, NOGAPS background) simulated AMVs (left) and real Meteosat-8 AMVs from the 6.2 micron water vapor (cloudy) channel. The height interval is 200-300 hPa and the time period is 6 hours (2 Jan 2006 12-18UTC).Quality indicator threshold for simulated and real observations is 60.

A more detailed view on the AMV vs model statistics in zonal and vertical direction is given in Fig. 4.2 for simulated (middle figures) and real Meteosat-8 AMVs (lower). In general, the observed systematic deviations are in the expected range of -7 to +7 m/s. There is agreement that high level IR and WV cloud AMVs reach higher in the atmosphere over the Tropics and lower over the extra-Tropics. Furthermore, there are few mid-level IR winds in both data sets. One quite important difference is that real WV cloud AMVs reach much lower in the atmosphere and exhibit a large positive obs-fg bias. Similarly, clear WV AMVs are confined to a narrow band between 500 and 300 hPa for the real observations, whereas for the simulated AMVs these extend up to 130 hPa. It can be suspected that underrepresented cirrus clouds in the simulation trigger both effects and many scenes are classified as cloud-free in the AMV processing for the simulated data. This hypothesis is supported by the fact that the number of real Meteosat-8 clear WV observations is considerably lower. However, Table 4.4

shows that the quality of real clear WV AMVs is much worse than that of simulated AMVs, i.e. bias and NRMSVD are much smaller for the simulated AMVs in final quality compared to real AMVs

The picture is different for high-level IR winds where EUMETSAT's real AMVs have a smaller bias and also slightly smaller NRMSVD. For high-level WV cloudy AMVs the NRMSVD is comparable for simulated and true AMVs. However, real AMVs show strong positive biases over the Tropics and southern extra-Tropics below 300 hPa while the simulated AMVs show the commonly known negative speed bias for high level winds. This might be related to the comparably small sample size in the time window of only 6 hours. However, clear WV winds are not the focus of this study since clear-sky WV radiances of all geostationary satellites are assimilated at ECMWF.

For high-level cloudy AMVs, it is interesting to compare the real AMVs to the 'raw' quality CIMSS winds in Fig. 4.2. It can be seen that in the 'raw' quality winds clusters of negative speed biases occur in the same way as they occur in the real AMVs. Due to CIMSS' quality checks and the auto-editor the negative speed bias problem in CIMSS' final winds is masked.

In summary, the simulated AMVs exhibit a number of systematic features that are commonly observed in comparisons between real AMVs and model fg, such as negative biases at the highest levels in the extra-tropics and positive biases in the mid-level tropics. This is encouraging as it underlines the realism of the simulations and suggests that the simulations provide a useful framework for the study of systematic differences in real AMVs. The finding that the magnitude of the systematic errors is broadly similar to that of AMV-fg biases in real data confirms that a large proportion of this bias is due to biases in the AMVs, rather than in the fg. Nevertheless, differences between statistics for the simulated and the real data, for instance in vertical extent and sampling, are most likely due to limitations in the representation and structure of certain clouds in the simulated imagery (Fig. 3.1). Unfortunately, it is not possible to quantify the differences that arise from the different AMV processing in the real observations (EUMETSAT processing) and the simulated AMVs (CIMSS processing).

4.2 Impact of post-processing on data quality

The post-processing plays a very important role in CIMSS' AMV derivation procedure. The different steps and terminologies have been introduced in Section 3.2.

Zonal/vertical obs-fg speed for the 'raw' quality winds are shown at the top of Figure 4.2. The distribution of speed biases is much more heterogeneous and strong negative speed biases are present for high level cloud winds, in particular in the extra-Tropics. For instance, the IR speed bias (high level) is -5.89 m/s and is reduced in the post-processing to -1.64 m/s Table 4.5 provides a detailed overview on the difference in 'raw' and 'final' wind quality).

It will be discussed in Section 4.3 which steps in the post-processing are responsible for the quality improvements that are gained.

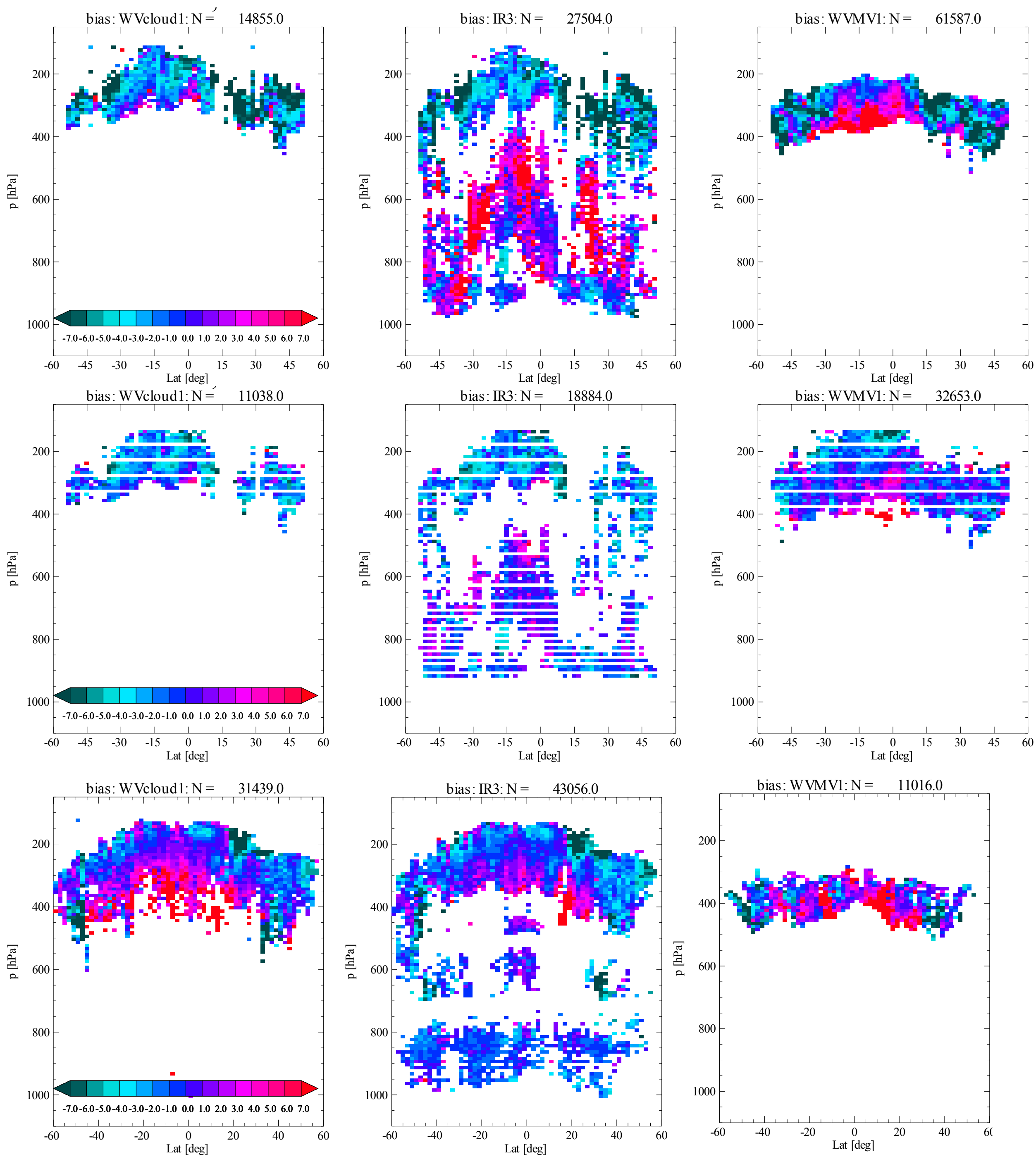


Figure 4.2: Zonal mean obs-fg bias [m/s] for simulated (<u>NOGAPS background</u>) AMVs (top, raw quality and middle, final quality) and real METEOSAT-8 AMVs (bottom) for 6.2 micron cloudy water vapor AMVs, 10.8 µm *IR AMVs and 6.2 micron clear water vapor AMVs. The time period is 2 Jan 2006 12-18UTC).Quality indicator>60.*

Figure 4.3 and Table 4.1 show the improvements that are gained for each IR data set in the post-processing. The application of a QI threshold (of > 60) to the 'all' data set has a strong thinning effect at mid and low-levels. NRMSVD values for high level winds are considerably reduced (especially in the tropics), whereas improvements in bias are less pronounced. The bias in the northern extra-Tropics is reduced from -6.6 to -5.8 m/s. This is in line with the experience from real data in that applying a QI threshold primarily reduces the noise. The 'raw' data set is almost unchanged from the 'all' data set.

A more prominent quality improvement occurs when the cirrus IR wind and slow check are applied (‘check’). In this step about 20% of ‘raw’ winds are removed and the northern extra-Tropics bias drops from -5.9 to -4.2 m/s. At the same time, NRMSVD is almost unchanged. This is different in the auto-editing (‘autoe’) step where NRMSVD drops in each area by about 0.2 (Table 4.1). In terms of bias, the largest impact can be seen in the northern extra-Tropics where the bias decreases from -4.2 to -2.0 m/s. Again, about 15 % of the winds are removed from the data. It will be discussed in the next section (Section 4.3) whether improvements are solely due to removed observations or due to corrections applied to the winds by the auto-editor. The auto-editor is responsible for the striping effect in Fig 4.3 e) as the auto-editor permits only certain discrete pressure levels.
The quality of the ‘final’ winds is almost unchanged compared to ‘autoe’.

Most work in this report concentrates on ‘raw’ data and on ‘final’ data (QI>60 is also applied). QI is the quality indicator for which no first-guess information is used.

