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Françoise Désalmand, André Szantai, Michel Desbois. An attempt to retrieve low cloud motion winds over land in the African Monsoon flow on Meteosat pictures. *Geophysical Research Letters*, 1999, 26 (3), pp.319-322. 10.1029/1998gl900286 . hal-02087547

HAL Id: hal-02087547

<https://hal.science/hal-02087547>

Submitted on 2 Apr 2019

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An attempt to retrieve low cloud motion winds over land in the African monsoon flow on Meteosat pictures

Françoise Désalmand, André Szantai and Michel Desbois

Laboratoire de Météorologie Dynamique du CNRS, Ecole Polytechnique, Palaiseau, France

Abstract. It has been possible to extract cloud motion winds corresponding to the African monsoon flow during the rainy season over land from the set of all cloud wind vectors provided by a crude cloud tracking method on VIS Meteosat pictures. The selection cannot be based only on IR radiances, due to the presence of semi-transparent clouds and partial coverages of the pixels. Several tests have been proposed with an additional selection, based on the analysis of the histogram of cloud motion directions. Cloud motion winds obtained on VIS pictures are clearly separated in this diagram and justify the selection of a direction range where only clouds embedded in the monsoon flow are tracked. These winds are also validated by comparisons with NCEP analysed fields.

Introduction

The interest of determining winds from satellites at low latitudes arises from the impossibility to deduce winds from the mass field and from the scarcity of conventional wind measurements. The knowledge of low-level winds in these regions is fundamental for the estimation of water vapor transport and convergence, which feed the convective systems and the associated precipitations.

Since the early seventies, clouds observed on sequences of satellite images were recognized to be tracers of atmospheric motions. Cloud motion winds (CMWs) were then deduced from these motion measurements. The thermal IR channel was the most commonly used, as it allows a crude detection of the cloud level from its estimated cloud top temperature. However, the recognition and tracking of low clouds ($P > 700$ hPa) on IR pictures is very difficult because cloud top apparent temperatures are close to surface temperatures, which results in a lack of contrast. Furthermore, both in IR and VIS images, low tropical clouds are often smaller than the pixel (5 km at the subsatellite point in the case of Meteosat) and change in shape within a time below the temporal resolution (30 min), specially over land. Therefore, low tropical clouds over continents were claimed virtually impossible to track with the 30-min resolution (Shenk, 1991), and are not produced by operational satellite operators (Ottenbacher *et al.*, 1997).

This paper focuses on the measurement of low-level CMWs over the Guinean Gulf and Subsaharan West Africa on the area extending from the equator to the latitude 20°N and between the longitudes 20°W and 20°E . IR pictures

obtained with the resolutions (30 min - 5 km) of the geostationary Meteosat are used. Full resolution VIS images have been sampled to obtain the same 5 km spacing between pixels and have undergone a solar correction (instead of averaging, the sampling does not alter the 2.5 km original resolution which increases the small cloud detectability). CMWs are computed by an usual window matching method, and a special attention is paid for the selection of the lowest level clouds.

Meteorological situation

The Intertropical Convergence Zone (ITCZ) over West Africa separates the dry NE flow from the humid SW flow originating from the Santa-Helena anticyclone, and is a weakly inclined surface whose elevation above the ground decreases northwards (Fig. 1). The path on the ground of the ITCZ corresponds to a belt of about 150 km width with maximal temperatures and minimal pressures. Zone A in the monsoon flow (Fig. 1) is swept along by vortices which favor the mixing with the dry Saharan air mass, and very scarce cloudiness occurs. Zone B presents the maximal convergence/cloudiness/rainfall at about 1000 km towards the south in a deeper layer. Convective clouds are fed at the basis by the monsoon flow ($\approx 1-2$ km depth), and develop in the overlying easterlies (up to about 17 km). Sequences of satellite pictures commonly show the westward motion of these huge clouds which cannot be tracers for the SW flow.

