CLOUD MOTION WIND ESTIMATES IN EUROPE

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Summary: A review is presented of the status of the derivation of winds from the displacement of clouds in a sequence of satellite images in Europe. A brief summary of the work at research institutions demonstrates the amount of climatological information which can be gathered from cloud motion winds (CMW).

The operational European system for extracting CMWs from Meteosat IR images is in use at the European Space Operations Centre (ESOC) for more than a decade. The wind extraction works fully automatic and is followed by a manual quality control. At present about 3000 vectors (SATOB) per day are produced with four production runs. The system and recent changes are described. Based on our recent work on CMWs and the improvements made, we conclude that future work should divert from improving the CMW extraction as such. It seems better to concentrate on identifying the fraction of CMWs with gross errors (mostly underestimating the wind speed) and avoid their appearance in the analysis for numerical weather prediction.

1. INTRODUCTION

Global observation of the atmospheric winds is an important goal for atmospheric and oceanic climatological studies and for operational meteorology. This is especially true at low latitudes where the wind field cannot be inferred from the mass field and upper air soundings from the conventional network are scarce.

The global network of geostationary satellites provides the basis for the operational generation of cloud motion winds (hereafter CMW) from successive and carefully aligned satellite images. Basically the extraction of CMWs is very simple: images are taken at intervals of 30 minutes (or less) and the displacement is measured between successive images. Thermal infrared brightness temperatures of the clouds are used to assign the displacement vector to a certain level, whereby the knowledge of a temperature profile is a prerequisite.

In spite of the apparent simplicity of the method there are a number of difficulties, which prevent an unbiased estimate of the wind field, at least in certain cases. Nevertheless, CMWs play an established role in the analysis of the global wind fields at all centres for numerical weather prediction (NWP) , although the specific use of CMWs does vary amongst the centres. In particular there is a tendency to exclude CMWs from the analysis for NWP at higher latitudes of the relatively data rich Northern hemisphere. The major reason for discarding CMWs is that they tend to systematically underestimate high wind speeds in jet stream areas, which has a detrimental effect on analysis and forecast.

Fig. 1 illustrates the speed bias problem statistically: the monthly speed difference between high level CMWs (< 400 hPa) operationally derived from Meteosat and collocated radiosondes is plotted since January 1985. A collocation box is defined by 2 x 2 deg ; outside the 25 deg belt the longitudinal extent is 3 deg. Those comparisons are made routinely at ESOC for control. It is notable from Fig. 1 that the bias for the period 1985 through August 1987 was in the range of -2.7 m/s to -5.2 m/s. Since September 1987 the range is between -1.8 m/s and -3.5 m/s; an improvement which mainly was due to a better height assignment of semitransparent clouds because of a better calibration of the water vapour channel. In that context it is important to realize that the bias is not a consistent feature pertinent to all high level CMWs but rather due to a smaller fraction of extreme outliers.

In the following we first present a brief review of European research work on CMWs. Section 3 contains some general remarks about CMWs; section 4 describes the operational method to extract CMWs from Meteosat IR (10.5 - 12.5 μm) images as it used at ESOC. We describe recent changes and improvements to the operational tracking algorithm and the height attribution. Based on this development we come to the conclusion that future work on CMWs should concentrate on the task of identifying and deleting rogue winds.

