# OBJECTIVE DETERMINATION OF THE RELIABILITY OF SATELLITE-DERIVED ATMOSPHERIC MOTION VECTORS

Kenneth Holmlund[#] and Christopher S. Velden*

[#]EUMETSAT, Am Kavalleriesand 31, 64295 Darmstadt, Germany
*Cooperative Institute for Meteorological Satellite Studies, Madison, Wisconsin

## ABSTRACT

The coverage and quality of Atmospheric Motion Vectors (AMVs) derived from geostationary satellite imagery have improved considerably over the past few years. This is due not only to the deployment of the new generation of satellites like GOES-8/9/10 and GMS-5, but also a result of improved data processing and Automatic Quality Control (AQC) schemes. The post-processing of the derived displacement vectors at NOAA/NESDIS has been fully automated since early 1996, and at EUMETSAT the Manual Quality Control (MQC) was abandoned by operations in September 1998. The AQC schemes at the two organizations are quite diverse: At NOAA/NESDIS the AQC is based on a method developed at UW-CIMSS and involves an objective 3-dimensional recursive filter analysis of the derived wind fields. The fit of each vector to that analysis yields Recursive Filter (RF) quality flags. The AQC scheme employed at EUMETSAT derives a Quality Indicator (QI) for each individual vector based on the properties of the vector itself and its consistency with other AMVs in close proximity. The QI-based scheme has been proven to provide a good estimate of the reliability of the derived displacements, but fails to identify fleets of winds that are consistently assigned to a wrong height. The RF-based scheme is capable of re-adjusting the height of the winds, which yields a better fit to the analysis and ancillary data.

The ‘Working Group On Methods’ at the Third Winds Workshop in Ascona (EUMETSAT, 1996) recognized the progress being made in the derivation of objective quality flags and emphasized the importance to develop consistent methodologies that can be adaptable to all global data extraction centers. This paper will describe the two above-mentioned AQC schemes and preliminary inter-comparison experiments where the two AQC schemes were applied to the same AMV field. Finally, the goal of combining the advantages of each of these methods to maximize the AQC effectiveness towards optimal use and assimilation of the AMV-fields is discussed.

## 1. INTRODUCTION

The derivation and utilization of AMVs has constantly improved since the advent of the first operational geostationary satellites. Today the extraction frequency, coverage and density of the derived fields are too demanding for manual intervention. Therefore, emphasis has been placed on the research and development of robust automated quality control (AQC) procedures that are capable of removing suspect vectors related to tracking, height assignment and tracer representation errors. Furthermore, the AQC schemes are being designed to provide a quality estimate for each individual displacement vector, as well as provide information on how representative these are to single-level motion. These estimates can be employed by the users to select the part of the vector field that best suites their application, as well as in data assimilation schemes to modify the observation error estimates and for data screening.

The current operational AMV extraction centers all invoke AQC schemes. Traditional schemes (e.g. LeMarshall et al., 1994, Bhatia et al., 1996, Tokuno et al., 1996) are usually based on acceleration checks and simple threshold techniques comparing the derived vectors to their surrounding vectors or collocated forecast fields, and are usually used to identify/edit vectors with gross errors only. At EUMETSAT and UW-CIMSS (NOAA/NESDIS), alternative approaches have been explored. The EUMETSAT scheme utilizes similar tests as applied in the threshold techniques, however they are implemented as normalized continuous functions providing test results that can be combined into a final quality indicator (Holmlund, 1998). At UW-CIMSS, the derived vector fields are controlled by a series of quality checks and an objective analysis scheme called the auto-editor (AE, Hayden and Purser 1995), which results in RF quality flags.

## 2. THE EUMETSAT AQC SCHEME

The EUMETSAT AQC scheme is described in Holmlund (1998). The baseline configuration is based on five different tests described in Table 1.