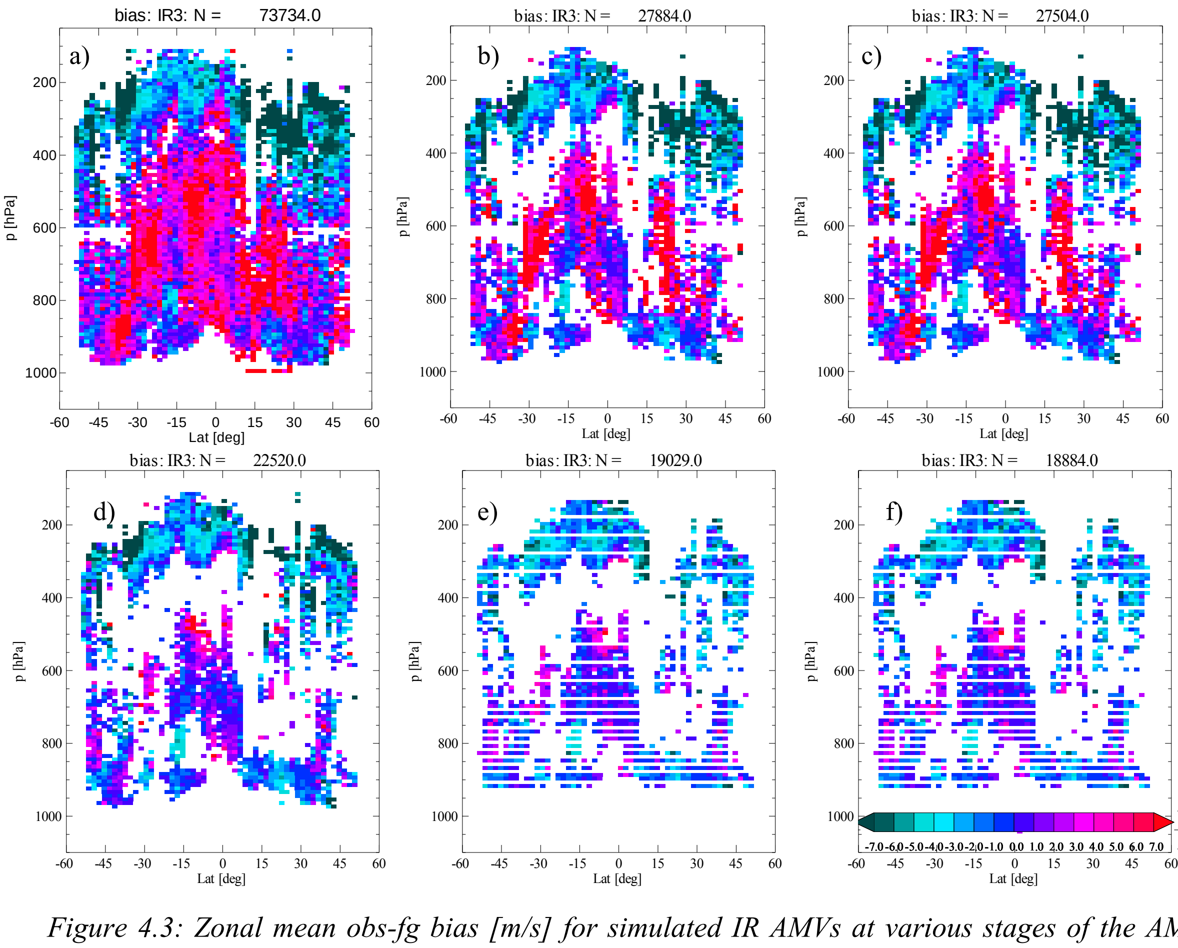


Figure 4.3: Zonal mean obs-fg bias [m/s] for simulated IR AMVs at various stages of the AMV post-processing. a) all derived AMVs (no QI filter), b) all derived AMVs, c) raw AMVs, d) checked AMVs, e) autoe AMVs and f) final AMVs. See text for details on different post-processing stages. QI>60 is applied in the last five figures.

	Bias [m/s]			NRMSVD		
	SH	Trop	NH	SH	Trop	NH
all QI	-3.4	-1.1	-6.6	0.69	0.95	0.65
all	-3.4	-2.1	-5.8	0.57	0.68	0.60
raw	-3.4	-2.1	-5.9	0.58	0.67	0.60
check	-3.1	-2.2	-4.2	0.58	0.65	0.56
autoe	-2.1	-1.9	-2.0	0.40	0.45	0.34
Final	-2.0	-1.8	-1.6	0.40	0.45	0.32

Table 4.1: Obs-fg statistics (bias and normalized root mean square vector difference) for simulated IR AMVs (<400 hPa) at various stages of the AMV post-processing subdivided into regions. QI threshold >60 is applied at all stages, except for 'all QI'. See text for details on different post-processing stages.

4.3 Quality improvement through auto-editing

CIMSS has developed an auto-editor to correct derived AMVs through changes in the speed of the winds and through height reassignment (e.g., Hayden and Purser 1995). At the same time a quality flag the so-called RFF, is computed.
This section investigates the impact of auto-editing AMVs, i.e. it must be assured that the same winds in the 'raw' data set and the 'final' data set are compared as the filtering (removal) of winds can have already a large influence on the quality of the remaining winds. Fortunately it is possible to locate all 'final' winds in the 'raw' data set when sub-dividing by computational method and height assignment method. Here, the position (latitude/longitude) and time is used to make a unique identification (synchronization).

Four height assignment methods are used: i) base height assignment (only IR channel) which is abbreviated 'Base'; ii) Window Channel (WinCh) height assignment (only IR); iii) histogram (Histo) method (only WV); iv) H_2O-intercept (H2O) method (IR and WV). For clear WV winds the histogram method is mainly used, WV cloudy winds use mainly H_2O-intercept method. To denote IR winds that heights are assigned with the Window Channel method the abbreviation IR:WinCh is used. Other combinations of channel (IR or WV) and computational method follow the same nomenclature.

Table 4.2 shows number of winds, bias and NRMSVD for each wind type (computational method and height assignment method). The left column shows the 'raw' data set and the right column shows winds in the 'final' data set. The middle column contains only the winds from the 'raw' data set that are also present in the 'final' data set, i.e. winds that are not filtered out in the post-processing steps. The fact that the numbers of winds are not matching exactly is due to the fact that in the statistical evaluation program winds with very low wind speeds (<2.5 m/s) are removed.

		raw			raw, Sync			Final, sync		
		N	Bias	NRMSVD	N	Bias	NRMSVD	N	Bias	NRMSVD
IR:Base	NH	2094	1.93	0.86	1441	0.16	0.43	1424	0.19	0.42
	Tropics	**1654**	**1.60**	**1.00**	**1362**	**0.34**	**0.55**	**1280**	**0.08**	**0.48**
	SH	*2411*	*2.78*	*0.91*	*1606*	*0.92*	*0.45*	*1578*	*0.75*	*0.41*
IR:WinCh	NH	1192	2.08	0.79	542	-0.41	0.39	518	-0.43	0.36
	Tropics	**3316**	**3.91**	**1.24**	**2370**	**2.17**	**0.76**	**2032**	**1.43**	**0.55**
	SH	*1450*	*3.95*	*0.74*	*658*	*1.15*	*0.40*	*641*	*1.25*	*0.36*
IR:H2O	NH	2624	-5.88	0.62	1278	-2.60	0.36	1281	-1.70	0.32
	Tropics	**3460**	**-2.37**	**0.66**	**2928**	**-2.01**	**0.48**	**2949**	**-1.80**	**0.45**
	SH	*3787*	*-3.14*	*0.59*	*2876*	*-2.19*	*0.44*	*2879*	*-1.76*	*0.41*
WVcloud: Histo	NH	431	-6.95	0.39	197	-3.41	0.30	197	-0.87	0.27
	Tropics	***293***	***-2.74***	***0.79***	***236***	***-2.65***	***0.65***	***236***	***-0.97***	***0.58***
	SH	*1234*	*-6.89*	*0.52*	*940*	*-5.58*	*0.44*	*940*	*-2.49*	*0.36*
WVcloud: H2O	NH	2999	-4.38	0.61	1605	-2.21	0.33	1615	-1.38	0.30
	Tropics	**5256**	**-1.65**	**0.62**	**4456**	**-1.60**	**0.46**	**4499**	**-1.48**	**0.43**
	SH	*4313*	*-2.00*	*0.59*	*3438*	*-1.62*	*0.42*	*3444*	*-1.23*	*0.38*
WVMV: Histo	NH	16381	-2.39	0.70	7283	1.05	0.39	7273	0.90	0.36
	Tropics	**25159**	**1.47**	**0.96**	**15926**	**1.57**	**0.61**	**15843**	**0.85**	**0.51**
	SH	*15874*	*-1.23*	*0.82*	*8632*	*0.74*	*0.42*	*8663*	*0.38*	*0.38*
WVMV: H2O	NH	31	-2.70	0.46	14	2.53	0.38	23	0.55	0.22
	Tropics	**60**	**-0.26**	**0.82**	**43**	**0.13**	**0.51**	**45**	**-0.26**	**0.46**
	SH	*194*	*0.87*	*0.58*	*173*	*0.79*	*0.47*	*179*	*0.86*	*0.45*

Table 4.2: Obs-fg statistics (number of observation, bias [m/s] and normalized root mean square vector difference) for simulated AMVs subdivided into regions, channels and used height assignment. The considered height is <400 hPa except for IR:Base and IR:WinCh where the height of the AMVs is >700 hPa and 400-700 hPa, respectively. A QI threshold of >60 is always applied. The left column contains all winds that are considered as 'raw' data. The right data is the 'final' quality. The middle column contains winds with 'raw' quality that are present in the 'final' data set.

Many winds are removed in the post-processing if they failed some of the applied checks. In the case of IR-winds with the H_2O-intercept height assignment method (IR:H_2O) about 29% are removed from the 'raw' data set (25% for WVcloud:H_2O). Obviously, this removal improves the quality as already discussed in the previous section (compare left column to middle column).

A very remarkable improvement occurs for high level WV clear-sky winds with the histogram height assignment method: in the Tropics the NRMSVD changes from 0.96 to 0.61. The improvements in the extra-Tropics are also very large. The low mean wind speeds in the Tropics leads to rather high NRMSVD.

Something similar happens for mid-level IR-winds with window channel height assignment where the NRMSVD in the Tropics is initially 1.24 and is reduced to 0.76.

Improvements in data quality due to the auto-editor can be seen when comparing the middle column to the right column in Table 4.2. In general, the improvements in bias and NRMSVD are small but positive, i.e. in the right direction. For example the negative bias for WVcloud:H_2O has improved by 0.1 to 0.9 m/s for all areas, while the NRMSVD is almost unchanged. Bias reductions for high-level IR-winds (H_2O-intercept) are of the same size (0.2-0.9 m/s) and are displayed in Fig. 4.4 in more detail, i.e. in the Tropics some dark green areas (figure top right) disappear after the auto-editing process.

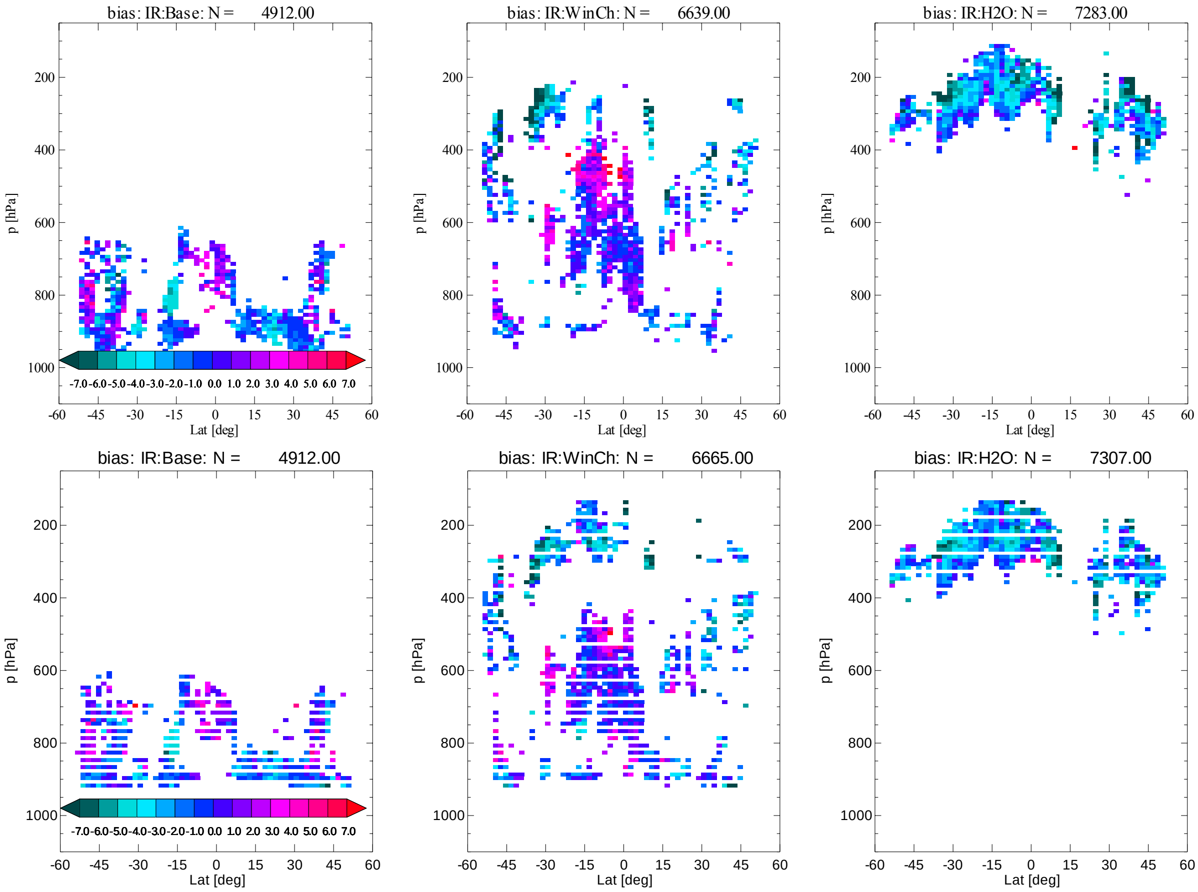


Figure 4.4: Zonal mean obs-fg bias [m/s] for simulated IR-AMVs with all different height assignment methods (left cloud base height, middle Window Channel and right H_2O-intercept method). A QI threshold of >60 is always applied. In the 'raw' data (top) only the AMVs are considered that are also present in the final data set (bottom).