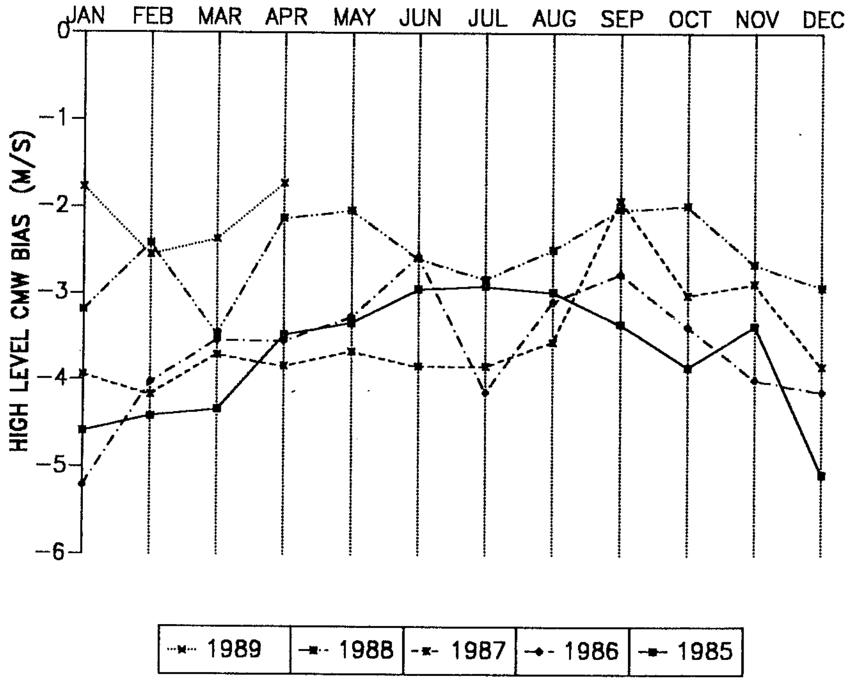

Figure 1. **Difference between monthly mean wind speed** from cloud motion winds and collocated radiosonde winds for pressure levels < 400 hPa and the period January 1985 through April 1989. {Solid: 1985; dash-dot: 1986; dashed: 1987; dash-double-dot: 1988; dotted: 1989}

2. SUMMARY OF EUROPEAN RESEARCH WORK ON CLOUD MOTION WINDS

The extraction of cloud motion winds (CMW) from satellite image data started with the advent of the first American geostationary satellite (ATS). Automatic methods for operational application were devised in the early seventies (e.g. Leese et al., 1971). In Europe research work on the derivation of winds from satellite images has been confined to limited number of institutions. Only one operational system was established at the European Space Operations Centre (ESOC) which provides CMWs on routine basis to users via the Global Telecommunication System (GTS). In the following we provide a brief summary of European work on CMWs. No claim is made that the review is complete.

Substantial research has been conducted at the Laboratoire de Meteorogie Dynamique near Paris since the mid-seventies. For instance, Cadet and Desbois (1980) exploited Meteosat images over the western Indian ocean to observe the onset of the Indian summer monsoon. Their observations of cloud motion winds revealed an abrupt change in the low-level airflow within two days, whereby the cross-equatorial flow establishes itself within two days. The change is impressively illustrated by the dense population with vectors consistent in direction and speed; such a clear delineation of the large scale flow would be difficult to obtain from conventional data.

In a study on the west African monsoon Desbois et al. (1984) used visible Meteosat images for the cloud tracking and a single IR image for the height discrimination. Their careful study with an optical correlator could differentiate between northward moving small cumuli at about 0.5 km and the southward travel of stratocumuli at an altitude of about 2 km. The study was validated with in-situ aircraft observations. It is interesting that a comparison with CMWs from ESOC revealed that the operational ESOC CMWs only captured the northerly flow at about 2 km. This preference of observing the highest cloud level in the operational ESOC scheme is still present and will be discussed below.

Zick et al. (1980) analysed high level wind fields from satellite IR images during the development of a cyclone; in particular they point out that the cloud structures and their change contains a wealth of additional information which helps improve the analysis. Zank (1980) has studied the relationship between the CMW from low clouds and surface winds at low latitudes. She has found that in the trade wind regions CMWs can be used to infer both the direction and speed of the surface wind. A similar conclusion has been drawn by Wylie and Hinton (1981) in a study aimed at producing a surface stress analysis. The result may be an incentive to consider low level CMWs in conjunction with surface winds from microwave instrumentation aboard satellites.

Morgan (1985) conducted an interesting study on the accuracy of operationally produced CMWs adopting the user point of view, i.e. he discusses the CMW product rather than the causes of errors. He has shown that for high level winds (< 400 hPa) the radiosonde-radiosonde comparison is more strongly affected by the separation distance than a CMW-sonde comparison. That is indicative of the fact that CMWs rather represent an average flow over larger areas. The corresponding RMS values of the vector difference at zero separation is about 5 m/s for the sonde-sonde comparison and more than 11 m/s for the CMW-sonde comparison. The value of 5 m/s for the sonde-sonde comparison should be kept in mind since it puts the CMW-sonde comparisons in a reference perspective.