Table 1. The EUMETSAT AMV consistency tests.

| Test name | Function ($\Phi$) | weight |
|---|---|---|
| Direction | $\lvert D_2(x,y)-D_1(x,y)\rvert/(20*\mathrm{exp}^{-((V_2(x,y)+V_1(x,y))/20)+10)}$ | 1 |
| Speed | $\lvert V_2(x,y)-V_1(x,y)\rvert/(0.1*(V_2(x,y)+V_1(x,y))+1)$ | 1 |
| Vector | $\lvert S_2(x,y)-S_1(x,y)\rvert/(0.1*(\lvert S_2(x,y)+S_1(x,y)\rvert)+1)$ | 1 |
| Spatial | $\lvert S(x,y)-S(x-i,y-j)\rvert/(0.1*(\lvert S(x,y)+S(x-i,y-j)\rvert)+1)$ | 2 |
| Forecast | $\lvert S(x,y)-F(x,y)\rvert/(0.2*(\lvert S(x,y)+F(x,y)\rvert)+1)$ | 1 |

The 5 tests return normalized values between 0 and 1, where 0 indicates poor quality and 1 high quality. The tuning of the tests has been achieved by deriving statistics for the different tests against collocated rawinsondes as well as by qualitative validations performed by experienced shift meteorologists. The current tests have been tuned to perform in a binary-like mode, i.e. most tests return values preferably close to 0 or close to 1. Figure 1 shows a frequency histogram of the different tests. It can be seen that for the sample case in question, for which 2910 vectors were produced, between 1000 and 1500 vectors received a quality close to 1 for all tests and 500 on the average received a poor quality. Only the forecast test behaves differently with only a small fraction of good winds.

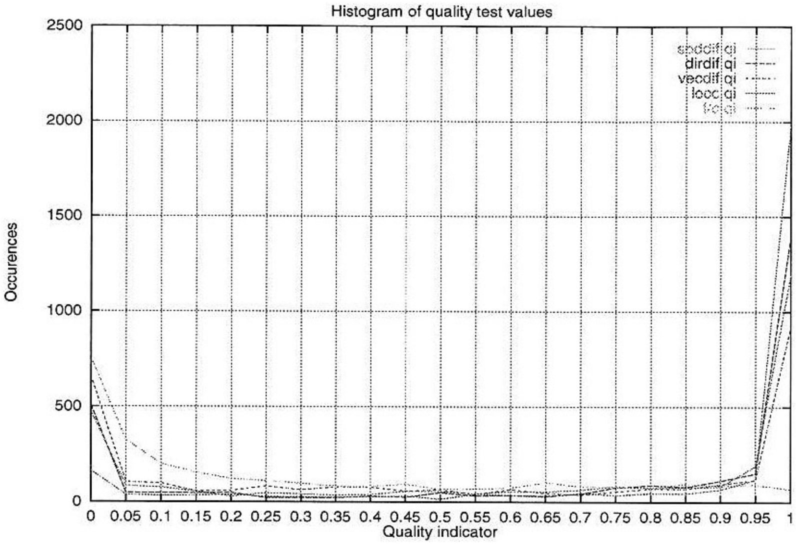

Figure 1. The frequency distribution functions of the five QI tests.

The selected setup was originally intended to be able to mimic the performance of the new scheme in comparison with the old thresholding technique. The disadvantage is that with the current settings the tests do not easily lend themselves to statistical analysis (Elliott, 1998). The second important step in the EUMETSAT AQC is the combination of the normalized test values to provide a final quality estimate. As the distribution of the tests results do not generally follow statistically well behaved functions, the combination of the results to provide probabilities of vector quality is not possible. Instead a simpler approach, where the final quality indicator (QI) is a linear weighted average of the individual results, has been selected.

$$QI = \frac{1}{\sum w_i} \sum w_i \Phi_i \qquad (1)$$

The current weights ($w_i$) are also presented in Table 1. Additional to the tests described above, the QI scheme also involves an inter-channel consistency check. This check compares low level IR and VIS winds to corresponding clear sky water vapour (CSWV) winds. Based on the notion that the IR and VIS low level winds should describe completely different motion than the CSWV winds, low-level winds that are similar to the CSWVs are removed. This test has proven to be important in removing vectors related to extremely thin cirrus that have remained unidentified in the image analysis and are therefore erroneously assigned to a low level.

