DEVELOPMENTS IN OPERATIONAL SATELLITE WINDS FROM METEOSAT

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Summary: The displacements of clouds and water vapour features in successive satellite images reflects the atmospheric circulation at various scales. The main application of the satellite derived motion vectors, is their use as winds in the data analysis for numerical weather prediction. In particular at low latitudes they constitute an indispensible data source for numerical weather prediction. This paper summarizes the operational method of deriving cloud motion winds (CMW) from the IR images (infrared: 10.5 - 12.5 μm) of the European geostationary METEOSAT satellites. A long term comparison with radiosondes provides estimate RMS errors of about 3 m/s at low level (>700 hPa and mean wind speeds of 10 m/s) and about 5 m/s at higher altitudes (<400 hPa and a mean wind speed of 24 m/s).

The CMWs have been complemented recently by the production of wind vectors from the Meteosat water vapour channel (WV: 5.7 - 7.1 μm). The disseminated winds are, at present, restricted to high level features (<400 hPa) chiefly representing clouds. The estimated RMS error of WV winds is about 6 m/s. Ongoing work shows the potential of the visible channel especially for the derivation of low altitude wind fields.

1. INTRODUCTION

Global observations of atmospheric wind fields are potentially the most important data in the analysis for numerical weather prediction (NWP) (e.g. Baker, 1991; Kalnay et al., 1985). Direct wind observations are indispensible at low latitudes where winds cannot be inferred from the mass field. Wind observations from satellites also constitute the sole source of wind data over wide regions of the Southern hemisphere.

The global network of geostationary satellites provides the basis for the derivation of cloud motion winds (CMW) from successive and carefully aligned satellite images. It is important to realize that CMWs are not a direct measurement of the wind field and, therefore, may possess properties that compromise their use as single level observations of the wind field. Firstly, clouds are are not always passive tracers. Secondly, the location of cloud occurrence may be in areas that are not representative for the wind field. Cloud motion may also represent a layer-mean flow rather than a wind vector at a specific level. In spite of those reservations, winds from satellite observed motions are for the time being used as a single level vector in NWP. Consequently the improvements principally tried to enhance the usefulness of CMWs as single level wind data. The advent of variational analysis techniques may enable a different use of the data, i.e the use of directional information only or the use of satellite winds as volume averages rather than single level vectors.

This paper provides a description of the operational method for extracting CMWs from METEOSAT images at the European Space Operations Centre (ESOC). The description is essentially a shortened version of the detailed algorithm description by Schmetz et al. (1993). The paper is amended by a documentation of more recent algorithm improvements. Section 4 describes the operational water vapour wind algorithm and section 5 the experimental wind extraction from the visible channel.

2. CLOUD MOTION WINDS

The geostationary METEOSAT satellites observe the Earth with an imaging radiometer in three channels: in the solar spectrum (VIS) between 0.4 and 1.1 μm , in the infrared window region (IR) between 10.5 and 12.5 μm, and in the water vapour (WV) absorption band between 5.7 and 7.1 μm . Images are taken at half hourly intervals and the spatial sampling at the subsatellite point corresponds to 2.5 km x 2.5 km for the VIS, and 5 km x 5 km in the IR and WV channels. The operational derivation of CMWs uses IR images for the cloud tracking; the WV channel is used in a bi-spectral algorithm for the height attribution of wind vectors from semi-transparent clouds (see Schmetz et al., 1993). CMWs are derived four times per day from a triplet of successive IR images. The processing is confined to the 55 ° arc around the sub-satellite point, since image distortion becomes too large toward the horizon. Basically the generation of a CMW from a sequence of registered satellite images requires two steps: in our algorithm a pressure altitude is first assigned to a cloud tracer, then a displacement vector is computed that estimates the wind speed.

In the following we briefly describe the individual steps of the present algorithm for deriving CMWs from METEOSAT IR images.

2.1 Tracer selection and image filtering

The first step in the processing is a multispectral image analysis (Tomassini, 1981), that extracts the dominating scenes in an image segment corresponding to an area of 32x 32 IR pixels or about 160 km x 160 km at the sub-satellite point. The scenes can be sea, various types of land, and clouds at different altitudes. For the CMW algorithm no more than 3 cloud levels per target area or segment and only one surface scene are allowed, otherwise the number is reduced by merging scenes in close proximity.

