CHARACTERISING AND CORRECTING SPEED BIASES IN ATMOSPHERIC MOTION VECTORS WITHIN THE ECMWF SYSTEM

Niels Bormann, Graeme Kelly, and Jean-Noël Thépaut

European Centre for Medium-Range Weather Forecasts (ECMWF)
Shinfield Park, Reading, Berkshire RG2 9AX, UK, n.bormann@ecmwf.int

ABSTRACT

Speed biases in Atmospheric Motion Vectors (AMVs) are discussed in a data assimilation context, and the biases are characterised in detail in terms of the atmospheric environment. There is evidence that the speed biases are related to height assignment problems and the use of a suboptimal observation operator. A statistical scheme is suggested to correct the biases in the extra-tropics through a First Guess dependent height reassignment and a revised observation operator. The concepts are tested within the ECMWF data assimilation system.

The speed bias and root mean square vector difference can be significantly reduced through the height reassignment and the revised observation operator which uses layer averaging rather than interpolation to a single level. The concepts lead to a more symmetrical distribution of First Guess departures.

Preliminary forecast experiments show a mainly neutral forecast impact from the revised assimilation of METEOSAT-5 and 7 AMVs. The changes allow a detailed revision of various aspects of the assimilation of AMVs such as quality control procedures and observation errors.

1 Background

Atmospheric Motion Vectors (AMVs) have long exhibited considerable speed biases against model data or other observations (e.g., Fig. 1a, ECMWF 2000). The geographical characteristics are well established, such as a slow bias (about 1–5 m/s) at higher levels[1] in the extra-tropics and a fast bias (1–3 m/s) at middle levels in the tropics. While some seasonality is observed with a stronger extra-tropical bias for winter, the general zonal pattern are fairly constant. The slow speed bias is not accompanied by a similarly significant directional bias.

Currently, the origin of the speed bias is not well-understood. The most commonly suspected reasons are problems in the height assignment, clouds that are not acting as passive tracers, or deficiencies in the observation operator. The observation operator (ie, the link between the model fields and the AMVs) is usually an interpolation to the assigned pressure level (e.g., Holmlund 2000). Different height assignment schemes for geostationary satellite data show root mean square errors (RMSE) of 60–110 hPa and mean differences of 30 hPa (e.g., Nieman et al. 1993). A number of areas contribute to height uncertainties: For instance, it is unknown if the cloud top is the best representative height for the observed cloud motions at higher levels or if the wind at levels within the cloud determines the cloud motions (e.g., Hasler et al. 1979). Also, the AMV processing

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[1]Throughout this contribution, "high level" refers to "above 400 hPa", and "middle level" to "700–400 hPa". Also, "extra-tropics" refers to the region outside 20° latitude, and "tropics" within 20° latitude, unless indicated otherwise.
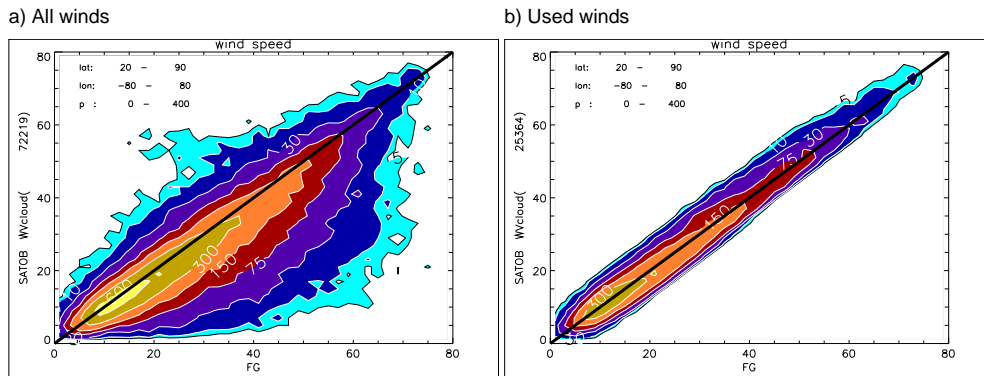
Figure 1: a) Density plot of model First Guess versus AMV wind speeds for all METEOSAT-7 WV cloud winds at high levels over the Northern Hemisphere (north of 20 N) for 1–15 February 2001. Bin size is (2 m/s, 2 m/s). b) As a), but only for the winds used in the assimilation.

and in particular the height assignment methods rely on a number of assumptions, and if these are not satisfied the resulting product will have dubious quality. For EUMETSAT AMVs, the water vapour (WV) intercept method is applied for winds above 600 hPa to account for high-level semi-transparent cloud (e.g., Schmetz et al. 1993).

