Low-Level Winds from High-Resolution Visible Imagery

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Abstract

Low level wind fields over the Atlantic have been derived from clouds in METEOSAT high resolution visible images experimentally with one production cycle per day over a period of more than one year. The cloud motion winds from VIS imagery (VIS-CMW) use a template size of 32 x 32 VIS pixels, corresponding to about 80 km x 80 km at the subsatellite point which is four times better than for the corresponding IR (infrared window) winds (160 km x 160 km). The better spatial resolution of VIS images and better contrast between cloud and ocean surface leads to an increase in wind vectors by a factor of six. The spatially dense vector fields lead to a much better description of the low level atmospheric flow by the VIS-CMW as compared to IR winds. The height allocation of the low level cloud winds has been ameliorated through an attempt to assign vectors to cloud base. This improved significantly the error of the wind vectors which is explained by the characteristics of the atmospheric boundary layer in the trade wind regions where most of the wind vectors are found.

1. Introduction

Wind fields derived from tracking cloud motions in successive satellite images infrared (IR: 10.5 - 12.5 μm) have been produced routinely since the early seventies from US geostationary satellites (Hubert and Whitney, 1971). They have become the most important product derived from geostationary meteorological satellites and they are an important data source for numerical weather prediction (NWP) (e.g. Thoss, 1992; Kelly, 1992).

This study focuses on the high-resolution aspect of VIS images from METEOSAT. Low-level clouds are tracked in successive high resolution VIS images (2.5 km x 2.5 km) over all ocean areas within the METEOSAT field of view. Since this is being done in a quasi-operational mode the standard time interval of 30 minutes between successive images is retained.

The paper proceeds as follows: Section 2 gives an account of the derivation of low-level winds from high-resolution METEOSAT images. The subsection on tracer selection also points out the advantages of shorter imaging intervals. The subsection on height assignment includes a discussion on the atmospheric boundary layer in the trades where most of the low-level winds are found. Section 3 presents the results.

2. Cloud Motion Winds from VIS Images

a. Image data

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 (lR) between 10.5 and 12.5 μm, and in the water vapor (WV) absorption band between 5.7 and 7.1 μm. Images are taken at half-hourly intervals and the spatial sampling at the sub-satellite 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. In this study the derivation of CMWs uses VIS images for the cloud tracking. The IR channel is used for the height attribution of wind vectors.

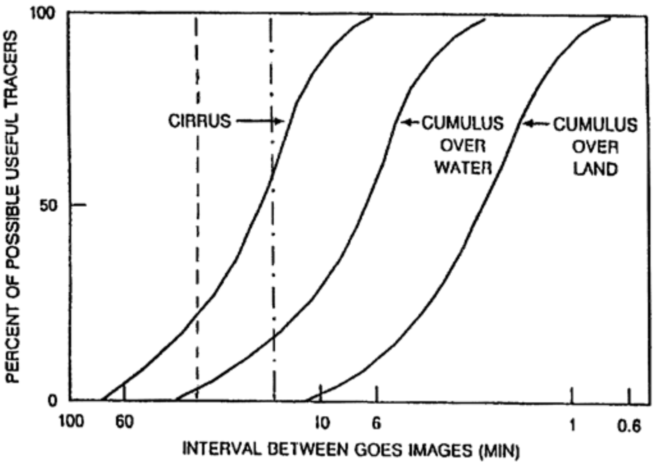

Figure 1:
Optimum time interval between successive images for computing winds from cloud motions (after Shenk, 1991). The vertical lines indicate the 30 and 15 minutes that are being used for METEOSAT and will be used for METEOSAT Second Generation (MSG).