For IR:WinCh winds it can be noted that a considerable amount of winds in the southern Tropics are shifted from around 450 hPa upwards to 200 hPa. Before the shift the winds have a large positive bias and after the shift to 200 hPa they have a negative bias. When assuming that the model speed increases with heights, it can be concluded that the winds are shifted too high upwards.
The blank lines in the lower figures of Fig. 4.4 are due to discrete values for the reassigned pressure by the auto-editor.

The distribution of water vapour clear-sky winds (histogram method) has been clearly broadened by the auto-editor (Fig. 4.5). The majority of the retrievals has been moved up in the atmosphere and the prevailing positive bias has been reduced by 0.2-0.7 m/s. Nevertheless, the distribution of biases is very inhomogeneous.

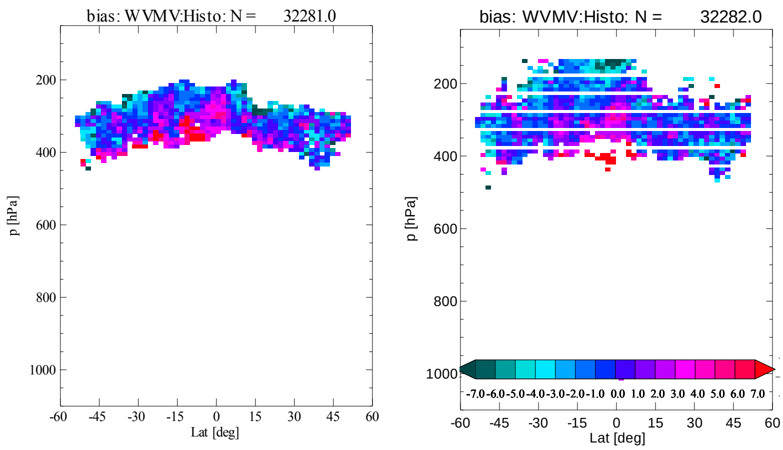


Figure 4.5: Zonal mean obs-fg bias [m/s] for simulated water vapour clear-sky AMVs with histogram height assignment. An QI threshold of >60 is always applied. In the 'raw' data (left) only those AMVs are considered that are also present in the 'final' data set (right).

4.3.1 Detailed analysis of auto-editor changes

For the end-user it is not visible whether and which of the alterations by the auto-editor (height reassignment or speed changes) improved a particular observation. It is possible that two changes counteract (balance themselves), e.g. an observed speed that is underestimated, is increased but at the same time the wind is reassigned higher up in the atmosphere (assuming positive wind shear and thus increases model wind).
In this paragraph the detailed changes by the auto-editor are analyzed in terms of coherency of speed-up and height reassignment and in terms of impact (improvement of wind quality)

The impact of height reassignment is investigated first. Figure 4.6 shows the distribution function of pressure differences due to the height reassignment (blue line) for all IR-winds and height assignment methods and for water vapour clear-sky winds. The positive skewness of the distribution for IR:Base AMVs indicates that more winds are shifted up in the atmosphere. The exact value can be seen in Table 4.3 that shows average values of assigned pressure, equivalent model speed, etc. before (old) and after (new) auto-editing. In this case the average height was shifted from 844 hPa to 835 hPa. The equivalent model speed (first guess) is unchanged (9.35 to 9.37 m/s) as apparently the wind shear is very small. NRMSVD has improved to 0.43 (from 0.47). Low level IR-winds will be studied in more detail in Section 4 and the fact that AMVs are shifted upwards is discussed.
The most pronounced upward shift by 25 hPa is noted for IR:WinCh AMVs (Fig. 4.6, b). As a consequence the initial bias of 0.7 m/s is reduced to 0.17 m/s, because the average first guess speed has increased.
IR:H_2O winds are moved slightly downwards from, on average, 270.8 hPa to 273.5 hPa. Thus, the model speed has only dropped by 0.16 m/s and the large initial wind speed bias of -2.16 m/s was not reduced significantly (to -1.75 m/s). In general, the speed-up changes are also very minor (+0.25 m/s) and are not sufficient to balance any biases. The pressure re-assignments appear only on average minor, as can be seen in Figure 4.6c (blue line). The standard deviation between old and newly assigned pressure is about 20 hPa.

The largest speed-up occurs for WVcloud:Histo AMVs with +1 m/s. However, the large initial bias is only reduced to -2 m/s despite a strong downward shift of AMVs by 25 hPa.

As expected from Fig. 4.5 the average WV clear-sky wind (Histo) is shifted upwards and the model speed is increased by 0.5 m/s. However, a positive bias of 0.77 m/s remains. No speed-up is applied to clear-sky winds.

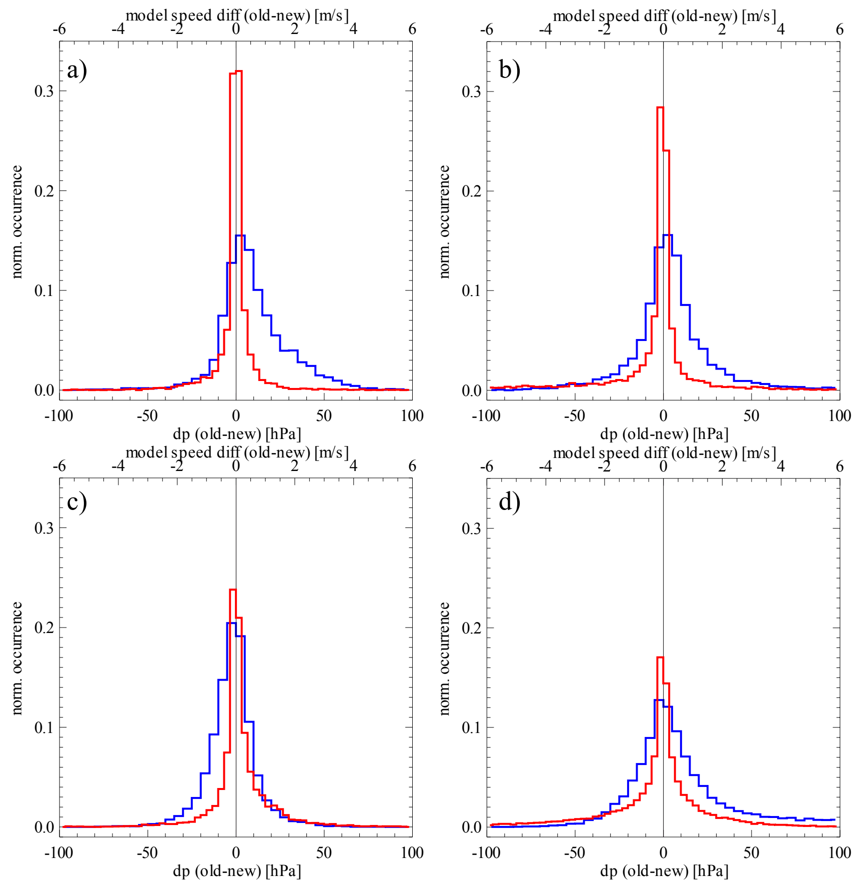


Figure 4.6: Impact of height reassignment applied by the auto-editor (old-new). Pressure (blue) differences and corresponding model wind speed changes (red) for a) IR cloud base height b) Window channel and c) H_2O intercept assignment method. d) is for water vapour clear with histogram method.

	ff_{old}	ff_{new}	P_{old}	P_{new}	FG_{old}	FG_{new}	bias old	bias new	MVD old	MVD new	nvd old	nvd new
IR:Base	9.91	9.91	844.4	835.0	9.35	9.37	0.56	0.55	3.69	3.44	0.47	0.43
IR:WinCh	11.04	11.16	583.6	557.7	10.34	10.99	0.70	0.17	4.49	4.17	0.53	0.45
IR:H2O	12.10	12.35	270.8	273.5	14.26	14.10	-2.16	-1.75	5.20	4.83	0.43	0.40
WVcloud:Histo	15.95	16.90	245.1	270.9	20.72	18.90	-4.77	-1.99	7.72	5.86	0.43	0.36
WVcloud: H2O	12.68	12.95	257.5	259.4	14.38	14.30	-1.70	-1.35	5.00	4.64	0.42	0.38
WVMV: Histo	14.64	14.64	308.0	294.9	13.39	13.87	1.25	0.77	5.56	5.13	0.49	0.43
WVMV: H2O	10.82	10.82	389.8	384.7	10.31	10.56	0.51	0.26	3.75	3.48	0.43	0.38

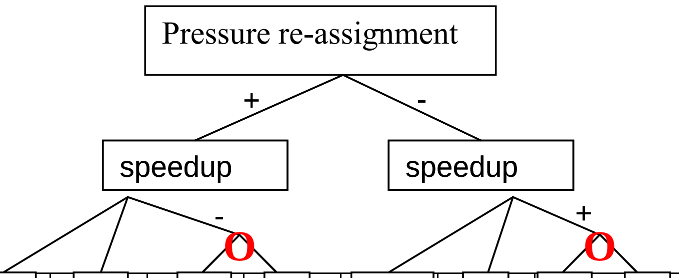
Table 4.3: Overall changes by the auto-editor for all channels and different height assignment methods in terms of observed wind speed (ff [m/s]), assigned pressure (P [hPa]), corresponding model wind speed (fg [m/s]), bias (obs-fg [m/s]), mean vector difference (MVD [m/s]) and normalized root mean square vector difference (nvd). Only matching AMVs that are in the final and raw data set are considered.

In the following, we diagnose how often the height reassignment or the speed-up, performed in the CIMSS processing, leads to an improvement or a degradation in the final AMV set. Table 4.4 shows the number of cases (as counts), separated by whether height reassignment or speed-up had a positive or negative impact, respectively. The tree on top of Table 4.4 helps to explain the different columns. The top-level decision is whether height reassignment improved the agreement between the observed and model speed compared to the initial deviation. The deviation is expressed in the absolute wind speed difference and counts (hits and misses) are written in bold in Table 4.4. Counts for the vector difference as measure for deviation are written with normal font. Table 4.4 simply lists the number of hits (i.e., improvement was gained) and misses (i.e., the change increased the deviation between obs-fg). The second decision is whether the speed-up leads to an additional improvement. In most of the cases no speed-up was applied, i.e. this is marked by n/a. In other cases, the change is indicated with '+' when the deviation decreases or '-'when the deviation increases. A third decision level (marked with a red O) is needed to distinguish cases for which the height reassignment alone or the speed-up alone led to an improvement (or degradation), i.e. it is interesting to know whether the overall result is better or worse.
All columns with a better overall result are indicated in green. The two columns on the right summarize all green and red columns.