Fea (1980) reports on the quality of early results from Meteosat-1 produced at ESOC. An extensive validation campaign of Meteosat-1 winds was conducted with data from April, Julyand November/December 1978 by several European Weather Services (ESA/MOAG). For instance, the UK Met Service indicates mean vector differences between radiosondes and CMWs of 5.2, 8.8, and 16.5 m/s in the case of low, medium and high clouds, respectively. (Present values are rather of the order of 5.0 m/s, 7.8 m/s and 10.5 m/s, respectively.) Various groups noted the low bias in high level CMWs (see also Bizzarri and Sorani, 1980).

Other investigators used successive WV images (around 6.3 μm) from the polar orbiting Nimbus 5 (Kaestner et al., 1980) and the geostationary Meteosat (Eigenwillig and Fischer ,1982) to estimate mid-tropospheric winds. The methods were based on manual tracer selection and tracking; for a limited sample of comparisons with radiosondes a reasonable agreement was found. Desbois et al. (1988) used the sampled ISCCP images of the Meteosat water vapour channel to study the climatology of mid-troposheric flow in July for three consecutive years (1983 - 1985). Their study shows significant differences in the tropical high level circulation (near 300 hPa) between the record drought month of July 1983 and the other two months. Recently Eriksson (1988) applied a novel differential method to WV images.

3. SOME GENERAL REMARKS ON THE NATURE OF CLOUD MOTION WINDS

A wind measurement with a radiosonde can be considered as a random sampling of the air flow so that a sufficiently large number of radiosondes could determine the true mean wind. CMWs could give an unbiased estimate only if clouds were conservative tracers randomly distributed within and floating with the airflow. Obviously, this postulation is hardly fulfilled:

all clouds do not move with the wind while others follow the wind at a level lower than cloud top; evident examples are wave clouds in the lee of mountains or convective cloud systems, respectively;

in jet stream areas the major part of clouds is found below the level of maximum wind speed and there are seldom clouds above that level (e.g. England and Ulbricht, 1980). The jet core itself is also mostly cloud-free. The vertical and horizontal wind shear can be in the order of 10 m/s per 1 km and 5 m/s per 100 km, respectively. Consequently errors in the horizontal and vertical allocation of a CMW are likely to introduce considerable errors in the wind speed estimated from cloud displacment. It is also clear from the above that a speed error is most likely an underestimation.

The vertical height attribution of jet stream clouds is especially difficult due to their semitransparency to radiation from the atmosphere beneath the cloud. In an operational scheme - like the one at ESOC - the geographical allocation of a CMW is done on standard grid, the size of which is of the order of 200 km, which is escpecially crude in the case of strong horizontal wind shear.

Considering the above arguments it is fair to say that a CMW is not a byword for a wind measurement. However, this is of little concern to the user - all they want is realiable wind measurements. In particular users in the NWP community do not want to see the low biased CMWs which slow down the jet stream. It is somewhat unfortunate that research studies were mostly set to demonstrate the compatibility of CMWs and radiosonde winds: however, this is only a part of the story, even though the lion share of operationally produced CMWs are of acceptable quality for the NWP, it is important to realize that there exist situations when a CMW fails to represent the true wind. Whether those gross errors are system dependant or an inherent problem of the physics, is of no importance to the user.

In the following sections we present a review of the operational derivation of CMWs from Meteosat IR images at ESOC. We start with a brief history and then go about the present status of the retrieval scheme and how it evolved over the last years. The description goes along with a critical review of the performance of the scheme, the improvements made over the last couple of years and an outlook on future developments. In particular we intend to set out a future perspective which concentrates less on improving the 'tracking techniques' and the height assignment (though there is scope for improvement) but rather emphasizes the need for better methods of quality control.

4. OPERATIONAL PRODUCTION OF CMWs AT ESOC

The operational production of CMWs from Meteosat IR images started in the late seventies, where the fully routine operation started in November 1978 after a sequence of development and test sequences (Morgan, 1979). A major feature of the processing scheme was that it right from the beginning derived all CMWs in an automatic manner (Bowen et al., 1979; Morgan, 1979); man-machine interaction was confined to the editing for quality control. The manual editing is still the last step of the processing before dissemination to the user.