b. Tracer selection

The first step in the production of VIS CMWs is a multispectral image analysis (Tomassini, 1981, Schmetz et al., 1993) which extracts the dominating features or clusters (sea, land or clouds at different levels) in an image segment corresponding to an area of 32 x 32 IR pixels. An area is selected for the cloud tracking if the segment, firstly, is over sea and secondly, low level clouds with tops at altitudes below 700 hPa have been identified. Furthermore the segment should not contain any medium or high level clouds. The restriction to ocean areas, that is mainly to marine stratus and stratocumulus, has been introduced since the yield of low level cloud motion vectors over the continents is very small due to scarcity of good tracers. This seems to be due to a lack of contrast over land which hampers tracking accuracy. More important is a general lack of long-lived low level cloud tracers over land. Figure 1 (after Shenk, 1991) provides an estimate of the percentage of clouds which are trackable in an image with a given temporal resolution. The three curves are for different cloud types and refer to the spatial resolution of the GOES VAS instrument which was about 7 km in the IR window. It is evident that a 30-minutes interval is far from being the optimum, since not all low clouds over water are trackable and low clouds over land are virtually impossible to track. This general conclusion by Shenk (1991) is corroborated by the following researchers:

- Hamada (1983) suggests imaging intervals of 15 minutes to better cope with the short life-time and deformation of target clouds
- Uchida et al. (1991) obtain low-level winds of higher spatial density and closer to the typhoon center when using 7.5 and 15 minutes as imaging intervals
- Rodgers et al. (1979) show that high-spatial resolution and short imaging intervals (7.5 minutes) increase the number of low-level winds around a hurricane
- Johnson and Suchman (1980) recommend to use imaging intervals of 6 - 10 minutes for low-level cloud tracking

c. Wind vectors

The derivation of the displacement vector from successive VIS images is very similar to the operational tracking using the IR channel (Schmetz et al. 1993). A fully automated cross-correlation technique is applied to the high-resolution VIS images. As for the IR tracking a target area of 32 x 32 VIS pixels is moved in a search area of 96 x 96 VIS pixels in order to find the best match between successive images. Three successive images are used which provides pairs of vectors. The automatic tracking for the generation of displacement vectors is applied to the four sub-segments of the 32 x 32 IR pixel segment corresponding to areas of 32 x 32 VIS pixels. Typically about 600 - 800 out of 1863 IR segments located over oceans contain possible tracers.

d. Height assignment

The height allocation of a wind vector derived from tracking features in VIS images is based on the IR channel. A brightness temperature observed for the low-level cloud is interpolated into a short-term temperature forecast profile from the European Centre for Medium Range Weather Forecasts (ECMWF). The observed brightness temperature is also corrected for the water vapour continuum absorption above cloud top. This effect is typically an increase in temperature of the order of 1 - 2 K which corresponds to a lowering of heights of up to 40 hPa.

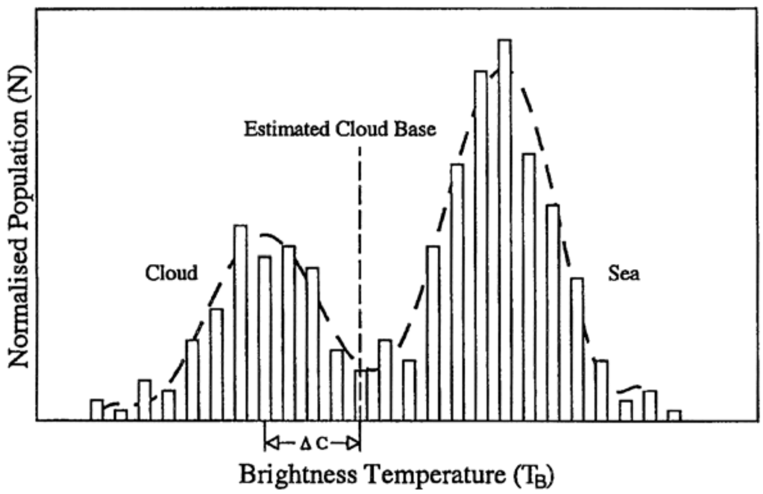

Figure 2:
Schematic diagram showing the histograms of brightness temperatures from a low level cloud and clear ocean. The estimated cloud base is indicated (for details see text).

The brightness temperatures for assigning the height of a cloud tracer are taken from the multispectral analysis which provide, for the sea segments under consideration, mean values for clear ocean and low cloud as well as standard deviations for the clusters identified in the histogram. Figure 2 schematically shows the histogram of a cloud and a sea cluster. Taking the mean value of the cloud cluster for the height assignment would assign the displacement vector to a mean cloud top. Although this is commonly done for medium and high level CMWs, Hasler et al. (1979) demonstrated that the approach is inappropriate for low level clouds. They found in a comparison of accurate aircraft winds with low level satellite tracked wind over the trade wind and subtropical high regions, that the cumuli type marine clouds rather travel with the wind at cloud base.