Typically about 1900 - 2300 out of about 3500 possible segments per image are found with cloud tracers and only those segments are considered for the automatic cloud tracking.

In a second step an image enhancement is performed for areas with more than one identified scene. This enhancement increases the contrast between the coldest cloud, which is being tracked, and the scenes below that cloud (Hoffman, 1990).

2.2 Height assignment

The height assignment of opaque clouds is based on the IR cloud brightness temperature. ECMWF forecast temperature profiles are used as ancillary data. The pressure level of a CMW is determined as the level where the brightness temperature fits the forecast temperature; that is, a vector is assigned to the cloud top altitude. Although this procedure generally yields satisfactory results, it can be improved as it is known that, for instance, low level cumulus clouds rather travel with the wind speed at cloud base.

Large errors in the height assignment occur for semi-transparent or sub-pixel clouds, since the satellite observed IR radiance contains contributions from below the cloud; a CMW then would be assigned to too low a level. Corrections for the semi-transparency are possible with multichannel observations. Smith and Platt (1979) developed a radiance ratioing method (also referred to as 'CO_2 slicing') that has been successfully applied to the height attribution of CMWs from the U.S. GOES satellite (Menzel et al., 1983; Merrill et al., 1991). Further applications have been presented by Smith and Frey (1990).

With METEOSAT imagery it is possible to use a conceptually similar technique based on simultaneous IR and WV images (Cayla and Tomassini, 1978; Szejwach, 1982; Pollinger and Wendling, 1984; Bowen and Saunders, 1984). The method operationally in use for the height attribution of METEOSAT wind vectors is referred to as 'semi-transparency correction' and it is described in Schmetz et al. (1993).

2.3 Cloud tracking

The automatic cloud tracking employs cross-correlation and three successive IR images are used to determine a displacement vector. A segment of 32x32 IR pixels of an image at the time *h* forms the target area that is correlated at times $h + 30$ min and $h - 30$ min with areas equivalent to the size of a segment. The search area consists of 3x3 segments which yields 65x65 possible displacements to be correlated. For the different positions n, m of the target window within the search area, the standard pattern correlation coefficient is calculated. In order to save computer run-time the search starts at the cloud displacement suggested by a wind forecast, yet the pattern correlation extends over a region large enough so that the dependence on the forecast is minimized. The final displacement velocity is computed as the mean norm of the vector pair and the direction is computed from the vector sum.

The CMWs are produced four times per day and the range of the forecast used for deriving the wind varies between 12 hours and 30 hours. It is noted that the use of forecasts for periods beyond 6 hours is less than optimal, especially in the tropical region.

2.4 Quality control

The use of three images enables a symmetry check of the two corresponding vectors which efficiently rejects inconsistent tracking of features. Even after the symmetry check there is still a considerable number of poor cloud motion winds produced by the automatic scheme. Most often errors can be traced to difficulties in allocating the appropriate altitude to a tracer. Furthermore, clouds may be correctly tracked and assigned to the right altitude but their motion is not representative of the air flow at the assigned altitude. An example for the latter are stationary wave clouds. Obviously such situations are not captured by the symmetry check. Therefore an extended quality control is required that goes beyond the symmetry check of the two corresponding displacements vectors.

At present the extended quality control is done in two steps. Firstly, the cloud motion winds are subject to an automatic quality control and secondly, CMWs are manually checked by an experienced meteorologist. The automatic quality control consists of a rough check against the ECMWF forecast winds. CMWs are assigned a 'poor quality flag' when the norm of the vector difference between CMW and forecast wind exceeds 55% of the norm of the forecast vector. In order to limit the rejections at low forecast wind speeds, CMWs are not flagged when the speed difference between forecast and vector difference is less than 5 m/s.

The final step before dissemination is a manual quality control where CMWs are displayed and scrutinized by an experienced meteorologist. The meteorologist has the possibility to delete any CMW and to reinstate CMWs previously flagged by the automatic quality control. It turns out that, in particular in the tropical regions, reinstatement of CMWs occurs due to incorrect forecast fields. This suggests that in future developments one should only use short-term forecasts (up to 12 h at maximum) in tropical regions or discount the forecasts.