As the ECMWF system assumes unbiased observations, a special check against the model's First Guess field (FG) is applied to AMVs to select a roughly unbiased sample. This check rejects more of the slower winds and is tighter than for other wind observations (e.g., Järvinen and Undén 1997). The selected sample of AMVs is thus heavily constrained by the FG (e.g., Fig. 1b) and has a non-Gaussian error distribution with correlations between FG and AMV errors. These aspects are not accounted for in the ECMWF system, potentially leading to a suboptimal use of the data. If the biases cannot be improved through a revised processing on the winds producer's side the preferred approach to address the biases is a correction before screening based on known characteristics of the observations. This is commonly applied to radiance data, where regressions correct airmass-dependent biases (e.g., Harris and Kelly 2000). We hypothesise that a similar approach is also more beneficial for AMVs, and this study reports on the ongoing development of such an approach.

2 Bias study

2.1 Data and method

This study concentrates on EUMETSAT's cloud track winds from 160 km processing segments from the infrared (IR) and the water vapour (WV) channel from METEOSAT-7 (MET-7). The processing algorithm is described in detail by Schmetz et al. (1993). We restrict our study to winds above 600 hPa, as only these use the WV-intercept method for height assignment. Also, we concentrate on extra-tropical winds with a quality indicator (QI, Holmlund 1998) $\geq$ 60 %. The speed bias for low-level winds from the visible channel is considered small and is therefore not discussed here (e.g., ECMWF 2000).

The AMVs are compared against operational 6-h forecasts interpolated from $1 \times 1°$ fields from the ECMWF 60-level model for the period January–June 2000. The AMVs were grouped into 6-h time windows around synoptic times and compared to the nearest (in time) forecast. The 6-h forecasts were also used to derive a number of parameters likely to be related to wind speed or height assignment biases, such as an estimate of the wind shear at the assigned pressure level, an estimate

of the second derivative of wind speed vs. pressure at the assigned pressure level, a temperature lapse rate, etc. To calculate these parameters, the model fields were horizontally interpolated to the AMV locations, to yield 60-level profiles of the two wind components, temperature, and the mixing ratio of humidity.

In addition, we derived a "best fit" pressure level p_{best}, calculated as the local minimum of the vector difference between the model wind profile and the AMV, closest to the originally assigned pressure level, in the direction of decreasing vector difference. To avoid the restriction of this "best fit" pressure level to model levels the minimum was calculated from a parabolic fit from the 3 model levels around the minimum. It is important to stress that without detailed in-situ observations (e.g., aircraft data from field experiments) it is impossible to estimate a "best" height which is most representative for the motion of the tracked cloud. Therefore, the "best fit" pressure level calculated in this study is merely another estimate for the height of the wind with systematic as well as random errors.

2.2 Characterisation of the speed bias

The departures show some correlation (≈ 0.2) with a number of predictors, such as the second derivative of speed with respect to pressure at the assigned pressure level ($\frac{\partial^2(ff)}{\partial p^2}$), the local wind shear ($\frac{\partial(ff)}{\partial p}$), the 500 hPa temperature ($T_{500\ \text{hPa}}$), the integrated water vapour in the column above the assigned pressure (Top WV), or, for IR winds, the brightness temperature (T_b) of the tracked cluster. More importantly, these correlations are fairly constant for the 6 months studied, giving further evidence for a relationship between these predictors and the speed bias. Some predictors show no linear relationship to the forecast departures, such as the total column water vapour, indicating less relevance to the speed bias problem.