In 1984/85 the manual quality control was amended by an automatic one in which CMWs are compared with forecast winds from ECMWF; winds exceeding certain error measures are edited with a flag during the automatic quality control which leaves the possibility to reinstate winds deleted due to an erroneus forecast. In 1985 we started work on improving the automatic tracking of clouds; a radiance slicing method was introduced in the operational system in February 1987 (Schmetz and Nuret, 1987). The height assignment of semitransparent clouds was positively affected by a new vicarious calibration of the water vapour channel, which became operational in September 1987 (Schmetz et al., 1988; Schmetz, 1989). Recently (March 1989) the tracking algorithm has been modified so that it uses a wind forecast as 'first guess' in the correlation search (Nuret and Schmetz, 1988; Nuret, 1989).

4.1 Image Data

The geostationary Meteosat satellites observe the Earth with an imaging radiometer in three channels:

- in the solar spectrum (called VIS) between 0.4 and 1.1 μm
- in the infrared window region (IR) between 10.5 and 12.5 μm
- in the water vapour (WV) absorption band between 5.7 and 7.1 μm

Images are routinely taken at half-hourly intervals and the spatial resolution is 2.5x2.5 km^2 for the VIS, and 5x5 km^2 in the IR and WV channels.

Meteosat IR images form the database for the automatic tracking of clouds with a cross-correlation. Images are subdivided into segments of 32x32 IR pixels, corresponding to about 160 km x 160 km at the subsatellite point at 0° longitude.

A segment is the target area or template window which is moved within a search area of 3x3 segments from the previous or subsequent image to find the best correlation. Routine processing is confined to the 55 ° circle arc around the subsatellite point.

4.2 Tracer Selection

Before an attempt is made to determine a CMW within a given segment it is necessary to know whether a suitable tracer is present in the segment. This information is available from a multi-spectral histogram analysis using all image channels available (Tomassini, 1981). Typically more than 2000 segments out of 3456 possible segments contain potential tracers. At present the image analysis does not provide information on the quality of a tracer. The use of quality flags from the image analysis will be considered in the near future.

After all quality controls typically about 750 winds (SATOBs) are disseminated to the user. Four wind production runs are conducted per day. Fig. 2 shows an example of disseminated CMWs for the three altitude intervals: high ($<$ 400 hPa), medium ($700 < p < 400$ hPa) and low ($>$ 700 hPa).

4.3 Automatic Tracking

Three successive IR images are used to determine a wind vector by cross- correlation (for details see Schmetz and Nuret, 1987), which provides for the possibility to derive two complementary vectors. They are obtained from correlations of the centre image with the following image (30 minutes later) and the previous image. The two vectors are used for a symmetry check. No CMWs are produced with speeds less than 5m/s.

With the present computing power we cannot compute the full correlation surface; the maximum in a correlation surface is obtained via a search strategy. Since correlation surfaces are usually multipeaked, there is a chance to find the wrong local maximum. In the original design of the processing the search always started at the centre and stopped at the first peak found, which may introduce a low bias. In February 1987 we introduced a radiance slicing method for the high level cloud: an additional cross-correlation is performed using only the radiance information pertaining to high cloud. This alleviates the problem of determining apparent motions due to the superposition of high and lower level clouds drifting with different velocities. The radiance windowing brought about a slight decrease of the speed bias of high level CMWs, although it required several thousands of CMW-radiosonde collocations to prove the significance of the reduction of less than 0.5 m/s (Schmetz and Nuret, 1987).

Based on discussions with the user community the next change envisaged was the use of a forecast as a starting point for the search algorithm for high level CMWs. A new software version including this feature became operational on 7 March 1989; now, for high level winds, the search for a peak starts at the location in the correlation surface suggested by the forecast wind. Then the full correlation is computed for an area of 37 x 37 pixels around the peak suggested by the forecast; this area is large enough so that there is virtually no dependance on the forecast.