2.5 Monitoring the quality of CMWs

The quality of CMWs is monitored routinely by comparisons with collocated radiosondes where the collocation area extends over 2°x2° and is within a time interval of one hour. Poleward of 20 ° the longitude interval of a collocation box is increased to 3 °. The comparison is conducted on a daily basis with the sonde data received through the Global Telecommunication System. Monthly mean statistics are routinely computed. Two quantities are directly derived from a comparison with radiosondes (RS). The average speed difference is defined as:

$$BIAS = < |\vec{v}_{CMW}| > - < |\vec{v}_{RS}| > \qquad [1]$$

where < . > denotes a monthly mean and | . | is the norm of a wind vector. The second quantity considered for quality monitoring is the monthly mean of RMS vector difference:

$$\sigma_{CMW,RS} = < [(\Delta u)^2 + (\Delta v)^2] >^{1/2} \qquad [2]$$

where:

$$(\Delta u)^2 = \sum_{i=1}^{N} (u_i^{CMW} - u_i^{RS})^2 \qquad [3]$$

$$(\Delta v)^2 = \sum_{i=1}^{N}(v_i^{CMW} - v_i^{RS})^2 \qquad [4]$$

N is the number of collocations in a month, u and v are the zonal and meridional wind components of a wind vector.

Assuming that a radiosonde provides an unbiased measure of wind velocity, Equation 1 defines the mean velocity bias inherent in CMWs. $\sigma_{CMW,RS}$ in Equation 2 is only a relative measure of the CMW error, because it comprises the error of the radiosonde measurement and the differences due to separation in both time and space. The representativeness error due to the different nature of both wind measurements, i.e. CMWs rather being a volume average, will be considered as part of the CMW error.

Following the work of Morgan (1985) and Kitchen (1989) one can estimate the RMS error σ_{CMW} of CMWs from:

$$\sigma_{CMW}^2 = \sigma_{CMW,RS}^2 - \sigma_t^2 - \sigma_d^2 \qquad [5]$$

where $\sigma_{CMW,RS}$ is the RMS vector difference between radiosonde and CMW, σ_t and σ_d are the vector differences associated with the separation in both horizontal space and time, respectively. While $\sigma_{CMW,RS}$ is available to us through our comparisons with radiosondes, the two quantities σ_d and σ_t need to be estimated (Schmetz et al., 1993). The values adopted for σ_d and σ_t vary for different levels from 4 - 7 m/s and 2 - 4 m/s, respectively.

3. IMPROVEMENTS TO THE CMW ALGORITHM

The infrared CMW derivation has been improved since 1987 continuously. Table 1 summarizes the algorithm changes. An assessment of the impact of those changes requires some processing of the monthly mean speed bias and RMS vector difference between CMWs and radiosondes, since both the speed bias and the RMS vector difference increase with wind speed (Woick, 1990). Therefore a normalization has been computed in the following way: Linear regression is calculated for the speed bias and the RMS vector difference versus the monthly mean radiosonde speed for the time periods between changes.

Adopting the regression method and taking a monthly mean radiosonde speed of 24 m/s as reference the decrease of the speed bias and RMS vector difference can be computed from the regression lines (e.g. Schmetz et al. (1993) Figs. 4 and 5). The results are plotted in Figure 1 for the high level winds. The time periods refer to the intervals between algorithm changes as given in Table 1, where the third column indicates the time period. We note that the bias at the reference wind speed decreased from 4 m/s to about 0.8 m/s over the period from 1987 until fall 1993. Simultaneously the RMS vector difference decreased from about 10.9 m/s to less than 8 m/s.

With Equation 5 we can also estimate the actual error of the high level CMWs; the result is that the vector error of high level METEOSAT CMWs decreased from about 7.8 m/s before

August 1987 to about 5 m/s. The slight deterioration for the time period '8' is presumably due to problems with image rectification during a few months of the period.

Figure 1 also provides performance figures for the operational water vapour which are discussed in section 4.