## 3. THE UW-CIMSS AQC SCHEME

The auto-editor (AE) scheme is described in Hayden and Purser (1995). It was developed at UW-CIMSS and is currently used operationally by NOAA/NESDIS for processing high density GOES winds. The scheme is housed in MCIDAS architecture and relies on a series of steps highlighted by two passes of a recursive filter objective analysis on the subject wind field. The recursive filter determines the fit of each vector to the analysis. In addition, a variational penalty function is applied to each vector that seeks an optimal level for height assignment.

$$B_{m,k} = \left(\frac{V_m - V_{i,j,k}}{F_V}\right)^2 + \left(\frac{T_m - T_{i,j,k}}{F_T}\right)^2 + \left(\frac{P_m - P_{i,j,k}}{F_P}\right)^2 + \left(\frac{dd_m - dd_{i,j,k}}{F_{dd}}\right)^2 + \left(\frac{s_m - s_{i,j,k}}{F_s}\right)^2 \qquad (2)$$

Subscript m refers to a single wind measurement; i and j are horizontal dimensions in the analysis and k is the vertical level. The denominators $F_x$ (x=V, T, P, dd, s) are weights defining the relative importance of the different terms in the penalty function.

This step usually results in minor height assignment adjustments, and not major vertical displacements of vectors. This process is described and illustrated in Velden et al. 1997 and Velden et al. 1998. The UW-CIMSS AQC scheme results in the attachment of a quality flag (recursive filter flag, RFF) between 0 and 100 to each vector based on the final fit. Only higher quality vectors with flags equal to or exceeding 50 are passed to the users (this threshold was determined empirically through a multitude of rawinsonde match statistics).

## 4. VALIDATION

The validation of the performance of the two schemes has generally been based on comparisons against collocated rawinsondes or numerical weather prediction (NWP) background fields. Table 2 presents some of the current quarterly statistics derived by the extraction centers for the Coordination Group for Meteorological Satellites (CGMS) against collocated rawinsondes.

Table 2. CGMS statistics for summer 1998 for GOES and Meteosat high-level water vapor winds.

| | RMS vector difference | Speed bias | Mean R/S speed | NRMS |
|---|---|---|---|---|
| Meteosat | 8.5 m/s | -1.6 m/s | 25.3 m/s | 0.336 |
| GOES | 5.6 m/s | -0.9 m/s | 16.9 m/s | 0.331 |

The results in Table 2 indicate some of the problems in comparing winds derived with different satellites, over different areas and with different algorithms. One obvious candidate for measuring the representativeness of the vectors as single point measurements is the RMS vector difference against collocated rawinsondes which for the two satellite-derived wind-sets is quite different. Based on long term statistics Schmetz et al. (1993) found that the RMS has an almost linear relationship to wind speed:

$$RMS = a*speed+ b \tag{3}$$

More accurate analyses (e.g. Velden et al. 1997) show that there is some non-linearity in the relationship, but generally the linear relationship is a good approximation. Therefore, when comparing different collocation statistics it is important to take the speed dependency into account. One possibility is to derive a normalized RMS (NRMS) where the normalization is provided by the mean rawinsonde wind speed:

$$NRMS = RMS/|vel_{R/S}| \tag{4}$$

Results of applying the above equation to the CGMS statistics is shown in Table 2. It can be concluded that the quality of the disseminated winds for the two data-sets in question is about equal, within the accuracy of the NRMS. At EUMETSAT the NRMS is routinely utilized to monitor the quality of the AMV fields.

Figure 2 shows the verification of the EUMETSAT high-level water vapour winds for different mean QI. The indicated error bars are based on neglecting the offset (b) in the linear dependency of (3). The offset has been estimated by performing a linear regression analysis between RMS and mean wind speed using all winds in the collocation period. Also the fit of a linear regression is shown.