The results show that in about 63% the auto-editor has improved the overall result for IR:H_2O winds (62% for WVcloud:H_2O). This means that in more than one third of all cases the auto-editor degrades the quality for the final wind. As speed-up is not applied to many winds, it can be concluded that mainly the pressure height reassignment is imposing problems, i.e. the auto-editor shifts the AMVs in the wrong direction.

Table 4.4 reveals that in some cases height reassignment and speed-up are working against each other. Luckily, there are more cases with an overall positive result. For example, for WVcloud:Histo 237 (from 9596) winds are degraded by the speed-up change once the height reassignment was positive. On the other hand, in 376 cases the height reassignment was negative and the speed-up improved the overall result.

It can be concluded that the changes applied by the auto-editor are small and that they do not reduce biases completely. Obviously, as indicated in Table 4.1 the autoediting step removes large negative biases, but as detailed above most of these changes are due to data selection and not correction (height re-assignment or speed-up). There are two potential ways to improve the autoediting step in terms of correction: i) the increments in pressure changes may need to be larger or ii) a procedure or algorithm is developed that prevents the shift (pressure re-assignment) in the 'wrong' direction. 'Wrong' direction means the direction when the deviation between observed speed and model speed increases.



	n/a	+	+	-	n/a	-	+	-		
IR:Base	**2976** 3219	**0** 0	**0** 0	**0** 0	**1936** 1693	**0** 0	**0** 0	**0** 0	**2976** 3219	**1936** 1693
IR:WinCh	**3758** 3805	**138** 129	**34** 36	**29** 33	**2429** 2377	**90** 93	**67** 64	**94** 97	**3997** 4037	**2642** 2602
IR:H2O	**3847** 3952	**458** 438	**26** 63	**164** 166	**2298** 2193	**194** 209	**259** 198	**38** 65	**4590** 4651	**2694** 2633
WVcloud:Histo	**420** 448	**486** 474	**37** 60	**63** 53	**188** 160	**76** 73	**75** 65	**28** 40	**1018** 1047	**355** 326
WVcloud: H2O	**4944** 5026	**600** 582	**58** 112	**237** 247	**2993** 2911	**309** 301	**376** 297	**79** 120	**5978** 6017	**3618** 3579
WVMV: Histo	**19408** 19679	**10** 9	**22** 14	**0** 4	**12842** 12571	**7** 11	**1** 2	**3** 3	**19441** 19704	**12852** 12589
WVMV: H2O	**197** 192	**0** 0	**0** 0	**0** 0	**147** 152	**0** 1	**0** 0	**1** 0	**197** 192	**148** 153

Table 4.4: Decision tree of hits and misses for the auto-editor for all channels and different height assignment methods in terms of improvement of the auto-edited wind compared to the original wind with respect to absolute wind speed error (in bold) and vector difference (obs-fg). Given numbers are counts. First decision level is the height reassignment. The speed-up is at the second decision level. See text for further details.

4.4 Comparison of NOGAPS and ECMWF backgrounds in AMV processing

CIMSS derived AMVs using ECMWF and NOGAPS forecasts as background in the AMV derivation chain. In case of the ECMWF forecast, the forecast data was taken from the experiment used to simulate the images for the AMV derivation, i.e. it is the truth in our framework. Providing the truth to the processing eliminates any impact of errors in the forecast data in the processing. It is often suspected that the NWP data has some influence on the final AMVs. This question is investigated in this section. Note, that all winds presented so far in this report were derived with the NOGAPS model.

Fortunately this study enables a look at two different stages of the processing chain: 'raw' quality winds and 'final' quality winds (see Section 3.2). Table 4.5 lists bias and NRMSVD for all three types of high-level winds: WV clear-sky, IR cloudy and WV cloudy separated into NH, Tropics and SH.
Surprisingly, the quality of NOGAPS and ECMWF winds is almost identical for the raw data set. The largest difference in terms of wind speed bias is 0.15 m/s (WVcloud), rather small compared to the absolute bias of -1.71 m/s for NOGAPS. This suggests that errors in the tracking or height assignment are not dominated by errors in the NWP fields. This is a positive aspect and an interesting result, given that the height assignment step makes direct use of NWP fields.
However, it was already discussed in Section 4.2 and 4.3 that the post-processing (filtering and auto-editing) has an important influence on the final data quality (for NOGAPS winds). The same is true for ECMWF winds. It can be seen that (almost) always the final quality of ECMWF winds is better, i.e. ECMWF winds have a smaller 'final' bias and NRMSVD. The

bias is up to 0.9 m/s smaller and the NRMSVD is 0.02 or 0.03 smaller. In terms of NRMSVD, ECMWF winds are always better.

It can be concluded that the CIMSS post-processing shows some influence from the NWP fields and their errors. Therefore, AMVs obtained from the CIMSS-processing will exhibit errors that are partially correlated with errors in the NWP fields. From a data assimilation point of view, this is undesirable, as the observations are assumed to be independent. Also, any spatially correlated errors in the NWP fields will introduce spatially correlated errors in the AMV data. It was not explicitly checked whether filtering or auto-editing is responsible for the better quality of ECMWF winds, but the experience with NOGAPS winds (Section 3.3) showed that filtering is the main factor to improve data quality. Nevertheless, since the reduction in the bias or NRMSVD is small compared to the remaining bias or NRMSVD, errors in the NWP fields are unlikely to dominate the AMV error in the final winds dataset.

Wind type		**High-Level WVMV**				**High-Level IR**				**High-Level WVcloud**			
Quality measure		**Bias [m/s]**		**NRMSVD**		**Bias [m/s]**		**NRMSVD**		**Bias [m/s]**		**NRMSVD**	
Data Set		**Raw**	**Final**	**Raw**	**Final**	**Raw**	**Final**	**Raw**	**Final**	**Raw**	**Final**	**Raw**	**final**
NOGAPS QI>60	NH	-2.39	0.90	0.70	0.36	-5.89	-1.64	0.60	0.32	-4.70	-1.29	0.57	0.30
	Tropics	**1.47**	**0.85**	**0.96**	**0.51**	**-2.13**	**-1.82**	**0.67**	**0.45**	**-1.71**	**-1.46**	**0.73**	**0.43**
	SH	*-1.21*	*0.40*	*0.82*	*0.38*	*-3.39*	*-1.99*	*0.58*	*0.40*	*-3.08*	*-1.49*	*0.58*	*0.38*
ECMWF QI>60	NH	-2.39	0.18	0.70	0.34	-5.79	-1.77	0.60	0.30	-4.59	-1.12	0.57	0.29
	Tropics	**1.39**	**0.48**	**0.95**	**0.48**	**-2.10**	**-1.42**	**0.69**	**0.43**	**-1.56**	**-1.08**	**0.64**	**0.40**
	SH	*-1.26*	*0.85*	*0.81*	*0.36*	*-3.59*	*-1.08*	*0.58*	*0.38*	*-3.19*	*-0.60*	*0.57*	*0.35*
MSG8 QI>60)	NH	-	1.17	-	0.50	-	-0.96	-	0.29	-	-0.43	-	0.28
	Tropics	-	**4.26**	-	**1.04**	-	**0.96**	-	**0.43**	-	**2.04**	-	**0.46**
	SH	-	*0.48*	-	*0.37*	-	*0.25*	-	*0.32*	-	*1.21*	-	*0.35*

Table 4.5: Comparison of statistics of simulated AMVs with NOGAPS and ECMWF in the derivation process and real Meteosat-8 AMVs for water vapour clear, IR and water vapour cloud AMVs (high level <400 hPa) in 'raw' quality and final quality.

5 Case Study I: Low-level IR winds in temperature inversion situations

In this case study, the dataset of IR winds from the cloud base height assignment method is used to investigate AMVs that are derived in atmospheric situations that exhibit low-level inversion clouds. The data sets in 'raw' and 'final' quality are used although winds that are not in the 'final' data set are excluded in the 'raw' data set. This procedure ensures that in both datasets the same winds are present (4912 AMVs). 1507 winds are selected to fulfill the requirement that low-level inversion clouds are present. This selection process will be described after the next paragraph.

Routine monitoring statistics for real AMVs suggest that, mainly in subtropical inversion regions, low-level winds are assigned too high in the atmosphere and therefore exhibit poor quality (Fig. 5.1). The example in Figure 5.1 is for visible winds but their height is also assigned with the cloud base height assignment method. As no simulated visible winds are available in this study, the investigation with low-level winds is done with IR AMVs.
One explanation for the observed problem (AMVs are assigned too high) is that the cloud base height assignment method is misled by a temperature inversion and its representation in the NWP temperature profile. The method either assigns the observation to the topmost level where the observed cluster brightness temperature matches the temperature in the background NWP profile (as illustrated in Fig. 5.2), or it is unable to find the right level as the inversion may not be captured in coarse-resolution NWP fields.

In AMV processing it is assumed that low-level winds are assigned to the cloud base. The cloud base of low-level inversion clouds can be well located with the model profiles searching for the temperature inversion and the cloud content/cover. All differences between the derived AMV and the model wind at the cloud base are due to uncertainties in the AMV derivation or due to deficiencies in the assumption of clouds to be passive tracers of wind.

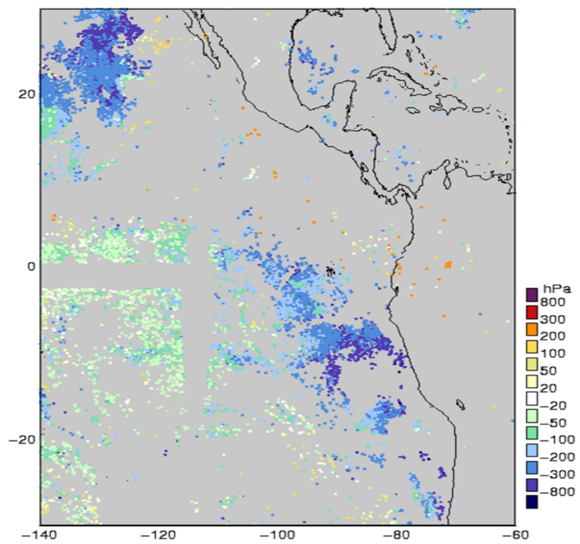


Figure 5.1: Pressure difference between the observed AMV pressure and model best-fit pressure for the unedited GOES-12 VIS winds at 3 July 2007 15 to 21 UTC. Note, the large AMV positive height bias (blue colours) off the coasts of Peru and Mexico. (Forsysthe, 2008).

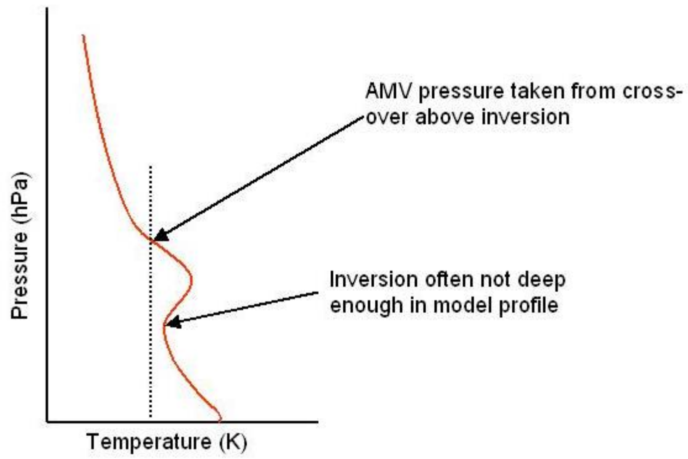


Figure 5.2: Illustration of positive height bias in inversion regions for AMVs (Forsysthe, 2008).