An analogous analysis has been conducted for medium and low level CMWs. Results are presented in Figures 2 and 3, respectively. Medium level winds were most significantly improved by the initial radiance slicing and the advanced image filtering using the spatial coherence method. This points at the particular sensitivity of medium level cloud winds to tracer selection and enhancement. The error of medium level CMWs was reduced from about 6.0 m/s to 3.5 m/s at a reference wind speed of 15 m/s.

Interestingly low level CMWs experienced a noticable improvement only through the initial radiance slicing whereas the three following changes to the algorithm did not produce any further improvement. The radiance slicing had a positive impact on low level CMWs because the tracking of unsliced images had the potential of tracking some upper level cloud remnants while using the low level cloud radiance for the height allocation. The error improved from 4.1 m/s to less than 3 m/s at a reference wind speed of 10 m/s.

4. WINDS FROM THE WATER VAPOUR CHANNEL

An automatic water vapour wind extraction scheme has been developed (Laurent, 1990) and implemented into the operational software suite at ESOC (Laurent, 1993). The most important initial results were as follows:

i) the tracking of moist/cloudy features in the water vapour channel provides a much better spatial coverage with high level vectors than the IR channel because of the better sensitivity of the WV channel to high altitude cloud and moisture.

ii) the quality of cloud tracking in the water vapour channel is at least as good as the IR tracking if the same tracer is tracked.

iii) the quality of winds from clear-sky water vapour features is inferior to the winds from cloud tracers presumably due to the fact that those winds represent a mean displacement of a layer as deep as 300 - 400 hPa. Therefore the representativeness error is large; i.e. it is extremely difficult to find a unique strategy for the assigning the vector to a single altitude.

Based on these results it has been concluded that the operationally disseminated water vapour winds are confined to areas where cloudy tracers exist at altitudes higher than 400 hPa. In the present operational algorithm the height assignment is exactly the same as for IR winds (Holmlund, 1993). Because of the large number of vectors it is possible to perform a spatial consistency check which very efficiently rejects poor wind vectors (Holmlund, 1993).

A statistical analysis of water vapour winds for the period January 1993 through October 1993 analogous to the procedure described in section 3 for the IR winds, brought about a mean RMS error of about 6 m/s and a speed bias (satellite minus radiosonde) of 0.4 m/s at a reference radiosonde wind speed of 24 m/s. The results are nearly on a par with the IR winds and we envisage that future high level cloud tracking will be mainly done with WV imagery.