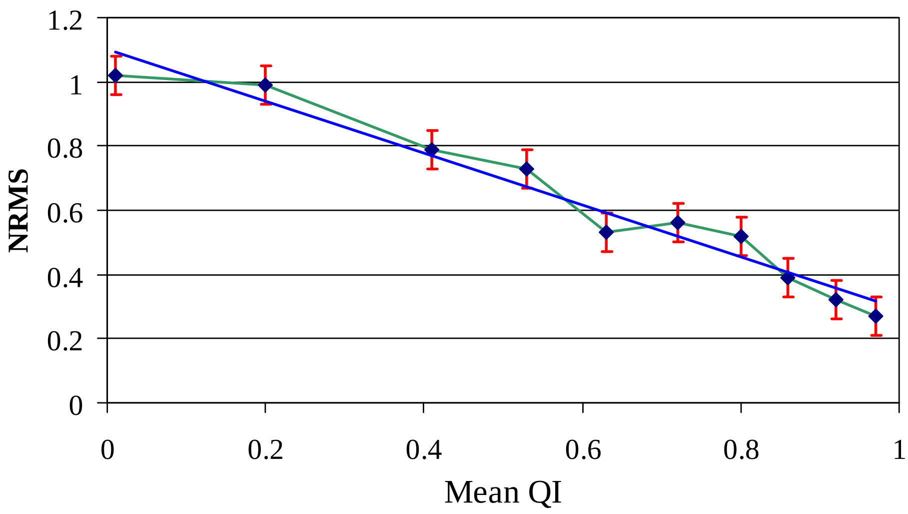

Figure 2. Mean QI vs. NRMS from collocated rawinsondes and high-level water vapour winds derived by EUMETSAT during July-September 1998.

The results presented in Fig. 2 indicate a linear relationship between the NRMS and the mean QI, indicating that the QI is a good estimator of quality, where quality is defined as being in good agreement with the point measurements provided by rawinsondes. Currently, the EUMETSAT QIs are operationally disseminated in BUFR file format together with the AMVs. Only vectors with a QI above 0.3 are disseminated.

Table 3 presents statistics derived in the United states in July 1995 for five different cases (Nieman et al., 1995). In this case a monotonic dependence between the RFF and the NRMS is evident.

Table 3. Rawinsonde collocation statistics for different RFF classes for five cases in July 1995 over the United States.

| | RMS vec diff | Speed bias | R/S speed | NRMS |
|---|---|---|---|---|
| RFF(50-60) | 7.40 | -0.99 | 14.57 | 0.51 |
| RFF(60-70) | 6.32 | -1.16 | 14.74 | 0.43 |
| RFF(70-80) | 5.49 | -1.10 | 15.45 | 0.36 |
| RFF(80-90) | 3.04 | -1.23 | 13.09 | 0.23 |

The EUMETSAT data-sets are routinely monitored at ECMWF. Figure 3 presents monitoring statistics for low level infrared and visible winds and high level WV winds. The statistics for the high level infrared winds are very similar to the high level WV winds, whereas the medium level infrared statistics resemble the low level infrared results and are therefore not presented The figures show that there is generally, to within the accuracy of NRMS, a monotonic agreement between the mean QI and NRMS. The worst results are derived for the low level infrared winds. The problem for the low level IR statistics could be related to large errors in height assignment related to problems converting cloud temperatures to pressure in strong inversions (Rattenborg 1998). These winds are problematic to the AQC scheme due to the fact that they are still good tracers and often occur in fleets over large areas, supporting each other in the AQC. Another possible contributor could be the fact that the QI scheme has been mainly tuned with high level WV vectors, which show generally different characteristic behavior.