There is statistical evidence that the current observation operator is partly responsible for the speed biases, and that AMVs should be treated as layer-averages rather than single level data. Figure 2 shows an approximately linear relationship between the speed bias and the second derivative of speed with respect to pressure, and this behaviour is consistent with the following considerations: if a Gaussian weighting function w with variance σ^2 around the assigned pressure p_0 is used to
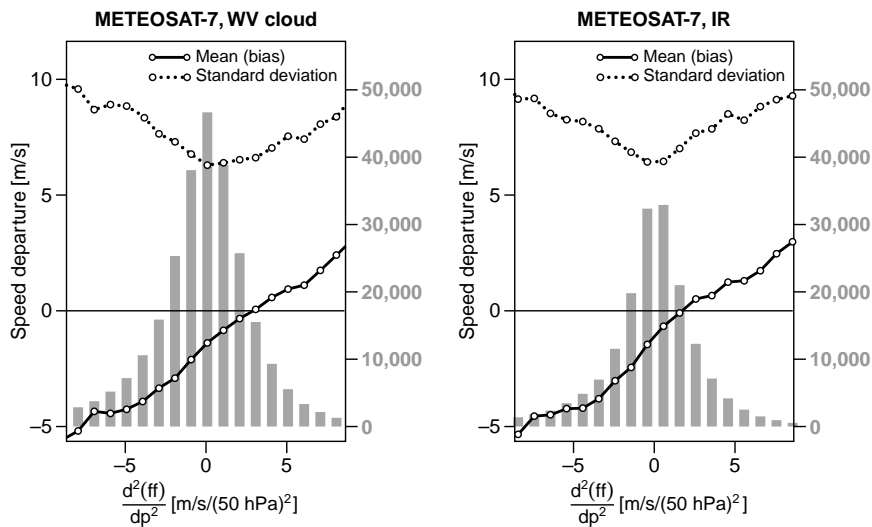

Figure 2: Speed bias (solid line) as a function of $\frac{\partial^2(ff)}{\partial p^2}$ for MET-7 WV cloud and IR winds for February 2000. The standard deviation of the speed departures is also shown (dotted line). The grey bars show the number of winds per bin (right axis).
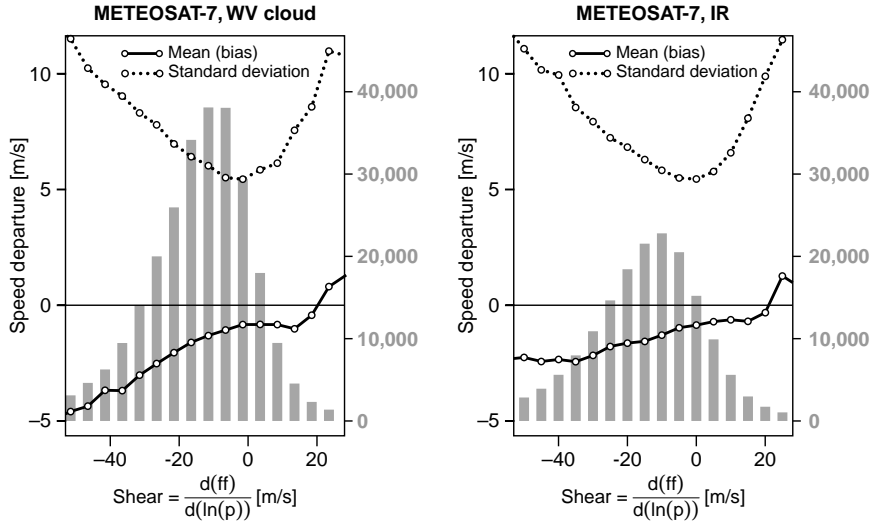
Figure 3: As Fig. 2, but for the speed bias as a function of wind shear.

calculate a weighted layer average then the relationship between the layer average $\langle ff \rangle_w$ and the single-level value $ff(p_0)$ is given by (e.g., Rinne 1997)

$$\langle ff \rangle_w - ff(p_0) \approx \frac{\sigma^2}{2} \frac{d^2(ff)}{dp^2}(p_0) \tag{1}$$

Thus, the behaviour shown in Fig. 2 can be explained as an over-/underestimation of the model wind in the single level approach compared to a layer-average, proportional to $\frac{\partial^2(ff)}{\partial p^2}$. Indeed, when calculating equivalent model values using a Gaussian weighting function with $\sigma = 50$ hPa, the relationship disappears, and a slow bias approximately constant with $\frac{\partial^2(ff)}{\partial p^2}$ remains. The remaining bias shows that there are also other factors responsible for the speed biases and these will be discussed below.