High Level Cloud Motion Winds

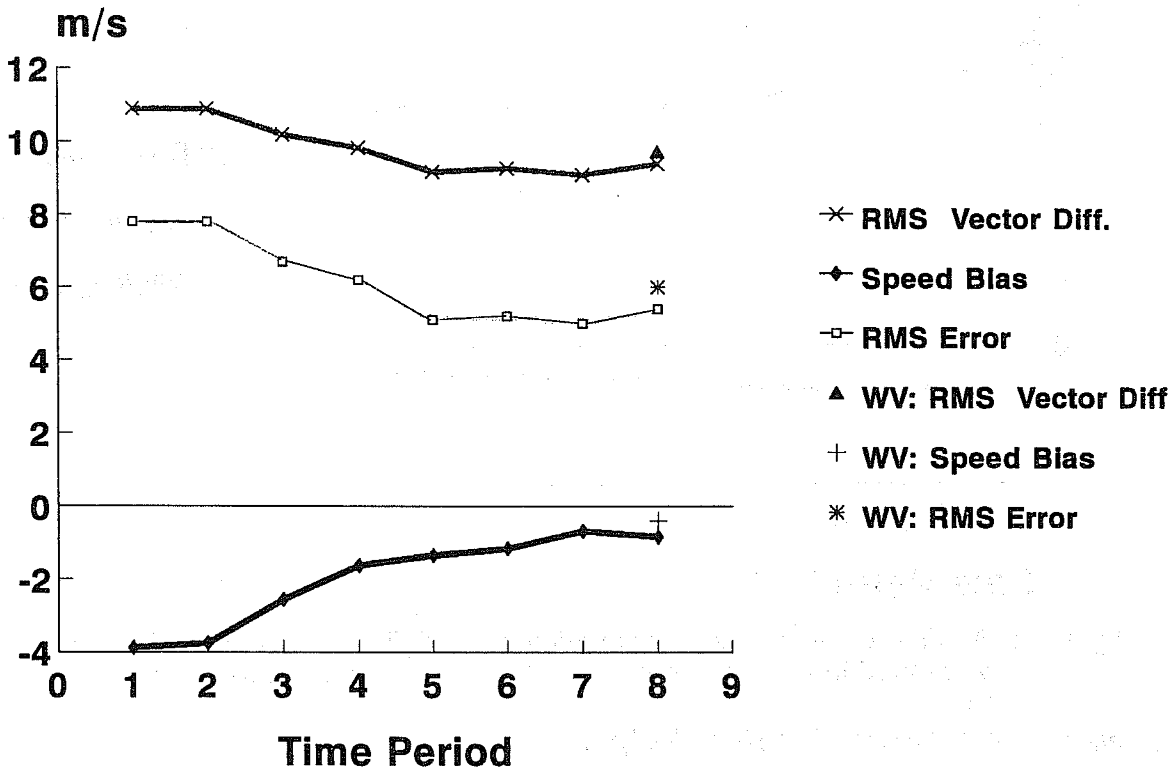

Figure 1: Comparison between collocated radiosonde winds and cloud motion winds. Vector difference, the speed bias and the estimated RMS error of high-level (< 400 hPa) CMWs are shown for November 1984 until October 1993. Time periods are defined by the changes to the CMW algorithm as given in Table 1; for instance, time period 1 corresponds to November 1984 through February 1987. The RMS error has been estimated from Equation 5. The values refer to a mean radiosonde wind speed of 24 m/s.