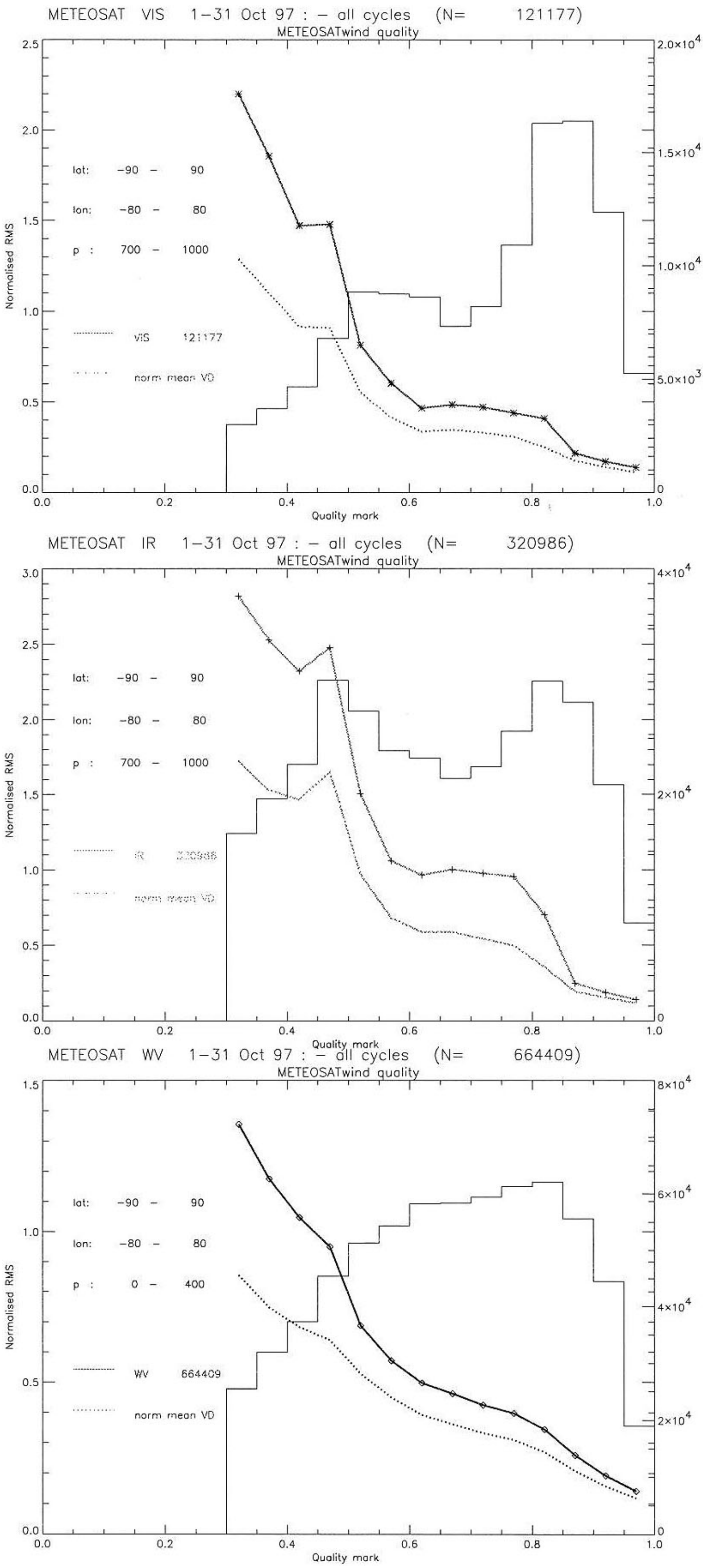

Figure 3. Statistics for low level visible and IR as well as WV winds for October 1997. Solid line normalized RMS dashed line normalized mean vector difference, thin line number of winds per quality bin.

## 5. COMPARISON OF THE EUMETSAT AND UW-CIMSS AQC SCHEMES

In order to identify the strengths and weaknesses of the two AQC schemes, extensive comparisons were performed using data from the NORPEX (NORth Pacific EXperiment; Langland et al. 1999) field experiment. During the NORPEX campaign high density wind fields were derived from GOES and GMS images over the North Pacific region using the UW-CIMSS winds algorithm. The derived vector fields were subjected to both the AE and QI AQC schemes. In order to investigate possible ways to combine the two schemes, the QI was additionally utilized as a pre-filter to the AE by removing winds with an estimated poor quality. Two different QI thresholds were used, 0.3 and 0.6. Some of the quality-controlled fields were visually compared and analyzed and all data-sets were disseminated to ECMWF for model forecast impact studies. Some results from the impact studies are presented in Rohn (1998, this issue).

Figure 4 presents an upper-level wind field for which vectors accepted by the AE only are presented in blue and the winds accepted by the QI scheme only are presented in red. Winds accepted by both schemes are in green. Only winds faster than 10 m/s are presented. Figure 5 presents the vector field derived from visible imagery with the same color coding. The main features of the flow (most coherent and consistent flow) are depicted by the vectors accepted by both schemes. In the jet stream area in Fig. 4, the QI scheme keeps more winds, even those that show large accelerations in the vector components. The AE keeps more winds in the slow and also higher curvature regions e.g. in the anti-cyclic region in Fig. 5.