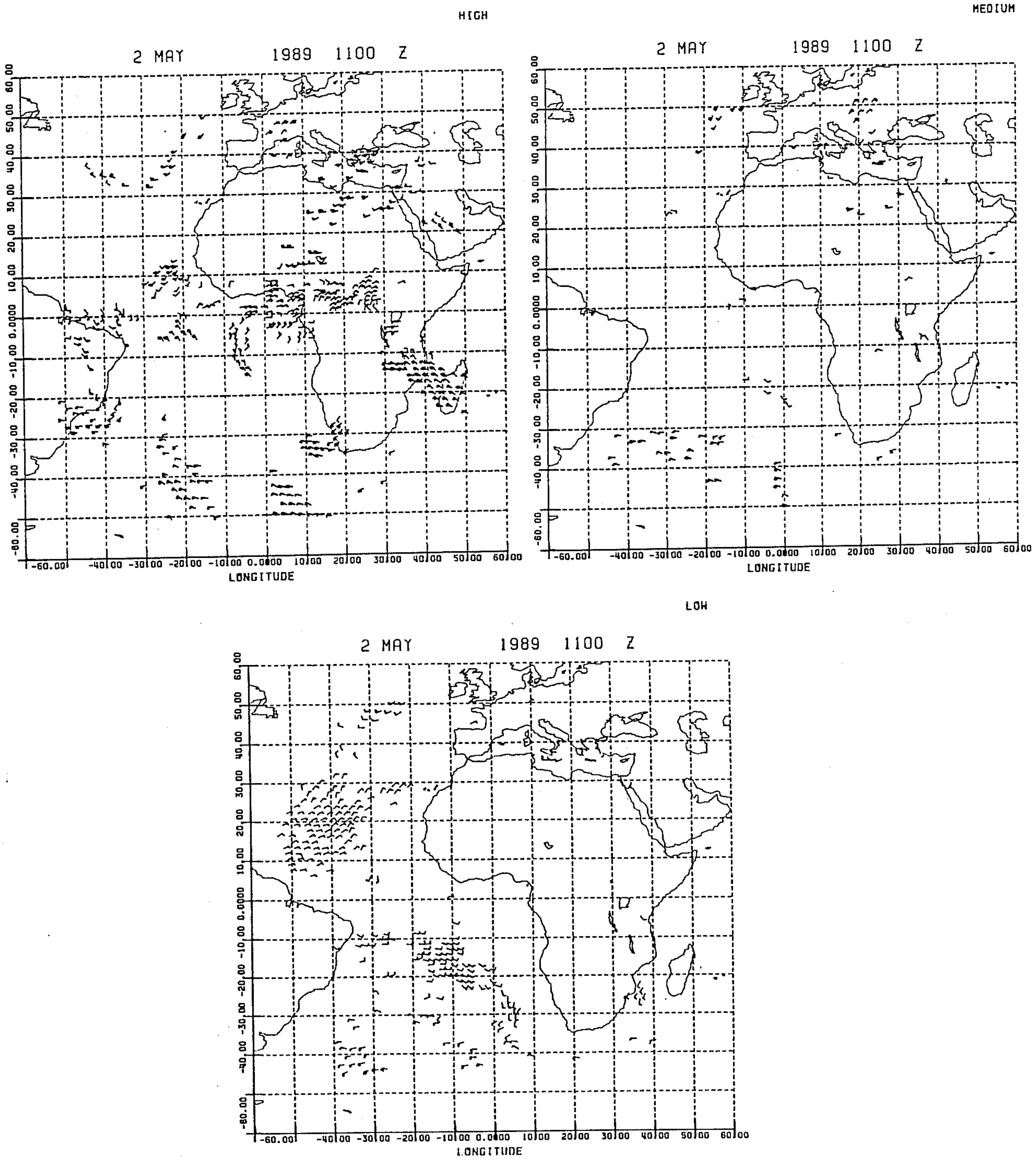

Figure 2. Disseminated CMWs produced at ESOC from Meteosat-3 IR images for 1100 UT on 2 May 1989. Typically 750 CMWs are produced four times per day.