Given the large uncertainty in the height assignment for AMVs (RMSE $\approx$ 60-110 hPa, Nieman et al. 1993), layer averaging can be viewed as a probabilistic approach to the height assignment in the observation operator. Also, the AMVs are likely to represent motions of cloud layers, providing a physical justification for layer averaging. Further research will determine an appropriate weighting function; for the meantime, experiments with different weighting functions suggest a Gaussian with $\sigma = 50$ hPa around the assigned pressure, set to zero above 100 hPa and linearly reduced to zero between 100 and 200 hPa to avoid unrealistic contributions from too high levels.

Wind shear also shows consistent and considerable correlations with the speed departures for IR or WV cloud drift winds. Shear is positively correlated with the departures and the bias is small around zero (Fig. 3). Note the increase in the standard deviation with the absolute value of shear. The dependence of the speed bias on shear points to systematic problems in the height assignment, as these will be most noticeable in areas of strong shear. The dependency is consistent with assigning the winds, on average, to too low pressure (too high). Differences between p_{best} and the originally assigned pressure show a correlation of about 0.65, further suggesting a relationship between the speed bias problem and height assignment.

For IR winds, the speed or height departures show considerable correlations with predictors describing the temperature environment of the tracked cloud, namely the brightness temperature of the tracked cluster, a temperature lapse rate ($\frac{\partial T}{\partial p}$), and the 500 hPa temperature (not shown). Slow speed biases (high height biases) are stronger for lower brightness temperatures in more stable environments with colder 500 hPa temperature. On the one hand, this behaviour could reflect

a dependence of the height biases on the cloud type, roughly characterised here by its temperature environment. Certain cloud types may require a lower or higher height assignment, reflecting their interaction with the environment. On the other hand, the above findings may merely reflect shortcomings in the processing, more likely to occur in certain atmospheric conditions. In any case, the dependence of the bias on cloud type appears worth investigating further.

3 Correcting the speed bias

3.1 Method

Following the above findings, we correct the speed biases through a height reassignment in addition to the use of a revised observation operator. The height reassignment suggested in this study uses multivariate linear regression, and is based on regressions between $log(p_{\mathrm{best}}/p)$ and suitable predictors (p is the originally assigned pressure). These regressions are currently calculated for one-month periods, and then applied to AMVs during the next month. The rationale is to carry forward in time the statistical information on the speed biases, based on an independent training dataset.

The predictors were chosen based on an objective stepwise search, allowing for different predictors for WV and IR winds. The final choice of predictors combines the results for individual months, and is presented in Table 1. It encompasses information about the approximate height of the cloud (through the brightness temperature or the Top WV predictor), and the general temperature and dynamical structure of the cloud environment. The objective predictor choice showed considerable consistency between months, even though the ranking of the predictors varied occasionally, and some of the lower ranked predictors differed for some months. This gives further evidence that the chosen approach indeed identifies some consistent deficiencies in the current height assignment to the estimated cloud top.

The reassignments provided by the regressions are relatively small and, on average, much smaller than those suggested by p_{best}. The reassigned and the originally assigned pressure show RMS differences of about 30–45 hPa with a mean of around 25 hPa.

Table 1: Predictors chosen for the height reassignment scheme.

IR	T_b, $\frac{\partial(ff)}{\partial p}$, $\frac{\partial T}{\partial p}$, mean temperature between 80 hPa and p
WV cloud	Top WV, $\frac{\partial(ff)}{\partial p}$, $\frac{\partial T}{\partial p}$, $T_{500\ \mathrm{hPa}}$

3.2 Impact on monitoring statistics

The impact of the layer averaging and the bias correction on the zonal means of the speed bias against the FG can be seen in Fig. 4 for IR winds. The combined approach successfully keeps the speed bias within ± 1 m/s in most areas. The contribution of the layer averaging is relatively small (≈ 1 m/s) and confined to the jet-cores at higher levels in the extra-tropics, where the second derivative of speed with respect to height is largest. Similar results can be reported for WV winds (not shown).