The selection of ideal cases to determine a unique level of the true wind follows two criteria: i) a temperature inversion of >1K must occur and ii) the cloud cover must exceed 0.2 in adjacent model levels around the level of temperature inversion. The cloud base is then set to the level of maximum cloud cover. It was checked that in most cases this level was representing the cloud base or one level above the cloud base. It is now assumed that, ideally, the AMV should be equal to the wind speed at the cloud base level.

Some examples of vertical profiles of temperature, model wind speed (u,v) and cloud liquid water content are shown in Fig. 5.3. The observed AMV is marked at its assigned height. The depicted examples have a temperature inversion >2K. The examples are not representative but are chosen to emphasize some of the spotted deficiencies. Figure 5.3 a) and b) are marked as positive examples where the derived AMV speed matches the wind speed at cloud base. However, the assigned height is too high in a) and a bit too low in b). Figure 5.3 c) and d) are less good examples as, in both cases, the derived AMV speed is too high assuming that the inversion cloud has been tracked. Note, that a very thin cirrus is present at around 550 and 300 hPa (Fig. 5.3c,d), respectively. Eventually in both cases the cirrus cloud has been tracked and the speed is in quite good agreement. Nevertheless the incorrect height assignment method was applied and leads to a completely wrong height.

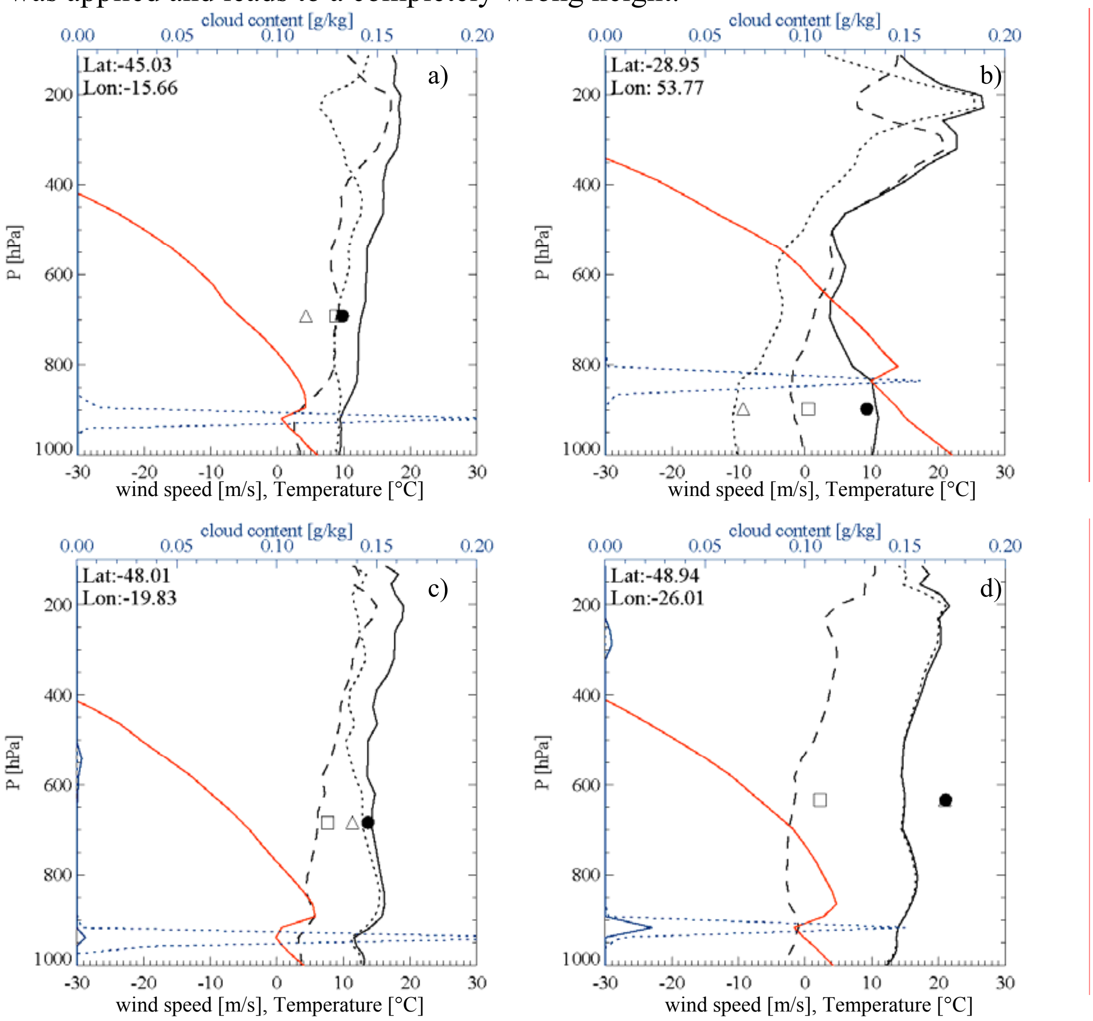


Figure 5.3: Examples of atmospheric situations with temperature (red, in °C) inversion. The model wind speed profile is solid and u,v components are dashed and long-dashed, respectively. The low-level water cloud is drawn (blue dashed line). The AMV observation (IR, base cloud base height assignment method) is shown as bullet, triangle and square, respectively for wind speed, u and v.

In the further analysis it is assumed that the derived AMV speed has tracked the inversion cloud as indicated by the height assignment method given in the data.

By locating the cloud base in the model data, the following investigation is possible: each AMV is shifted to the cloud base level as inferred from the model (i.e. true) clouds. This analysis will reveal whether AMVs are located too high in the atmosphere (as suggested by the monitoring of real data).
In Fig. 5.4 a) the assigned pressure is plotted against the pressure at cloud base. The majority of dots is beneath the diagonal which indicates that most of the AMVs need to be assigned higher in the atmosphere to match the true cloud base. The average (originally) assigned cloud height is 893 hPa and the true cloud base height is 866 hPa. Dots above the diagonal indicate that some AMVs have been assigned too high in the atmosphere and have been shifted downwards.

The original distribution of assigned pressures is continuous while the distribution of pressure at the detected cloud base is non-continuous due to the layering of the model levels. This is indicated by the vertically oriented clusters. For example, no cloud base pressures of 850 hPa are present. This is partly because only a limited number of clouds are present within the 6h period.
In general the standard deviation of cloud base pressures is very much reduced compared to the originally assigned pressures (from 48 hPa to 30 hPa).

The same analysis is shown in Fig. 5.4 b) for the ‘final’ data set. The originally assigned pressures have discrete values (from autoediting) as shown by the horizontal lines. The autoeditor increased the average AMV height from 893 hPa to 886 hPa and the standard deviation of assigned pressures has slightly decreased. It is not obvious that the correlation has improved by the autoediting process. In general the correlation in Fig. 5.4 a) and b) is extremely poor.

Figures 5.4 c) and d) show model wind speeds only. It is particularly interesting to note that the correlation between the model wind speed at cloud base height (ordinate) with the model wind speed at the originally assigned height (abscissa) is rather good (=0.92). As Figs. 5.4 a) and b) demonstrate, the heights are rather different. It must be concluded that, despite large height differences, the wind speeds are highly correlated, i.e. the wind shear is small. Consequently, it is not of primary importance to have a correct height assignment.
The average model speed at cloud base height is 7.85 m/s and is a little bit lower than the observed speed (8.34 m/s) (Fig. 5.4 c). Due to CIMSS’ auto-editing (height reassignment upwards) the average speed in the ‘final’ data set has been reduced to 8.26 m/s.

Finally, the originally derived AMV speeds are plotted against the model speed at the assigned height (Fig. 5.4 e and f). The correlation is very poor, i.e. the derived AMV speeds do not match the model speed at the assigned height. The same plot of observed AMV speeds against model speeds at cloud base looks virtually the same (not shown here) as model speeds at different heights are highly correlated.
As height assignment issues have been ruled out to be the reason for the poor correlation of observed AMV speeds with model winds, it can be concluded that the derived AMV speeds are of poor quality in general. The most likely reason for this is the still relatively low model resolution (10 km) combined with low wind speeds for these regions. Errors in the processing or the hypothesis that the inversion clouds are not suited as passive tracers for wind speed provide other possible explanations.

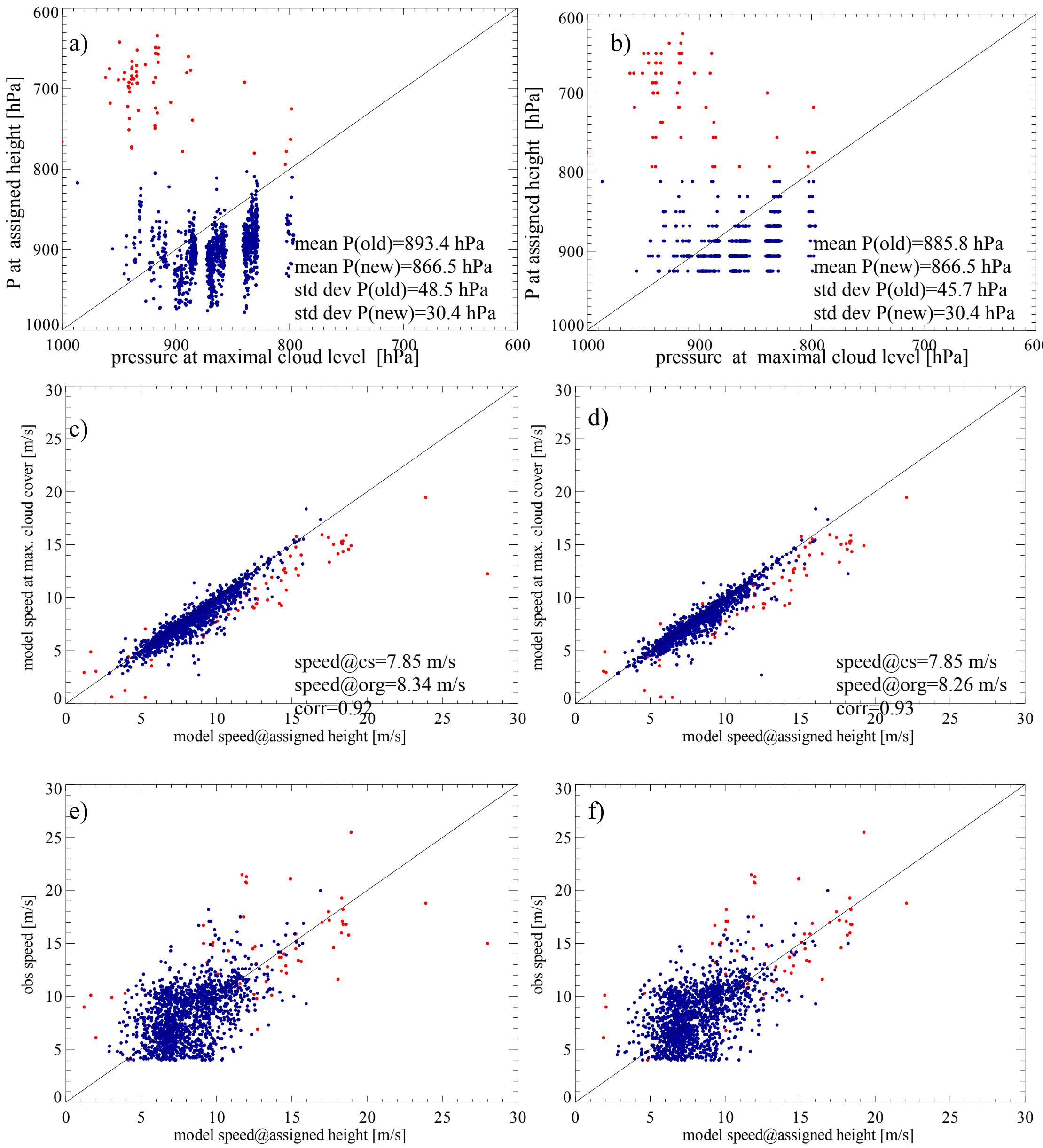


Figure 5.4: Extracted cases with low inversion clouds. Comparison of original assigned AMV observation versus model values at cloud base in terms of pressure (a, b) and wind speed (c-f). Results are shown for the raw quality data set (left column) and the final quality data set (right). Original observations above 800 hPa are marked in red.