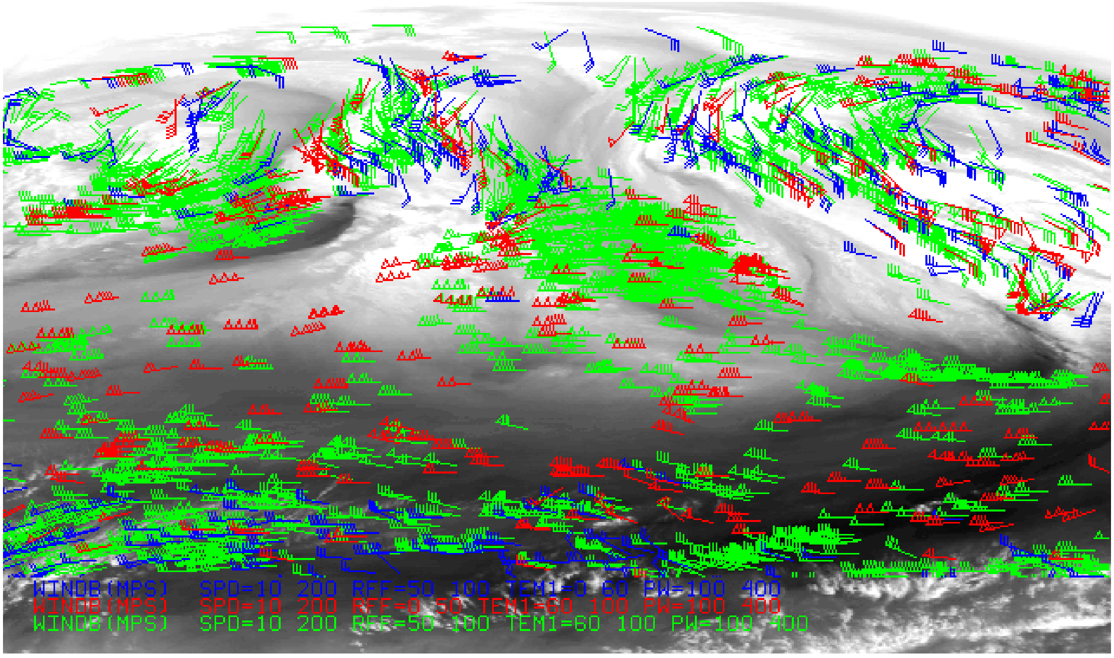

Figure 4. GOES water vapour winds for 3 February 1998 at 2330 GMT overlaid on the corresponding water vapour image. Green vectors are vectors accepted by both the AE editor and the QI scheme, the blue vectors are accepted by the AE scheme only and the red vectors are vectors accepted by the QI scheme only. The QI acceptance threshold in this case is 0.6.