As a further independent test of the bias reduction, monitoring statistics have been calculated for the reassigned AMVs collocated with wind observations from radiosondes. A significant reduction
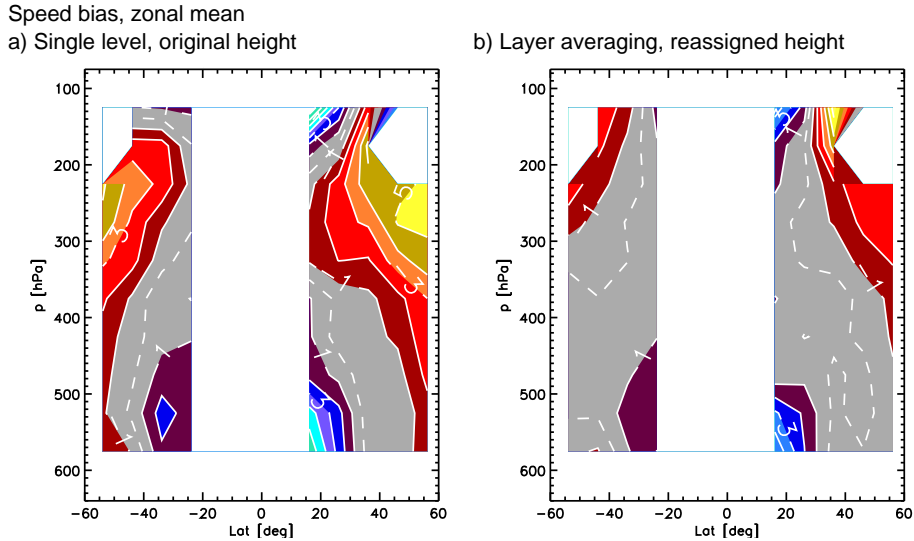
Speed bias, zonal mean
a) Single level, original height
b) Layer averaging, reassigned height

Figure 4: a) Zonal means of the speed bias against the FG (AMV-FG) for MET-7 IR winds with QI $\geq$ 60 % for February 2000 (over the MET-7 area). Contour interval is 1 m/s; light grey shading indicates biases within ± 1 m/s. Only extra-tropical winds above 600 hPa are shown. b) As in a), but applying height reassignment as described in the main text and using layer averaging as observation operator.

of the speed bias and reduced NRMSVD are evident (Table 2). This is an important result as a bias reduction which merely corrects observations towards the FG without drawing closer to other observations is likely to merely reinforce errors in the FG and is thus likely to be detrimental. While this "incest-danger" still remains, the above findings indicate that the improvements in the speed biases outweigh the expense of further FG dependency of the AMVs.

Table 2: Statistics for February 2000 MET-7 WV cloud winds with QI $\geq$ 60 % compared against radiosonde observations (according to CGMS recommendations, that is, collocation within 1.5 h, 150 km, and 25 hPa). The pressure of the AMVs has been reassigned as described in the main text, but no layer-averaging has been applied. Numbers in brackets give values for the original winds. Gross outliers are removed.

	MET-7 South. Hem. 90 S–20 S	MET-7 North. Hem. 20 N–90 N
NRMSVD	0.46 (0.49)	0.40 (0.43)
Speed bias [m/s]	-0.31 (-0.90)	-1.11 (-3.30)
Speed [m/s]	16.55 (17.07)	23.49 (26.02)
N	1046 (1046)	8699 (8922)