Since cloud base temperature cannot directly be measured from space a judicious estimation technique needs to be developed. Following the idea of Le Marshall et al. (1994) we infer cloud base T_{Base} from the histogram (Figure 2) according to:

$$T_{Base} = T_{Cld} - \sqrt{2}\ \sigma_{Cld}$$

where T_{Cld} is the cluster mean temperature of the cloud cluster and σ_{Cld} is the standard deviation of the cloud cluster. It is assumed that the histogram can be fitted with two half Gaussians to either side of the cluster. The value $\sqrt{2}\ \sigma_{Cld}$ then is the point taken as cluster boundary, where the probability density function attains the value 1/e. This cluster boundary is assumed as cloud base.

In agreement with Le Marshall et al. (1994) we find that lowering the height assigned to a low level wind vector generally provides a better fit to an analysis. This improvement is not surprising considering that cumulus type clouds travel with the speed at cloud base (Hasler et al., 1979).

It is of some interest to note that the bulk of the wind vectors is from oceanic trade wind regions. There the low-level winds in the atmospheric boundary layer (ABL) are marked by fairly high steadiness S, as defined by:

$$S = \vec{\mathbf{v}} / |\vec{v}|$$

where $\vec{\mathbf{v}}$ is the vector averaged wind and $|\vec{v}|$ the mean wind speed (Augstein, 1978). S was found to be rather constant with height below the inversion; values of S > 0.9 were measured for 14-day averaging period in the entire ABL, while directional variations increase rapidly above the inversion capping the ABL. This clearly illustrates why it is important that the low-level vectors are assigned to a level within the boundary layer.

Another interesting characteristic of the vertical profiles of mean wind speed in the trade wind boundary layers is the existance of a relative wind speed maximum between about 300 and 800 m (Figure 3 from Augstein, 1978). Since this height range is the typical altitude of the lifting condensation level (i.e. cloud base), it could well be a source of the positive speed bias of 0.2 - 0.5 m/s (cloud motion winds minus radiosonde) observed in many validation studies (e.g. Schmetz et al. 1993).

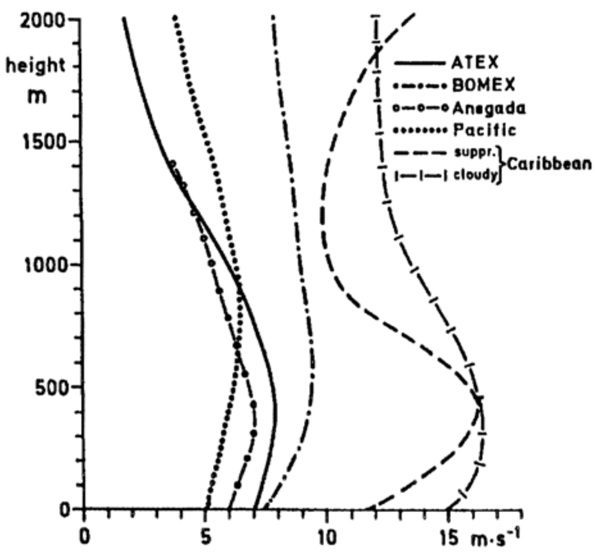

Figure 3:
Vertical profiles of mean wind speed in the atmospheric boundary layer in the trades from different experiments (from Augstein, 1978).

e. Automatic quality control

The VIS CMWs are subject to several internal consistency checks described below and a final rough check against a short-term forecast of the wind field. The quality control is fully automatic and no manual intervention is being performed, in contrast to the operational IR winds.

The first step in the automatic quality control is the symmetry check where a pair of vectors derived from the three successive images is checked for agreement. The internal consistency check considers a vector and its eight neighbours. As a minimum for a useful check there has to be one neighbour fulfilling the following requirements:

- cloud base heights have to be within 20 hPa
- wind directions have to be within 30
- wind speeds have to be within 2 m/s.

CMWs failing to satisfy one of the above criteria as well as isolated vectors with no direct neighbours are rejected.