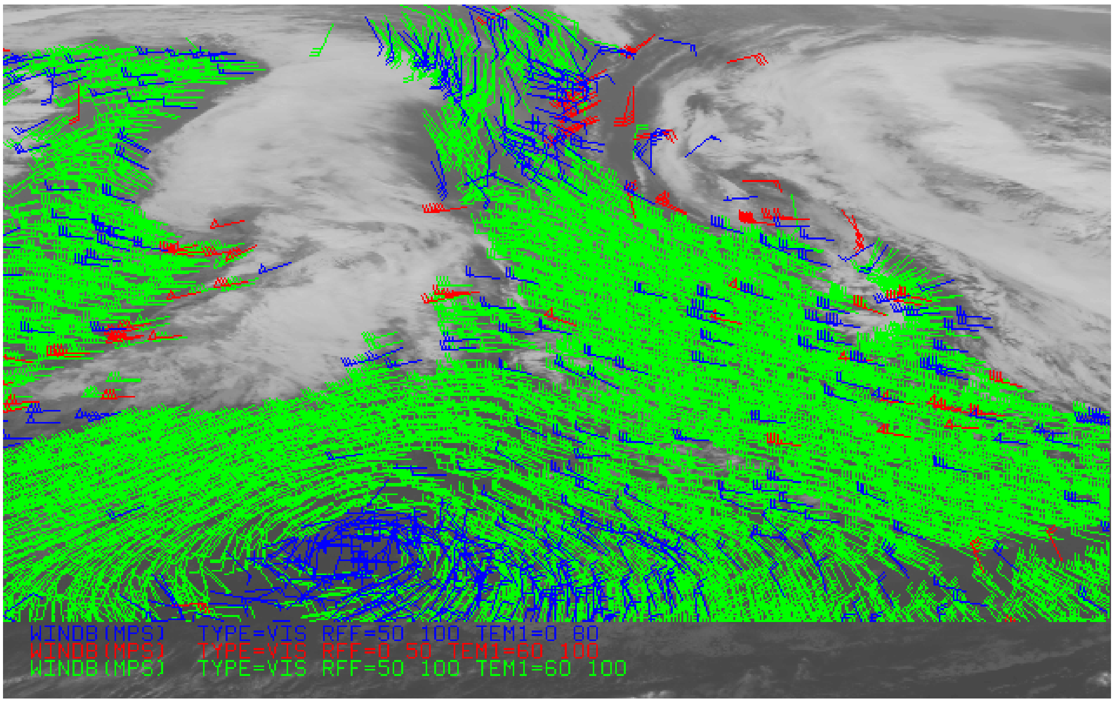

Figure 5. GOES low-level visible winds for 3 February 1998 at 2330 GMT overlaid on the corresponding visible image. Green vectors are winds accepted by both the AE editor and the QI scheme, the blue vectors are accepted by the AE scheme only and the red vectors are vectors accepted by the QI scheme only. The QI acceptance threshold in this case is 0.6.

Table 4 presents the NRMS as derived against the background field (model forecast) for winds at three levels and three channels and divided into four categories for one case during the NORPEX experiment. The main conclusion from Table 4 seems to be that the vectors which both schemes find to be good are indeed of high quality (as compared to the background field) and when both schemes rate the quality as poor, the NRMS is higher. The interesting groups are where the two schemes disagree. The statistics tend to suggest that the QI scheme is capable of keeping more good winds than the AE scheme. However, the winds accepted by the AE and rejected by the QI scheme seem better than those rejected by both schemes. This generally indicates that both schemes tend to have some skill in identifying good winds. It should also be noted that for low level IR winds the AE performs better than the QI scheme, which could be a result of the scheme being tuned mainly for Meteosat water vapour winds.

Table 4. NRMS for AMVs at different levels (High=H (above 400 hPa), Medium=M (400 – 700 hPa) and Low=L (below 700 hPa), for three channels (IR, WV and VIS) and for different combinations of RFF and QI.

| | **RFF > 50 QI > 0.60** | **RFF < 50 QI > 0.60** | **RFF > 50 QI < 0.60** | **RFF < 50 QI < 0.60** |
|---|---|---|---|---|
| **IR,H** | 0.39 | 0.47 | 0.70 | 0.78 |
| **WV,H** | 0.39 | 0.41 | 0.69 | 0.66 |
| **IR,M** | 0.26 | 0.56 | 0.57 | 1.12 |
| **WV,M** | 0.24 | 0.43 | 0.47 | 0.82 |
| **IR,L** | 0.35 | 1.48 | 0.51 | 1.45 |
| **VIS** | 0.32 | 0.37 | 0.72 | 0.93 |

The impact studies performed by ECMWF (Rohn, 1998) also tend to indicate that the combined approach identifies the best winds. The optimal combination is however still to be defined. One possibility is to use the QI as a pre-filter to the AE in a similar fashion to the NORPEX study, with an additional constraint of disabling the accelerator checks performed in the AE. Another possibility would to incorporate the QI indicators as weights in the AE recursive filter analysis. Finally, a third alternative would be to use the AE to provide quality information to the QI via a normalized test. All of these options will be explored in future research.

## 6. CONCLUSIONS

The current operational automatic quality control schemes as applied at NOAA/NESDIS (UW-CIMSS scheme) and EUMETSAT have been briefly summarized. Even though the two schemes differ in their respective approaches, they generally classify the quality of vectors in a similar fashion. Both schemes seem to have advantages and disadvantages. The UW-CIMSS scheme is capable of providing more coherent wind fields and adjusting for some height assignment problems. The EUMETSAT scheme is capable of retaining more winds in the fast flow regimes and lends itself more easily for analysis and interpretation due to its straight forward formulation. The best vectors are generally those accepted by both schemes, whereas winds rejected by the two schemes simultaneously seem to have a low reliability as single level point measurements. In the case of disagreement between the two schemes, the EUMETSAT QI-scheme is capable of identifying and retaining some good high-level water vapour and low-level visible winds, whereas the AE editor retains a better low-level IR vector field.

Future work will concentrate in optimizing a combined approach. Several possibilities are still to be explored, but the use of the QI as a precursor to the AE or the alternative approach of using the AE scheme to provide height reliability information, in conjunction with the penalty function, to the QI scheme seem to be the most promising.

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