4   Assimilation experiments

The above height reassignment scheme and the revised observation operator have been applied in data assimilation experiments at ECMWF, covering the periods 1–28 February and 1–31 July 2001 (59 days). The first experiment used all AMVs as in current operations ("CTL"). The second experiment ("EXP") applied the new concepts to IR and cloudy WV AMVs from METEOSAT-5 and 7, and used a symmetric FG check for these winds. The bias correction models were calculated for the previous month, and applied over the extra-tropics above 600 hPa only. Both experiments used incremental 12h 4DVAR with a model resolution of T511 ($\approx$40km), an analysis resolution of T159 ($\approx$125km), and 60 levels in the vertical. 10 day forecasts were run from each 1200 UTC analysis.
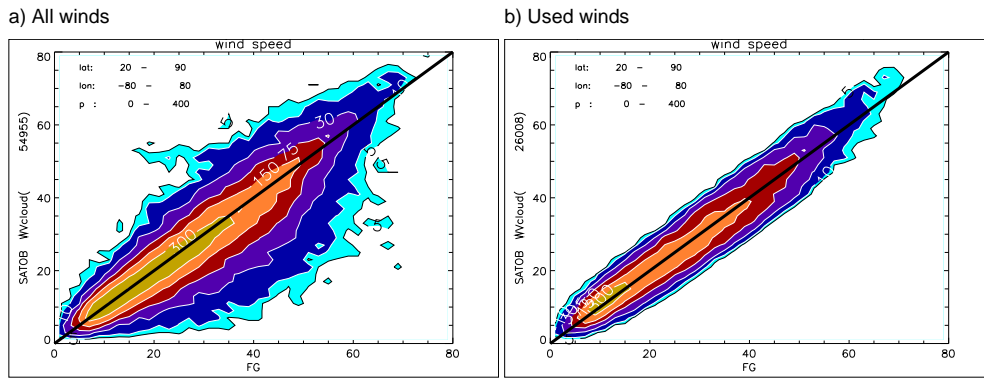
a) All winds

b) Used winds

Figure 5: a) Density plot of FG versus AMV wind speeds for all bias corrected METEOSAT-7 WV cloud winds at high levels over the Northern Hemisphere (north of 20 N) from the experiment EXP, 1–15 February 2001. Bin size is (2 m/s, 2 m/s). b) As a), but only for the winds used in the analysis.

The bias corrected winds show a much more symmetrical distribution around the FG, rendering the asymmetric FG check unnecessary (Fig. 5, cf Fig. 1). The changes introduced in EXP do not degrade the fit of the analysis to other observations compared to CTL, and the changes to the mean wind analysis are small (not shown). These findings indicate that the bias correction and the new observation operator agree well with the rest of the observational network. Also, the bias correction is at least as successful as the asymmetric FG check in preventing that AMVs slow-down the extra-tropical jets.

The overall impact of the changes on medium-range forecast scores is mainly neutral (e.g., Fig. 6). There is a tendency for a marginal positive forecast impact at higher levels over the Northern Hemisphere extra-tropics for some forecast ranges, whereas Southern Hemisphere forecasts are slightly degraded in the forecast range day 3 to 6, particularly at lower levels, but slightly improved at some levels later in the forecast. This indicates that the bias correction scheme is similarly successful in addressing the biases in the data assimilation framework as the asymmetric FG check. However, the bias corrected AMVs allow further revisions of the use of AMVs in the ECMWF system, highlighting the benefits of a better understanding and reduction of speed biases in AMVs for their use in numerical weather prediction.
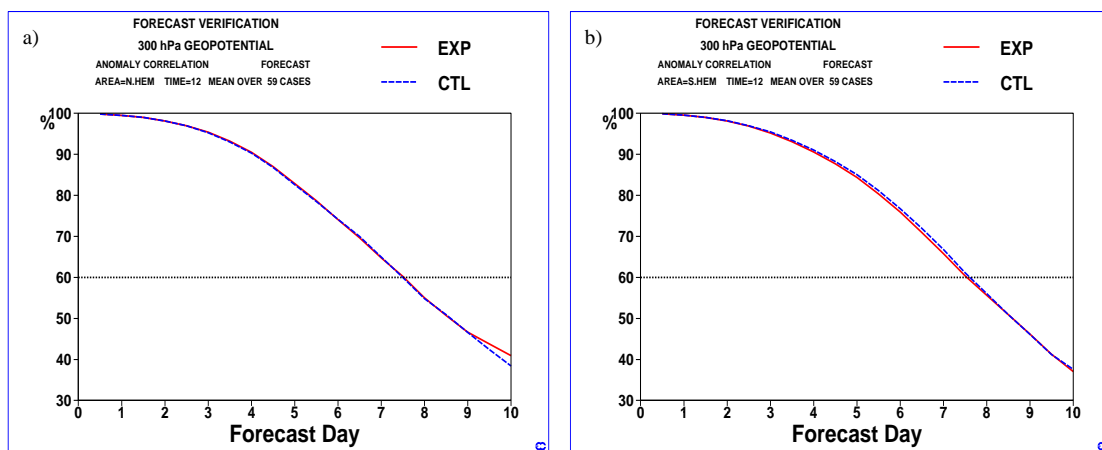