Medium Level Cloud Motion Winds

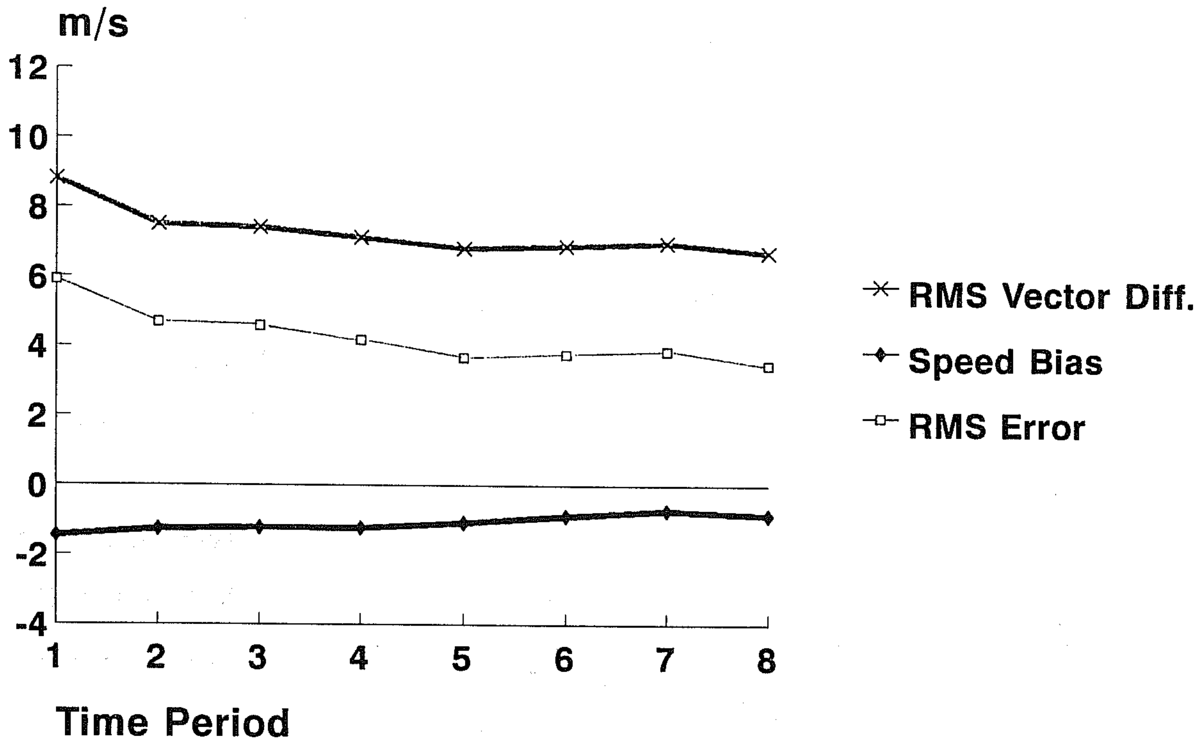

Figure 2: As Figure 1 except for medium-level cloud (700 < p < 400 hPa). The values plotted in the figure correspond to a mean radiosonde wind speed of 15 m/s.

Low Level Cloud Motion Winds

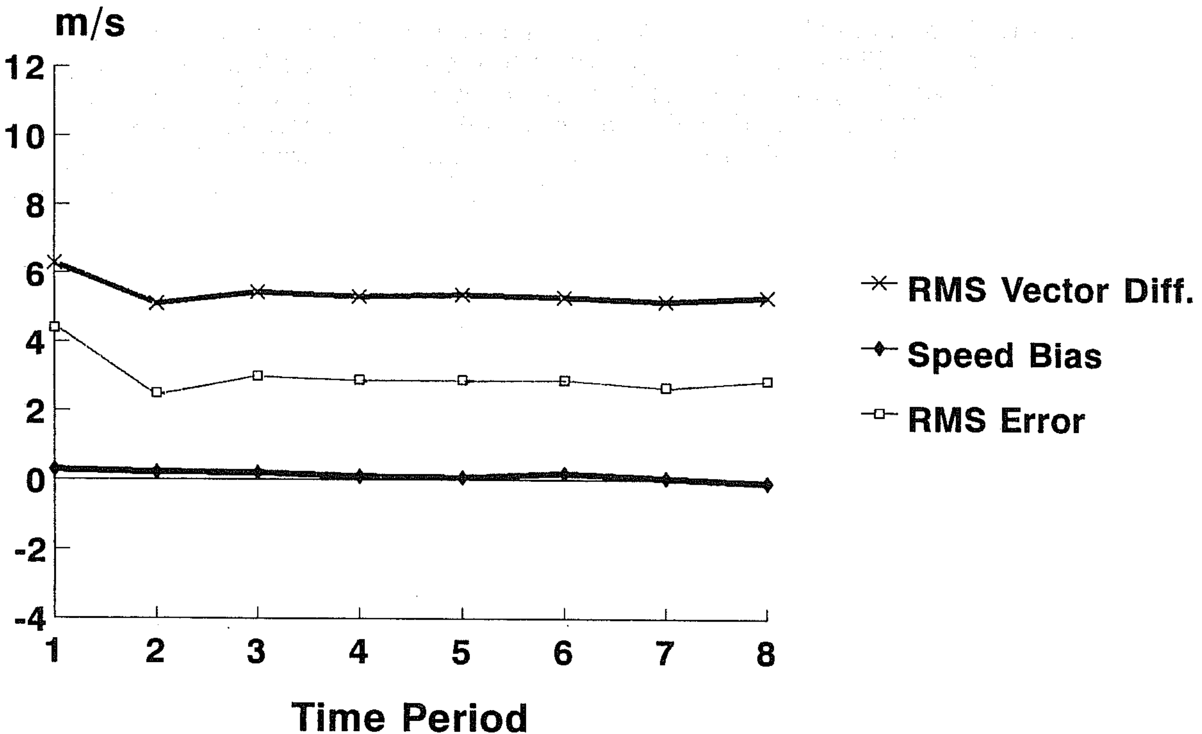

Figure 3: As Figure 1 except for low-level cloud (> 700 hPa). The values plotted in the figure correspond to a mean radiosonde wind speed of 10 m/s.