A detailed analysis (Nuret, 1989) of the new approach revealed a small positive impact using the forecast as quality measure; however, doubt is cast on the significance of the result, since we hardly find an improvement when using radiosondes as quality check. Therefore, we conclude that the use of a forecast in the peak-search did not improve the quality of high level CMWs. A very positive impact is the 10% higher yield with the same quality (see Fig. 3).

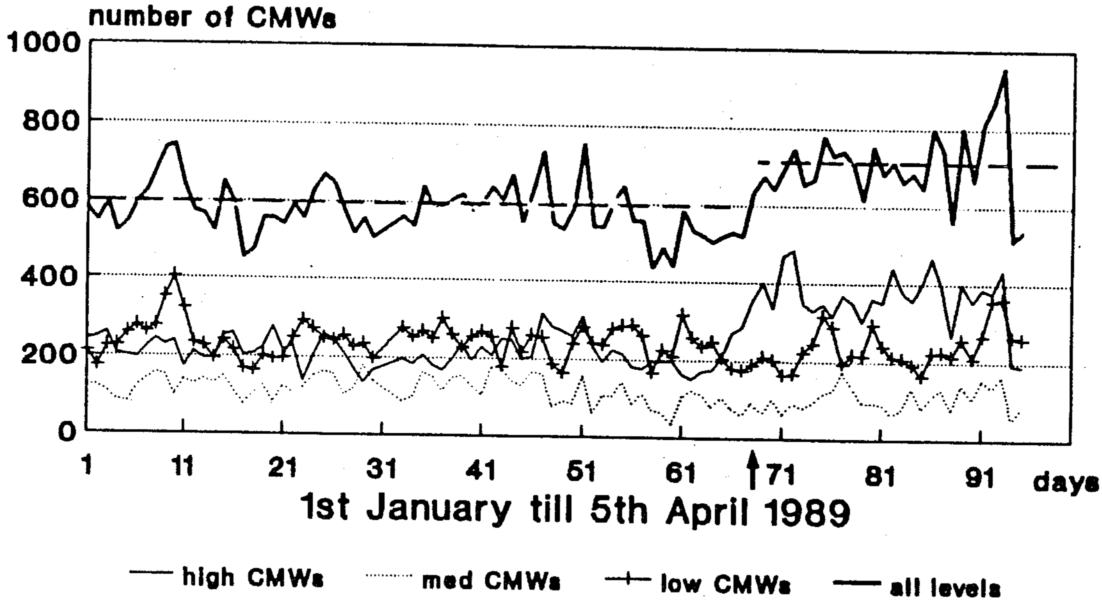

Figure 3. Number of CMWs disseminated for the wind run at 1100 UT (time of centre image) for 1 January through 5 April 1989. The arrow indicates the day when the use of a forecast for the peak-search became operational.

Fig. 3 also demonstrates that the operational system prefers to extract high level winds. This tendency was always present, since high clouds give a better contrast in IR images. With the recent change the preference is even more forced because the presence of a high cloud in a segment area rules out the generation of a CMW at lower levels. This will be overcome to some extent with the technique developped by Hoffman (1988) which enables the additional extraction of CMWs at lower levels even though clouds are partially obscured.

4.4 Height Assignment

The IR brightness temperature is used for the height assignment of clouds; the conversion into a pressure level uses a forecast temperature profile from the ECMWF. All clouds undergo a test for semitransparency in the multispectral image analysis. The test essentially checks whether a semitransparency correction (Szejwach, 1982) yields a sensible result (for details see MEP, 1987).

The semitransparency correction is a critical procedure in the process of CMW generation. Fig. 4 intends to illustrate the issues: results from radiative transfer calculation are shown for the Metesat-4 IR and WV channel, which demonstrates the impact of a thin cirrus cloud on the radiance received at the satellite in the two channels. The curves show the cumulative contribution function, defined as the radiance fraction which reaches the satellite without being absorbed between the corresponding level and the satellite (The contribution function simply is the derivative). Calculations were done for a clear tropical atmosphere (solid line), a moist layer between 8 and 10 km (dash-double dot), a cirrus with the IR optical depth of 0.8 (dotted), and a cirrus with an optical depth of 3.2.