The lessons learnt for simulated AMVs from low level inversion clouds are

i) Assigned AMV heights are too low in the atmosphere (~20 hPa), i.e. below the detected model cloud base. This finding is in contrast to the experience with real AMV retrievals.

ii) The correlation between model wind speeds at the assigned height and at the cloud base height is very high (Fig. 5.4d). It can be concluded that exact height assignment is of minor importance.

iii) The correlation between observed AMV speeds and model speeds (at cloud base height or assigned height) is poor (Fig. 5.4f). It can be concluded that the derived speeds are very noisy. This may be due to the lower wind speeds and the spatial resolution of the model simulation (~10 km) which is still considerably poorer than that of today's geostationary imagers (3-5 km).

6 Case Study II: Investigating high-level winds

In this case study the data sets of IR and cloudy water vapor winds obtained from the H_2O intercept height assignment method are used to investigate AMVs that are derived from semi-transparent high-level clouds. These primarily indicate cirrus clouds.

The methodology of this investigation is to locate cirrus clouds in the (forecast) model data and to investigate only idealistic cases where the cirrus clouds can be uniquely identified in the model data. In addition, if we consider only those cases for which the model wind speed within these cirrus clouds is rather constant (negligible wind shear), exact height assignment can be excluded as a reason why observed AMV speed and average model speed (in the cirrus cloud) disagree. The data sets of ‘raw’ quality (QI>60) are used here and encompass 13142 WVcloud:H2O and 10575 IR:H_2O winds, respectively[1].

Some examples of cirrus clouds are given in Fig. 6.1 and are discussed here. In the majority of these examples the derived AMV was assigned well near the layer with maximal cloud ice content. This gives a first hint that the height assignment has some skill. Nevertheless it can be seen from these examples that the agreement between derived speed and model speed is very poor and always underestimated. In many cases even the lowest model speed within the located cirrus clouds is still considerably higher than the observed speed. This raised the idea that height assignment is not the key problem but that derived AMV speeds are biased compared to the model truth. It must be noted, that the selection of examples is chosen to emphasize the raised hypothesis and is not representative.

6.1 Selection of idealistic cirrus clouds

This section describes the selection process of cirrus cloud samples under atmospheric conditions that can serve as ideal test cases in order to exclude height assignment errors. Firstly, all cloudy model levels are determined that are considered to be part of the cirrus cloud. The cloud top location is assumed where the cloud cover drops below 0.05 and the cloud bottom is determined where the cloud cover drops below 0.1.
Three criteria have been defined to ensure that the wind shear in the cirrus cloud can be considered small (i and ii) and to ensure that this particular cirrus cloud was tracked and not underlying features (i) of different clouds:

i) Wind shear in the cirrus cloud must be small, i.e. the wind at each level is assumed to be representative for the entire cloud. The wind shear or the variability of wind speed is expressed by the standard deviation of the wind speed that was chosen to be below 3 m/s.

[1] Of these 13142 WVcloud:H_2O AMVs only 12957 are available as the assigned pressure range is outside the considered interval. The obs-fg bias is -2.57 m/sand NRMSVD is 0.66 m/s.
Of these 10575 IR:H_2O AMVs only 10495 are available as the assigned pressure range is outside the considered interval. The obs-fg bias is -4.21 m/s and NRMSVD is 0.67 m/s.

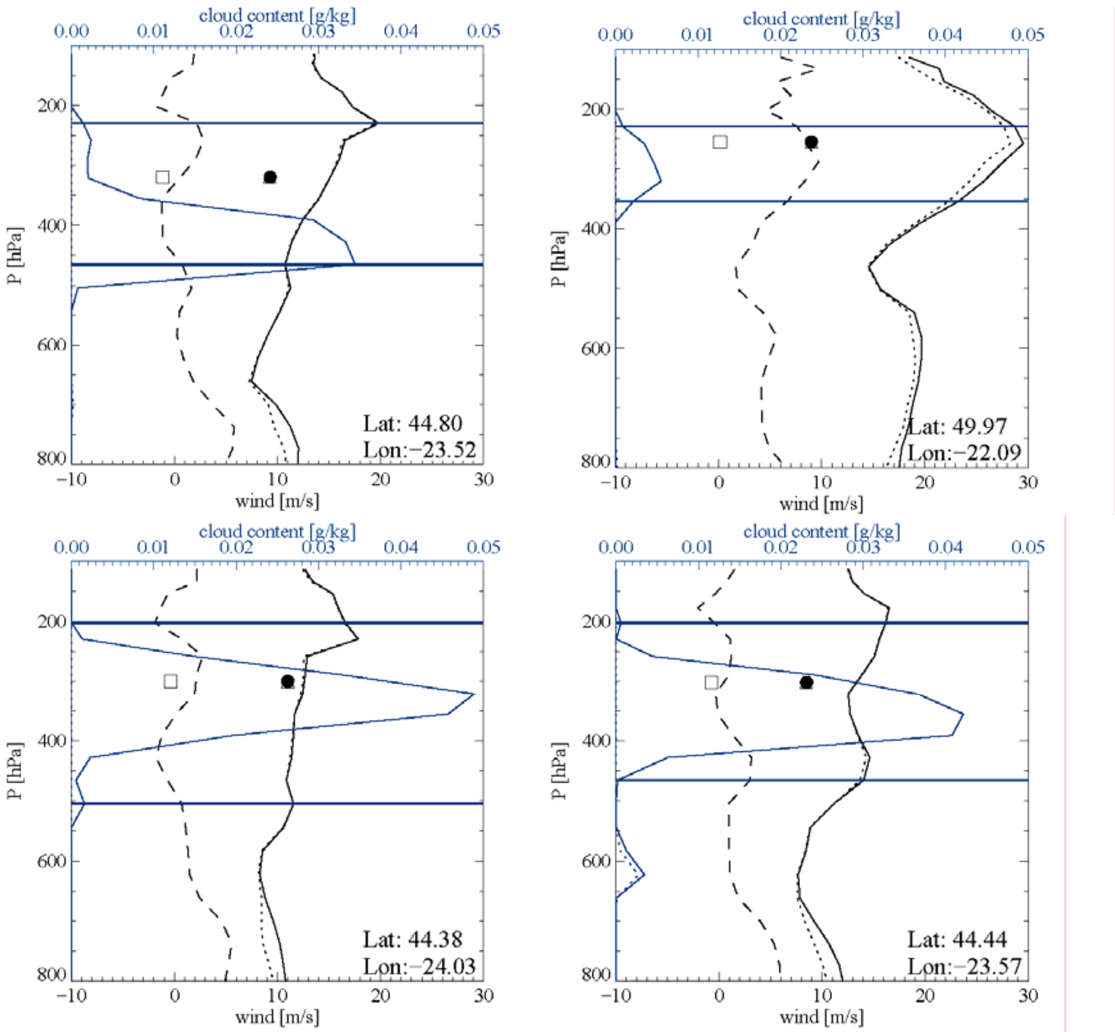


Figure 6.1: Examples of cirrus clouds (solid blue line) as cloud content profile [g/kg]. The model wind speed profile is solid and u,v components are dashed and long-dashed, respectively. The diagnosed range of cirrus cloud is marked by two horizontal lines. The AMV observation (IR, H_2O intercept method) is shown as bullet, triangle and square, respectively for wind speed, u and v component.

ii) The wind direction of the derived wind AMV and the direction in the cirrus cloud should match to ensure that not a completely different target was tracked. Therefore it is assumed that the deviation between the model wind direction in the cirrus and the observed direction is below a certain threshold. Finally selected value: < 20°.

iii) The ratio of total cloud ice[2] of the cirrus cloud and the total cloud ice/water below the considered cloud shall be high. This ensures that a tracking of any underlying clouds is less likely as they are thinner. Finally selected ratio value: > 2.

Table 6.1 shows the results of a sensitivity analysis of sample size and obs-fg bias and NRMSVD when different thresholds for one of the three criteria are chosen. While varying the threshold in one criterion the others are kept to <3 m/s, <20° and >2.
The tighter the wind shear check (decreased standard deviation of model speed) the less winds pass this criterion and the lower the quality of these winds becomes, i.e. the NRMSVD increases slightly. It was expected that the lower the permitted wind shear the better the

[2] Integrated ice water path (cloud cover is considered)

quality as height assignment becomes less important, but this was not the case. Therefore a rather relaxed threshold of 3 m/s was selected to maximize the sample size.
The strongest degradation in quality exists when cases are permitted where the observed wind direction deviates by up to 40° from the model speed. NRMSVD increases up to 0.59 from 0.50 (for deviations <20°). As a tighter threshold is not improving the quality of the remaining cases, the 20° threshold was kept.
As the winds comparison is not degrading (but improving) when relaxing the threshold for the cloud ratio it was set to 2 to include as many winds as possible in the sample.

ffstd dev.	**<1.0m/s**	**<2.0m/s**	**<3.0m/s**	**<4.0m/s**	
Bias [m/s], N	-3.55, 355	-3.61, 761	-3.80, 1045	-3.80, 1206	
NRMSVD	0.54	0.51	0.50	0.49	
dir fluct.		**<10°**	**<20°**	**<30°**	**<40°**
Bias [m/s], N		-3.97, 337	-3.80, 1045	-4.38,1545	-4.39, 1856
NRMSVD		0.50	0.50	0.57	0.59
Cloud ratio	**>6**	**>3**	**>2**	**>1**	**>0.5**
Bias [m/s], N	-3.82, 824	-3.73, 960	-3.80, 1045	-3.48, 1268	-3.4, 1534
NRMSVD	0.51	0.50	0.50	0.48	0.46

Table 6.1: Sensitivity of bias and NRMSVD to selection criteria of cirrus cases for IR winds (H_2O intercept method). Minimal wind shear in the cirrus cloud is determined through the standard deviation of the wind speed in the cloud and a maximuml allowed deviation in direction between AMV and model. Cloud ratio defines the amount of integrated ice water in the cirrus cloud to the integrated ice and liquid water below the cirrus cloud. The total number of IR:H_2O winds in the raw quality data set is 10575.

In the following sections, only the linearly averaged model speed in the cirrus cloud is considered. No attempt is made to allocate a height to this average speed. Note, that in the following it is assumed that the average model wind speed is representative of the speed of the entire cirrus cloud.

6.2 Height assignment

In the first analysis of the extracted idealized situations the average model speed in the cirrus cloud is plotted against the model speed at the originally assigned height (Fig. 6.2). Using the average model speed in the cirrus assumes that the tracked speed represents the wind speed somewhere in the middle of the cirrus cloud. The correlation for IR:H_2O and WVcloud:H_2O is very good, i.e. the originally assigned heights are representative for wind speed within the model cirrus. The obs-fg bias is only 0.39 m/s and 0.13 m/s for IR:H_2O and WVcloud:H_2O, respectively (Table 6.2). The biases and the NRMSVD are very small compared to obs-fg statistics (Table 6.1, bias of -3.80 m/s for IR:H_2O and -3.0 m/s for WVcloud:H_2O).