Figure 6: a) Anomaly correlation for the 300 hPa geopotential against the operational analysis for the experiment with height reassignment and layer averaging (solid red) and the experiment without changes (dashed blue). The scores have been calculated for the Northern Hemisphere extra-tropics. b) As a), but for the Southern Hemisphere extra-tropics.

5 Summary and outlook

Speed biases in extra-tropical IR or WV cloud winds have been investigated in detail. There is strong evidence that the speed bias is a result of deficiencies in the height assignment and the use of a suboptimal observation operator. We suggest a new statistical scheme to correct the speed biases in extra-tropical AMVs through a height reassignment in combination with a revised observation operator. The scheme significantly reduces the speed biases and the NRMSVD against the ECMWF FG as well as against other observations. Preliminary forecast experiments with the above changes show a neutral impact on medium-range forecast scores.

The bias correction discussed herein is not intended as a "final solution" of the AMV bias problem. Ideally, known sources of biases should be rectified on the winds producer's side, and this should try to avoid the use of forecast data as far as possible. If a bias correction cannot be achieved without the use of forecast data, it should be left to the users in order to avoid hidden "incest" problems.

The new bias correction concept allows and requires a detailed revision of the assimilation of AMVs at ECMWF. Further experiments indicate sensitivity of the forecast impact to quality control procedures, and these are currently being revised to reflect the new assimilation approach. Also, it is now possible to thoroughly revise the observation errors assigned to AMVs (e.g., Bormann et al. 2002). So far, the observation errors have been inflated at ECMWF, reflecting a cautious approach to the assimilation of AMVs.

In addition, close cooperation with EUMETSAT is needed to further alleviate bias problems in the AMV processing. In particular, the new capabilities for the AMV height specification for METEOSAT Second Generation should be explored.

References

Bormann, N., S. Saarinen, G. Kelly, and J.-N. Thépaut, 2002: The spatial structure of observation errors in atmospheric motion vectors from geostationary satellite data. In these proceedings.

ECMWF, 2000: *ECMWF SATOB data monitoring report, June–August 2000*. ECMWF, Reading, U.K.

Harris, B. A., and G. Kelly, 2001: A satellite radiance-bias correction scheme for data assimilation. *Quart. J. Roy. Meteor. Soc.*, **127**, 1453–1468.

Hasler, A. F., W. C. Skillman, and W. E. Shenk, 1979: In situ aircraft verification of the quality of satellite cloud winds over oceanic regions. *J. Appl. Meteor.*, **18**, 1481–1489.

Holmlund, K., 1998: The utilization of statistical properties of satellite-derived atmospheric motion vectors to derive quality indicators. *Wea. Forecasting*, **13**, 1093–1104.

Holmlund, K., 2000: *Proceedings of the Fifth International Winds Workshop*. EUMETSAT, Darmstadt, Germany, 298 pp.

Järvinen, H., and P. Undén, 1997: Observation screening and background quality control in the ECMWF 3DVAR data assimilation system. Technical Memorandum 236, ECMWF, Reading, U.K.

Nieman, S. J., J. Schmetz, and W. P. Menzel, 1993: A comparison of several techniques to assign heights to cloud tracers. *J. Appl. Meteor.*, **32**, 1559–1568.

Rinne, H., 1997: *Taschenbuch der Statistik*. Verlag Harri Deutsch, Frankfurt am Main, 650 pp.

Schmetz, J., K. Holmlund, J. Hoffman, B. Strauss, B. Mason, V. Gaertner, A. Koch, and L. Van De Berg, 1993: Operational cloud-motion winds from Meteosat infrared images. *J. Appl. Meteor.*, **32**, 1206–1225.