As an additional filter a rough check against a short-term forecast has been included. The purpose of that check mainly is to reject high speed winds derived from semi-transparent cirrus clouds that were falsely assigned to low levels because the semi-transparency detection and correction failed. The check against the forecast is very rough indeed since CMWs are only rejected if their vector difference against the forecast is larger than 75 % of the forecast vector. More stringent checks would obviously increase the agreement between data and short-term forecast however, at the expense of possibly rejecting good data in areas where the forecast is wrong.

3. Results

Between June 1994 and November 1995 cloud-motion winds from METEOSAT full-resolution visible images (VIS-CMWs) have been derived daily at 1100 UTC at the European Space Operations Centre (ESOC) and disseminated to the European Centre for Medium-Range Weather Forecast (ECMWF) in Reading, UK.

Figure 4:
Wind vectors derived from tracking clouds in high resolution VIS images on 28 September 1995, 1130 UT. A total of 2927 low level vectors has been obtained.

Figure 5:
As Figure 4 except that the wind vectors are derived from IR images. A total of 484 vectors has been obtained.

An example of the VIS-CMW product as obtained with one production cycle is provided in Figure 4. A total of 2927 low-level (≥700 hPa) VIS-CMWs was produced and disseminated to ECMWF for evaluation purposes. The example in Figure 4 shows that the derived VIS-CMWs clearly depict the low-level flow over the marine stratocumulus regions. Smaller scale wind features are also discernable. For comparison Figure 5 shows the corresponding low level wind product from the IR tracking. Only 484 vectors were obtained and disseminated. Although the broad flow is also depicted in by the IR tracking, the higher number of vectors from the VIS tracking demonstrates its superior performance. It is remarkable that the VIS tracking yields about six times more winds than the IR tracking. Since at best four winds can be derived in an area of one IR wind, the factor six can not be explained just by the smaller templates used in the VIS tracking but provides evidence that more clouds have been successfully tracked due to better contrast and resolution.

Since January 1995 two major software changes have been applied to the VIS-CMW retrieval algorithm. On January 2, 1995 the cloud-top based height assignment scheme for low-level VIS-CMWs has been replaced by the cloud-base height assignment (section 2d). It should be noted that the same change was applied to the operational IR winds. A second modification on March 1, 1995, enhanced the automatic quality control for the VIS-CMWs, i.e. the local consistency check was supplemented with a rough check against the ECMWF wind forecast.

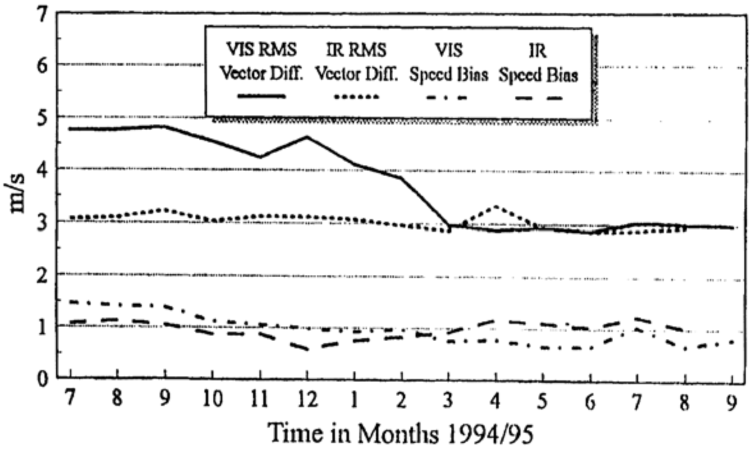

Figure 6:
Monthly mean RMS vector difference and speed bias between ECMWF first guess and satellite wind for both the operational IR winds and the high-resolution VIS winds.