The color coding in Fig. 6.2 indicates the thickness (number of cloudy model layers) of the cirrus cloud. In terms of NRMSVD and MVD, thin cirrus clouds (blue) have the lowest agreement. The average wind speed in cirrus is slightly higher than the model speed at the assigned height (0.83 m/s and 0.33 m/s for IR:H_2O and WVcloud:H_2O, respectively). With increasing cloud thickness the model speed at the assigned height becomes larger than the average wind speed in the cirrus cloud (negative bias). It can be speculated that for cirrus clouds with a large vertical extent and positive wind shear, wind speeds in lower altitudes reduce the average speed below the model speed at the assigned height. The number of very thick cirrus clouds is less than 8%.

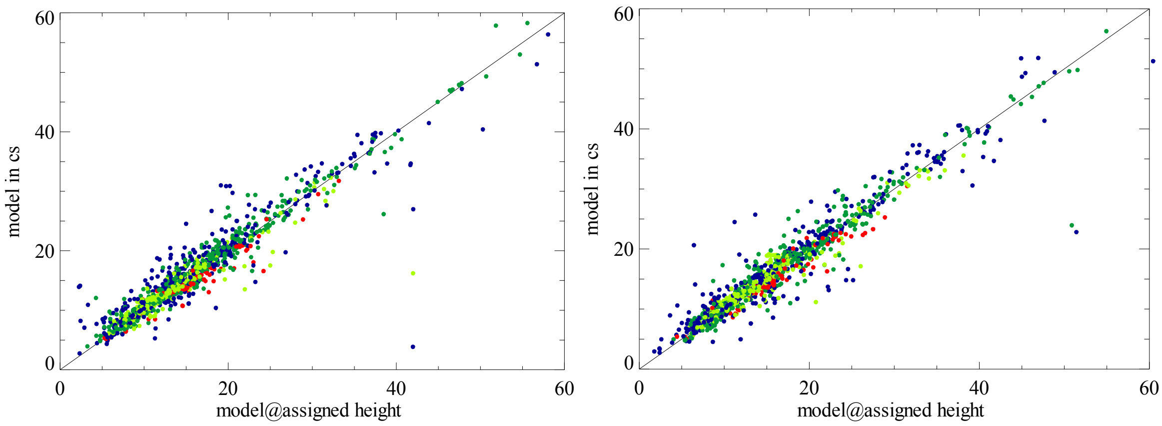


Figure 6.2: Model speed in idealized cirrus clouds versus model speed at originally assigned height for IR (left) and water vapor cloudy (right) AMVs. Colour coding corresponds to the vertical extent of the cirrus cloud (see Table 6.2 for legend).

IR:H2O	N	Bias	MVD	NRMSVD	corr
All	1045	0.39	2.15	0.21	0.950
1-3	337	0.83	2.98	0.28	0.927
4-6	407	0.56	1.74	0.13	0.977
7-11	226	-0.06	1.63	0.19	0.911
>=12	75	-1.08	2.13	0.16	0.944

WVcloud	N	Bias	MVD	NRMSVD	corr
All	1075	0.13	2.08	0.18	0.957
1-3	353	0.33	2.60	0.22	0.949
4-6	364	0.23	1.96	0.17	0.961
7-11	272	0.04	1.58	0.13	0.956
>=12	86	-0.91	2.05	0.15	0.949

Table 6.2: Statistics of differences between model wind speed in cirrus and model wind speed at assigned height in terms of bias (speed in cirrus minus assigned height), mean vector difference, normalized vector difference and correlation. Colour coding corresponds to the vertical extent of the cirrus cloud in numbers of model levels. The same colour coding is valid for Figure 6.2.

It can be concluded that in the compiled data sets with idealized cirrus clouds and little wind shear, height assignment issues can not explain the negative obs-fg bias that is observed. In the next two sections, the compiled data sets are investigated further and are subdivided to understand certain characteristics of the cirrus clouds that exhibit large obs-fg biases.

6.3 Comparison of model wind with observations

A plot of derived AMV speed versus the average model speed in the cirrus cloud (Fig. 6.3) shows much less correlation compared to Fig 6.2. The same colour coding as in the previous section is used to indicate the vertical extent of the cirrus cloud. The largest underestimation in the observed speed (negative speed bias) occurs for thin clouds, i.e. many blue dots are located below the diagonal at rather high speeds. There is virtually no difference between

IR:H_2O and WVcloud:H_2O winds. As already mentioned in the last section the obs-fg bias is -3.80 m/s for IR:H_2O and -3.0 m/s for WVcloud:H_2O. NRMSVD is 0.5 for both AMV data sets.

It was already pointed out that in the CIMSS post-processing winds of poor quality are removed by various checks. The lower figures in Fig. 6.3 show the same analysis as mentioned in the last paragraph, but only for the raw quality AMVs that are still present in the 'final' quality data set. Some AMVs from thin cirrus clouds are now missing and the obs-fg bias becomes considerably smaller, suggesting that the CIMSS quality control is able to identify some of the cases with the worst bias. Nevertheless, a significant bias is still present, and in the following we aim to characterize this error. An important detail/idea is given by the statistics in Table 6.3 and 6.4 (last three columns) which show the obs-fg bias and NRMSVD subdivided into four groups of vertical cirrus extent. In case of IR:H_2O AMVs and thin cirrus clouds (1-3 layers) the bias is -4.6 m/s while it is -4.7 m/s for clouds with 4-6 layers. The underestimation is about 0.8 m/s smaller for WVcloud:H_2O winds. AMVs derived from cirrus clouds with more than 12 vertical levels are almost unbiased. NRMSVD is also highest for thin clouds.

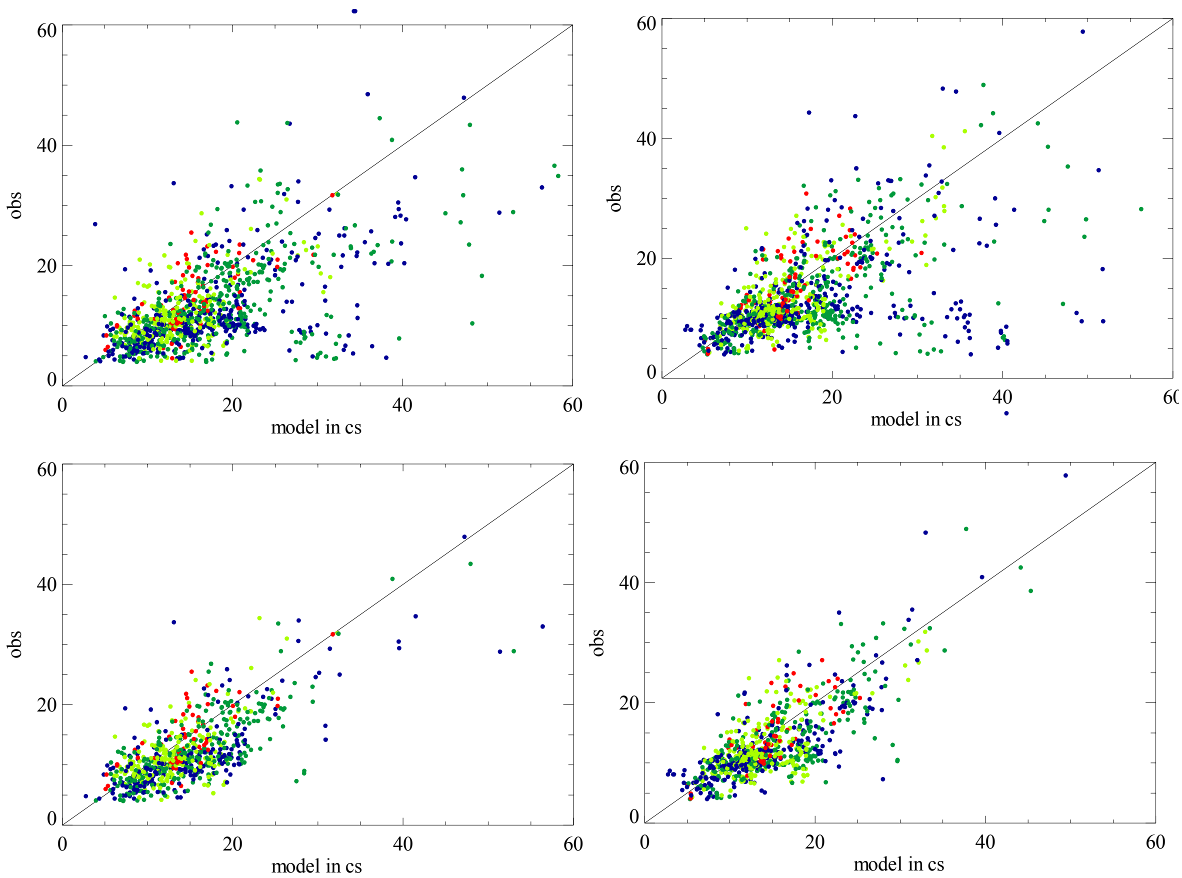


Figure 6.3: Observed AMV speed [m/s] versus model speed in idealized cirrus clouds for IR (left) and water vapour cloud (right) winds. In the upper figures all winds from the raw quality data set that passed the cirrus selection criteria are plotted. In the lower figures only raw quality winds that are found in the final data set are plotted.

6.4 Impact of the temporal cloud evolution

Above, we showed that AMVs derived from thin cirrus exhibit particularly strong obs-fg biases. In the following, we aim to establish how and why this happens.

Deriving AMVs by tracking cloudy features in subsequent satellite images assumes that the features are passive tracers, i.e. they drift with the local wind speed. It is also assumed that they are invariant in time. That means the features should not change their shapes, grow or dissolve, as the tracking of speeds will otherwise not represent the mean drifting speed anymore. However, particularly thin cirrus clouds are subject to growth and decay, in short changing their shape and affecting the tracking.

Figure 6.4 shows a sequence of four simulated IR images that are used for the AMV derivation. The time step between the images is 15 min. The red circle marks a little cloud free area that disappears (gets cloudy) within 45 minutes. Such situation is likely to provide a challenge for the automated tracking software used at CIMSS.