Fig. 4 shows that the cloud layer affects the radiance in different way in the two channels, a fact, which is exploited in the semitransparency correction. The effective brightness temperature varies considerably with the optical depth.

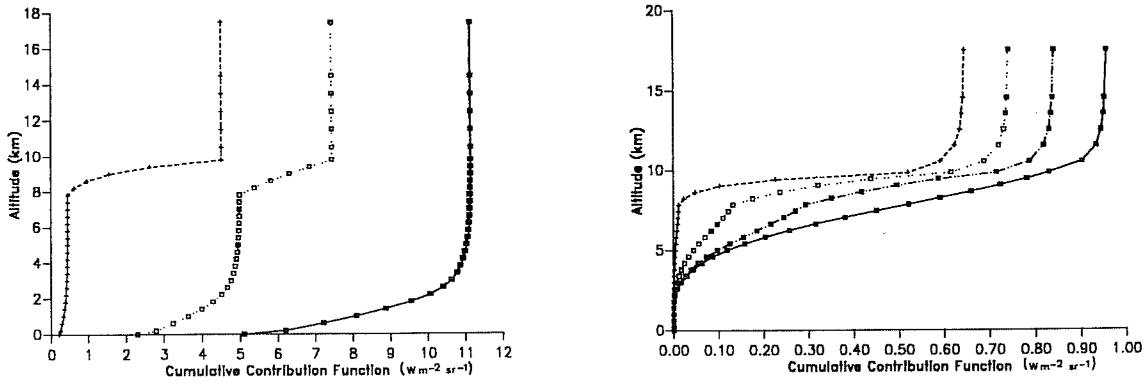

Figure 4. **Impact of a cloud layer on the radiance received by Meteosat** in the IR (left) and WV channel (right). The cumulative contribution function depicts that fraction of radiation which reaches the satellite without being absorbed between the corresponding level and the satellite. The atmosphere is characteristic of the tropics and the satellite zenith angle $\theta_{sat} = 0°$.

The curves show: clear atmosphere (solid),moist layer between 8 and 10 km (dash-double dot), cirrus with $\delta_{IR} = 0.8$ (dotted), and cirrus with $\delta_{IR} = 3.2$ (dashed). The corresponding brightness temperatures at the satellite level are:

IR (left): 294.7 K, 294.7 K, 269.4 K, and 243.9 K.

WV (left): 246.9 K, 243.5 K, 240.3 K, and 236.9 K.

Cloud top temperature is 237 K.

The operational semitransparency correction requires a simultaneous use of satellite measured IR and WV counts and results from a radiative transfer model. Both data sets are linked with a calibration which establishes a functional relationship between the satellite measured digital counts and the physical unit radiance. The calibration of thermal infrared channels must be monitored continuously as significant changes in radiometer response may occur due to aging, contamination or heating cycles. Absolute in-flight calibration in the thermal infrared would be possible with a blackbody source put in front of the radiometer's primary optics. Aboard geostationary satellites the large size of the main telescope prevents such a direct calibration. Therefore vicarious methods must be sought.

Until August 1987 the operational WV calibration of METEOSAT was not rigorous and consisted simply of finding a calibration slope by minimising the bias between the UTH product (Upper Tropospheric Humidity, see MEP, 1987) and a pseudo-UTH derived from radiosonde profiles. The radiosonde humidities were computed without considering the proper contribution function describing the actual radiative properties of the atmospheric column. Therefore, that 'calibration' was prone to systematic errors, although a reasonable humidity retrieval was guaranteed. Since September 1987 the calibration procedure has been altered to a physical vicarious method employing a radiative transfer model (Schmetz, 1989).

Figure 5 shows the impact the new water vapour calibration on the quality of high level cloud motion winds. The speed bias relative to radiosonde winds, which is the outstanding problem with high level CMWs, is shown for periods before (September 1986 to August 1987) and after the introduction of the vicarious WV channel calibration. Monthly mean biases are plotted as a function of radiosonde wind speed. The more recent period shows a markedly lower speed bias than observed prior to the new calibration. The reason for the improvement is that the higher calibration coefficient obtained with the new method has led to a lower height attribution of CMWs from semitransparent clouds which obviously agrees better with the in-situ radiosonde measurements. The strong impact is understood considering that semitransparent clouds are found in about 50% of all segment areas processed to derive cloud motion winds.