5. WINDS FROM THE VISIBLE CHANNEL

Experimental work on the derivation of winds from visible imagery is being conducted at ESOC (Ottenbacher, 1993). The wind vectors show a good potential in resolving smaller scale features since the spatial resolution is better than in the IR and WV channel. A better IFOV of the satellite measurements is necessary in order to obtain satellite winds with higher spatial density, since a sufficiently large number of pixels (minimum about 16x16) is required for a smooth tracking. Therefore a tracking with the visible channel is advantageous, however the high assignment has to rely on infrared methods.

The wind vectors from the visible channel show particular promise for the low level wind fields over the marine stratocumulus regions. Current research concentrates on developing a visible tracking scheme for low level cloud since that also diminishes the problem of a correct height assignment. An important perspective of the visible winds would be the supply of low-level wind information over the subtropical North Atlantic which could help the early analysis of tropical storm formation (Reed et al., 1986).

6. CONCLUSION

This paper has brielfy summarized the advances of the operational CMW retrieval from METEOSAT IR images at ESOC. Between August 1987 and fall 1993 the speed bias of high level CMWs (< 400 hPa) versus radiosondes within a 2 ° by 2 ° collocation box has been diminished from about 4 m/s to 0.8 m/s for a mean radiosonde speed of 24 m/s. At the same time the vector error decreased from 7.8 m/s to about 5 m/s. Improvements for the medium level CMW vector error were from 6.0 m/s to 3.5 m/s at a wind speed of 15 m/s. Low level CMW errors decreased from 4.1 m/s to less than 3 m/s at a reference speed of 10 m/s.

The improvements have been achieved through different changes to the CMW algorithm. Changes improved screening the highest cloud level for the tracking which in turn improved the height allocation of the cloud tracer. The use of a forecast for the tracking by automatic cross-correlation reduced the slow speed bias of CMWs, since the previous tracking invariably stopped at the first local correlation maximum obtained in a strategy search that started at zero-displacement. A new calibration of the METEOSAT 6.3 μm channel also improved the height assignment of displacement vectors through the altitude correction for semi-transparent and broken clouds at high altitudes.

More recent work (see Table 1), which not been described in Schmetz at al. (1993), improved the cloud classification algorithm, which provides information on suitable tracers, and also improved automatic quality control.

Current research work at ESOC also addresses the definition of quality flags for individual cloud motion vectors and better quality control (Holmlund, 1992). The use of quality flags would enhance the information content of the product for NWP analyses as lower error characteristics could be given to the high quality CMWs, thus increasing their impact in the analyses.

MONTH OF CHANGE	DESCRIPTION OF CHANGE	
November 1984	Revision of quality control	1
March 1987	Extraction of high level winds based on windowed IR radiances (reduced influence of lower level radiation on tracking)	2
September 1987	Water vapour calibration method based on radiative transfer model and radiosondes (affected height assignment of cirrus)	3
March 1989	Use ECMWF forecast to initialize the search algorithm (cross- correlation) for the cloud displacement	4
March 1990	Image filtering technique to better enhance the highest cloud tracer in a target area	5
February 1991	Automatic quality control employing wind gradient information in the forecast (winds are flagged and can be reinstated by manual quality control)	6
November 1991	The image histogram analysis preceding the cloud wind derivation uses 7 bit visible data (this improved cloud classification)	7
December 1992	Image filtering has been modified such that the background has a lower weight. The filtering uses the cold cloud radiance after semi-transparency correction rather than the original radiance.	8

Table 1: Changes to the Operational IR Cloud Motion Wind Algorithm for METEOSAT

Satellite winds derived from the water vapour channel are available on the GTS (Global Telecommunications System) to all interested users, since the beginning of November 1993. A comparison with radiosondes yields an estimated error of this new source of wind data of about 6 m/s. While this is slightly inferior to the infrared cloud winds it appears that there is less of a bias problem for the water vapour winds. Note that for the time being the disseminated water vapour winds are confined to cloudy tracers at altitudes above 400 hPa.

Research work on wind derivation from the visible channel complements the operational IR and WV wind products. Eventually winds derived from all channels should be combined to form a single satellite wind product. We do not think this would unduly mix information from different sources, since the height assignment of the IR, WV and visible winds already relies on more than one channel for the height assignment. The obvious advantage of a single wind product is that more data are available for checking data quality with respect to their consistency.

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