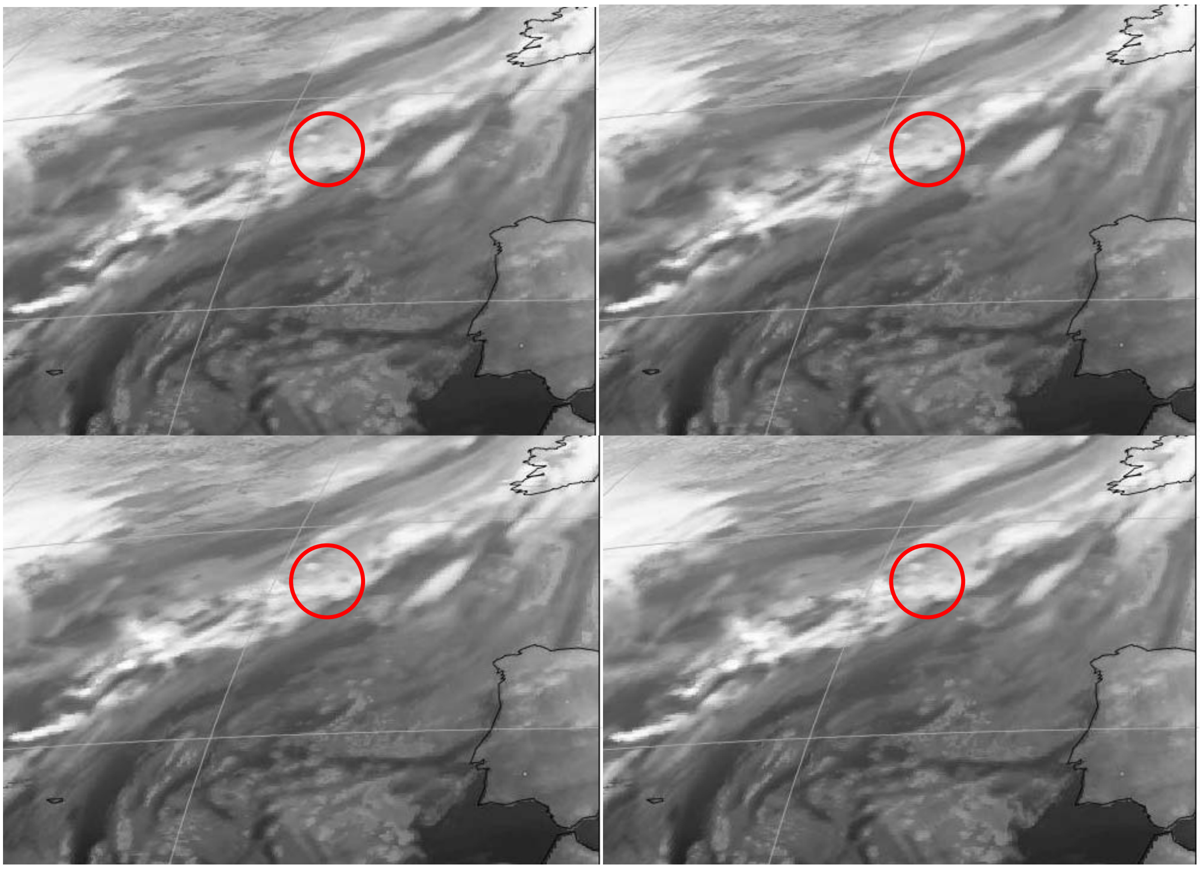


Figure 6.4: Four subsequent simulated IR images for Meteosat-8 (10.8 μm*) from left to right with a time interval of 15 minutes.*

In order to get a feeling about growth and decay of clouds in the forecast simulation a simple tracking study of the simulated model clouds was performed. Growth and decay of clouds were determined by the change of the integrated cloud ice water path (IWP) over the period used for the tracking. Changes of IWP are assumed to be equivalent to radiance changes. Although this relation is highly non-linear it can serve as a first order approximation.

The change in IWP was calculated as follows: The starting point for the model cloud is time t_0 (time of observation, see Fig. 6.5) and the average model speed and direction in the cirrus. The location of this cloud in the previous image is estimated from the location at t_0, the mean forecast model wind in the cirrus, and the image interval of 15 min. The cloud parameters at this location are extracted from the model fields at t_0-15min as described in Section 5.1, and the ice water path at t_0-15min is computed. The equivalent procedure is applied to compute the ice water path at t_0+15min. For instance, for a model wind speed of 30 m/s the distance between two positions is 27km. The grid spacing is 10km, i.e. the drifting cloud has crossed two or three grid boxes. Furthermore it should be noted that bi-linear interpolation was applied for all horizontal interpolations, and this can contribute to an additional smearing of gradients. It is therefore very likely that the temporal gradients in ice water path are underestimated.

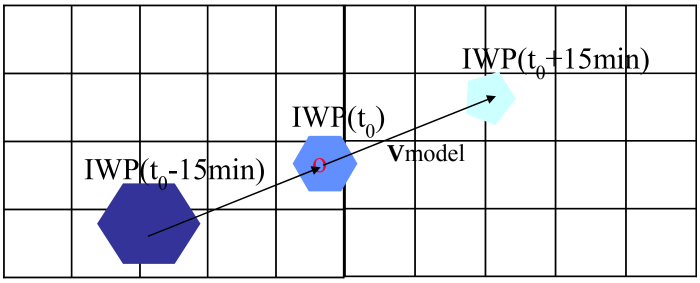


Figure 6.5: Illustration of fluctuating cloud shape and thickness (colors) with time.

The characterization of temporal changes in the cloud's evolution is kept very simple and only four categories are discriminated:

i) IWP decreases in the first 15min step and also becomes smaller in the second step, i.e. the cloud is constantly dissolving.
ii) IWP decreases in the first 15min step and then IWP increases, i.e. the cloud dissolves in the first step and then grows.
iii) IWP increases in the first 15min step and then IWP decreases, i.e. the cloud grows in the first step and then dissolves.
iv) IWP increases in both steps, i.e. the cloud grows constantly.

Growth and decay are calculated only in the vertical, but it is assumed that vertical and horizontal development are correlated, i.e. changes of the cloud shape and size are correlated to the activity in the vertical extent (here represented by the integrated ice path).

Tables 6.3 and 6.4 provide an overview of the obs-fg statistics separated into the various categories of cloud evolution and cloud thickness. The last row in each table summarizes the results for all four classes of could thickness. Undoubtedly, the category with dissolving and then extending cloud (smaller, larger) has the largest negative biases (last row in Tab. 6.3, 6.4) for IR:H_2O and WVcloud:H_2O with -5.5 and -3.8 m/s, respectively. NRMSVD is also higher than the average. The other category with two different evolutions (growth followed by decay) also shows the second highest negative biases with -3.5 m/s for IR:H_2O and WVcloud:H_2O. It can be suspected that clouds that first decay and then extend or vice versa have the highest activity and variability. This makes these clouds more difficult to track. Such clouds are also less likely to represent passive tracers, given their activity. The two categories with a steady development show biases and NRMSVDs that are considerably smaller.

All evolution categories are almost equally populated reducing the problem of sampling errors, i.e. the sampling error is the same in each category. Nevertheless it must be considered that the overall sampling size is rather low and more simulations are needed to confirm the findings. It could be useful to create additional categories for clouds that show almost no development (zero category).

In particular thin clouds (1-3 cloudy layers and 4-6 cloudy layers) that are categorized to decay and then to grow show very large obs-fg biases (-6.5 m/s (IR:H_2O) and -5.3 m/s (WVcloud:H_2O) for 4-6 cloudy layers). It is obvious that the impact of cloud evolution will be stronger for thin clouds as, for example, they may dissolve completely. In these cases tracking errors and increased uncertainties are unavoidable.

Thick cirrus clouds (>12 cloudy layers) are rather unaffected by how the cloud evolves. The obs-fg bias and NRMSVD are very small.

	Step1: smaller Step2: smaller			Step1: smaller Step2: larger			Step1: larger Step2: smaller			Step1: larger Step2: larger			All developments		
Cloudy layers	N	bias	nvd	N	bias	nvd	N	bias	Nvd	N	bias	nvd	N	bias	nvd
1-3	57	-5.3	0.69	129	-6.0	0.56	50	-3.1	0.47	86	-3.2	0.51	322	-4.6	0.56
4-6	92	-3.5	0.48	119	-6.5	0.54	110	-4.3	0.50	86	-4.0	0.52	407	-4.7	0.52
7-11	79	-0.8	0.38	34	-2.8	0.37	70	-2.9	0.41	43	-0.1	0.37	226	-1.6	0.39
>12	26	-0.6	0.27	11	-0.5	0.29	21	-1.7	0.35	17	0.7	0.27	75	-0.6	0.30
all	254	-2.8	0.49	293	-5.5	0.54	251	-3.5	0.46	232	-2.6	0.49	1030	-3.7	0.51

Table 6.3: Obs-fg statistics (bias [m/s] and normalized root mean square vector difference nvd) for IR AMVs in different cloud evolution scenarios during the tracking procedure and various vertical cloud extensions (layers). The model speed is the averaged wind in the cirrus.

	Step1: smaller Step2: smaller			Step1: smaller Step2: larger			Step1: larger Step2: smaller			Step1: larger Step2: larger			All developments		
Cloudy layers	N	bias	nvd	N	bias	nvd	N	bias	nvd	N	bias	nvd	N	bias	nvd
1-3	66	-3.3	0.65	110	-4.1	0.58	62	-4.2	0.69	101	-3.6	0.52	339	-3.8	0.59
4-6	95	-3.2	0.45	79	-5.3	0.53	114	-4.8	0.52	76	-2.6	0.47	364	-4.0	0.50
7-11	93	-0.2	0.35	52	-1.7	0.34	66	-3.5	0.39	61	-0.7	0.29	272	-1.4	0.35
>12	25	0.58	0.32	23	-1.5	0.24	22	-3.9	0.33	16	0.7	0.30	86	0.0	0.30
all	279	-1.9	0.47	264	-3.8	0.53	264	-3.5	0.53	254	-2.3	0.46	1061	-3.0	0.50

Table 6.4: *As Table 6.3, but for water vapour cloud AMVs.*

The lessons learnt by the case study of AMVs in idealistic cirrus clouds from situations in which height assignment can be ruled out as leading error source are:

i) Model speeds at assigned heights agree well with linear averages of model speeds in cirrus clouds. This confirms that height assignment is a minor error source, at least for the selected cases. The main obs-fg deviation must arise from uncertainties in the tracked speed.
ii) The negative obs-fg bias is larger for thin cirrus. IR:H_2O AMVs have larger bias than WVcloud:H_2O AMVs.
iii) Changing tendency in cloud evolution is linked with highest bias in the AMVs, i.e. temporal cloud development can degrade AMV quality.

7 Summary

In this study we used AMVs derived from images simulated from a high-resolution ECMWF forecast to investigate characteristics of AMV data. The main findings are:

- The simulated AMVs exhibit broadly similar characteristics against the model truth as are commonly observed in monitoring statistics of real AMVs against short-range forecasts. This indicates that, overall, the simulation is adequately representing the characteristics of the real data.
- Before the CIMSS quality control, the simulated AMVs show relatively little sensitivity to the source of forecast data used in the AMV processing. However, quality control in the CIMSS processing (including the auto-editor) is sensitive to the choice of forecast data. For the given dataset, the CIMSS quality control acted primarily through removal of poorer data, rather than through adjustments to the assigned height in the auto-editor.
- At least some of the negative bias observed at high levels in the extra-tropics appears to be due to the fact that clouds do not act as passive tracers and their motions do not fully represent the ambient wind. Biases are still present in situations in which height assignment is of less importance, and the largest biases are observed for thin cirrus clouds with considerable evolution between the images used in the tracking.
- Characteristics for AMVs in low-level inversion regions point to tracking problems in the simulated dataset. The characteristics for the simulated data agree less with experience from real AMVs in these situations.

The above findings for the simulated AMVs provide a number of interesting insights into AMVs and their interpretation. The interpretation of the results for real AMVs is 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 completely eliminate 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 whether stronger biases in real data can be related to very thin cirrus clouds and situations with a certain cloud evolution over the tracking period. If the current findings apply to real data, a quality flag that indicates cloud thickness could prove a useful addition to the AMV product.

There is also still scope for further investigations based on the current dataset. Comparisons to EUMETSAT-derived AMVs will further highlight the differences in the AMV processing and quality control used at CIMSS and at EUMETSAT. EUMETSAT-derived winds were not yet available for the present study, but should be available in due course. Furthermore, the aspect of interpreting AMVs as layer or horizontal averages rather than single-level point observations could be studied in more detail. Also, the simulation framework lends itself well to the study of spatial error correlations in AMVs (e.g., Bormann et al. 2003).

For future simulations, we recommend a higher model resolution and a longer study period.

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