The quality of the VIS-CMWs and the impact of the changes summarized above have been routinely monitored by comparisons with collocated ECMWF 6h forecast winds, because the number of rawindsonde stations in marine regions is too low to produce a reasonable statistic. Figure 6 shows the time series of monthly mean RMS vector difference and speed bias between ECMWF 6h forecast and observation for both the VIS and IR winds. The changes to the VIS winds derivation in January (cloud base height allocation) and March (rough check vs forecast) significantly improved the quality of VIS winds. It is also interesting to mention the reduction in the standard deviation of wind direction from 35.9° to 12.6°. This is consistent with the observation (see section 2d) that the steadiness of winds is much higher within the boundary layer than above the inversion and that clouds travel with the wind at cloud base which usually is within the ABL. It also is important to note that the quality of VIS winds has been improved without significantly altering the number of disseminated VIS winds. This confirms that the first guess check is a filter that only rejects a small number of gross outliers.

It is interesting to put the performance of the VIS-CMW into perspective by comparing them with satellite tracked winds from other satellites and channels. Table 1 presents summary statistics of all the low level CMWs received over a period of thirteen days at ECMWF, divided according to satellite operator and channel. The quality of all low level winds is similar although METEOSAT appears to perform slightly better in terms of direction as the standard deviation is somewhat lower. In that context one should note that the American GOES low level CMWs were assigned to a fixed height of 900 hPa, and the Japanese GMS IR and VIS to 850 hPa. This may be an indication of a slightly enhanced performance of the cloud base altitude height assignment as opposed to a fixed level height assignment.

	Speed (m/s)		Direction (degrees)		FG mean speed (m/s)	No. obs
	bias	std	bias	std		
METEOSAT VIS	0.0	1.9	0.2	16.1	9.5	68349
METEOSAT IR	0.1	1.9	0.1	15.1	10.1	22724
GOES IR	-0.5	2.0	-0.2	21.4	7.8	29091
GMS IR	0.2	2.3	0.0	24.2	8.3	13643
GMS VIS	0.4	2.2	0.3	24.5	8.4	11837

Table 1: Bias and standard deviation between observation and First Guess (FG) for the low level CMWs at 1200 GMT received at ECMWF for different satellites and channels during the period 24/08/95 to 09/09/95.

4. Conclusions

Winds have been derived from tracking clouds in high resolution METEOSAT VIS images, with a template size of 32 x 32 VIS pixels corresponding to about 80 km at the sub-satellite point which is four times better than the corresponding IR winds. The winds have been experimentally derived at the European Space Operations Center (ESOC) once per day (1100 UT) from July 1994 until November 1995. The utilization of the VIS channel increases the number of low level CMW over the yield by the IR tracking by typically a factor of six although the smaller template size used in the VIS tracking could at best account for a factor of four. The additional yield is due to better contrast and spatial resolution. The higher yield and smaller template size provides for a better description of the large-scale flow including features of smaller scales as evidenced by a comparison of Figures 4 and 5.

A comparison of IR low level wind fields from different geostationary satellites with the first guess of the ECMWF forecast model shows that the winds derived from the tracking of cloud in high resolution VIS METEOSAT images have a quality comparable to IR low level cloud motion winds. Generally the standard deviation between FG wind speed and observation is around 2 m/s. The low-level METEOSAT winds show a better performance in terms of directional standard deviation which is an indication that a fixed altitude height assignment is inferior to cloud base height assignment as used for METEOSAT low-level winds. This can be explained by the fact that most low-level winds are from the marine trade wind regions where the lifting condensation level is within the atmospheric boundary layer and clouds travel with the wind at cloud base. It is also noted that previously observed negative speed biases (radiosonde or first guesswind minus satellite wind) can be explained by the wind profiles often observed in the marine ABL (see Figure 3).

The high resolution VIS winds presented in this study have been derived at ESOC on an experimental basis between July 1994 and November 1995. Winds were disseminated to ECMWF for validation in their data assimilation system. On 15 November 1995 the derivation of satellite tracked winds from METEOSAT was transferred from ESOC to EUMETSAT. The satellite operation and product derivation at EUMETSAT are both based on a new concept and new systems that differ from the ones previously used at ESOC. Currently the new system at EUMETSAT does not provide winds from high resolution VIS images, however, in view of the success of the experimental work at ESOC the derivation of a high resolution VIS wind product will commence at EUMETSAT in 1996 with a method as described in this paper. The impact of the new VIS-CMW has been tested with a data assimilation experiment at the European Centre for Medium Range Weather Forecasts (ECMWF) with positive results as reported by Maria Tomassini (1996, this volume).

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