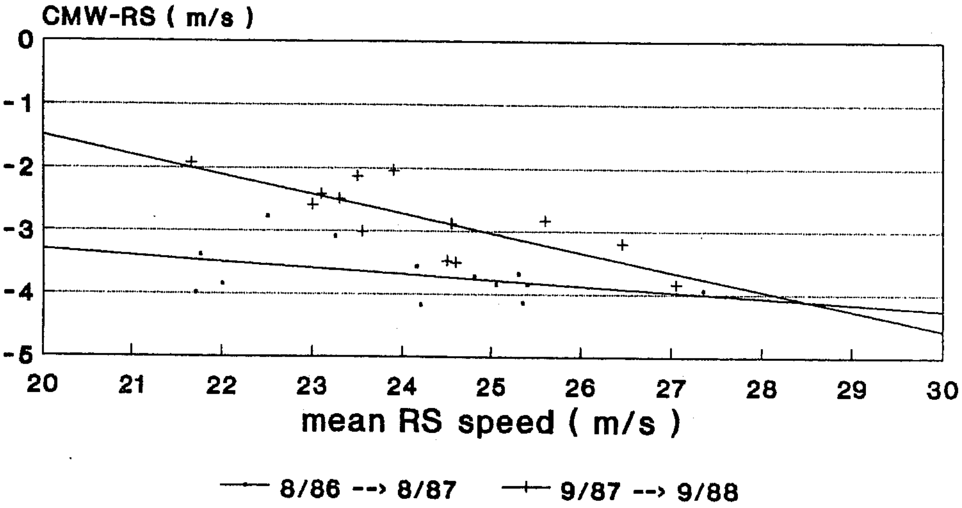

Figure 5. **Difference between monthly mean wind speed** from cloud motion winds and collocated radiosonde winds for pressure levels < 400 hPa. Crosses pertain to the period after the introduction of the new WV calibration while dots correspond to result prior to the calibration change.

4.5 Quality Control

All CMWs having passed internal quality controls (like the symmetry check) undergo an automatic quality control where they are checked against a forecast from the ECMWF; the check is fairly loose since it flags only CMWs with vector differences of more than 55% from the forecast.

The last step before dissemination is a manual quality control by an experienced meteorologist who can make further deletions and also reinsert CMWs which were flagged by the automatic quality control.

5. CONCLUSION

Recent development work on the improvement of the cloud tracking has brought improvements, however, it appears that the tracking itself bears only limited scope for improvement. This is also true for the most recent change of the operational software which now uses the forecast wind to start the search algorithm for the displacement of high level clouds. We conclude that the use of the forecast should be left to the automatic quality control.

The height assignment of semitransparent clouds has a larger potential for improvement. In particular, the unconditioned use of the semitransparency correction in the present ESOC scheme should be reconsidered; i.e. too tenuous clouds should not at all be considered as tracers. For some clouds it may also be better to simply use the WV brightness temperature for height assignment.

Further improvements include the extension of the present IR tracking to the WV and visible channels of Meteosat. The major gain expected from this is a better coverage with data; in specific instances this can of great importance to the user, for example, Reed et al. (1986) point out that a higher yield of low level CMWs could improve the analysis of the early development of tropical easterly wave disturbances. The generation of more than one CMW in a given area seems also in reach with the method presently developed at ESOC by Hoffman (1988).

The main suggestions for future work are:

- improve the capability of identifying situations where CMWs with gross errors are likely too occur.
- since the most serious error of CMWs is the vastly low bias in strong wind zones, a simple approach would be not to produce winds in jet areas. This could be achieved by a tougher automatic and a more selective manual quality control.
- a better way is to develop a method for identifying rogue winds. The method should consider the radiative properties of clouds and make use of pattern recognition and texture analysis. Apart from the definition of useful parameters for delineating poor CMWs, that neccessitates an extensive training period during which the usefulness of parameters is established. Considerable help and feedback from the user community will be required in order to identify the poor CMWs and establish their relationship to cloud characteristics.

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