Stratocumulus and cumulus clouds are found more south, in Zone C, the less convective area of the monsoon trades. They can also be submitted to non-advective effects, specially over the Guinean coastal regions, and diffuse clouds just above the monsoon flow clouds may disturb the determination of low-level motions.

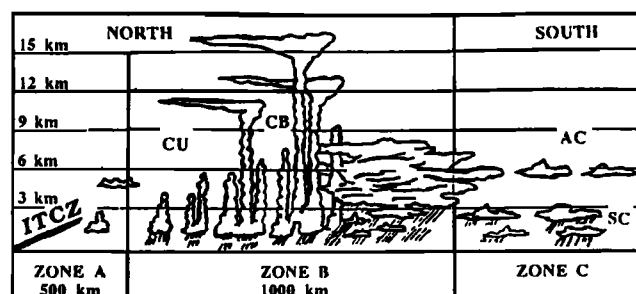


Figure 1. Meridional-vertical section across the ITCZ. (A) mixing of the NE and SW flows. (B) cumulonimbii and nimbostratii. (C) cumuli and stratocumuli.

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Paper number 1998GL900286.
0094-8276/99/1998GL900286\$05.00

Methodology

The method used to derive CMWs consists in finding the best match of a 16×16 pixel square ($\approx 75 \times 75 \text{ km}^2$), the correlation window on the first picture, with a square of the same size moving inside a larger 32×32 pixel square, the search window on the second picture. The best match between the correlation window centered at a given point and a square of the same size moving inside the search window centered at the same point is determined by the minimal value of the Euclidean distance between the ensemble of pixel counts of the compared windows for all possible displacements. The position corresponding to this minimal value gives the CMW (Leese *et al.*, 1971).

CMWs are computed on a grid of 27 rows and 57 columns (1539 gridpoints separated by 16 pixels). Two successive "raw" wind fields are determined in each channel, the first one between 11:30 and 12:00 UTC, and the second one between 12:00 and 12:30 UTC (4 Aug. 1989).

The quality tests

The comparison of two successive raw winds at the same point often reveals important differences in speed and/or direction, which do not correspond to a real variation of the wind. Therefore, these inconsistent vectors have to be removed with appropriate quality tests (Holmlund, 1996 ; Schmetz *et al.*, 1993).

First of all, preliminary tests suppress too small and too large vectors : vectors with zonal and meridional components lower than 1.5 pixel/30 min ($\approx 4.2 \text{ ms}^{-1}$) because they may be due to surface features ; vectors with zonal and meridional components equal to 8 pixels/30 min ($\approx 22 \text{ ms}^{-1}$), because a side of the correlation window reaches a side of the search window.

The time consistency tests is then applied to the consecutive and collocated wind vectors V_1 and V_2 : if the vector difference $|V_1 - V_2|$ is higher than 5 ms^{-1} , the vector V_2 is removed. Otherwise, the vector V_2 is retained for the spatial consistency test. This test can eliminate valid vectors, particularly in the case of strong acceleration, which is rarely observed in these regions where monsoon winds are known to be very weak (5 ms^{-1}). Note that the problem is here to keep only adequate winds with the risk of eliminating some correct winds with too severe tests.

After the preliminary and temporal consistency tests, the spatial consistency test consists in comparing the vector V_2 to the remaining vectors within a 5×5 neighbourhood (i.e. within a distance of 200 km) : if the difference in direction is lower than 45° with at least one neighbor

Table 1. Rejections of winds from two successive raw wind fields (2×1539 winds in each channel).
Remaining consistent winds : 87 IR and 102 VIS.

Raw wind fields	IR winds	VIS winds
11:30/12:00 UTC	rejected	rejected
12:00/12:30 UTC	12:00	12:00
4 Aug. 1989	UTC	UTC
Too small vectors	279	521
Too large vectors	397	293
Temporal consistency test	925	779
Spatial consistency test	606	731
10% coldest $T \geq 0^\circ\text{C}$	315	249

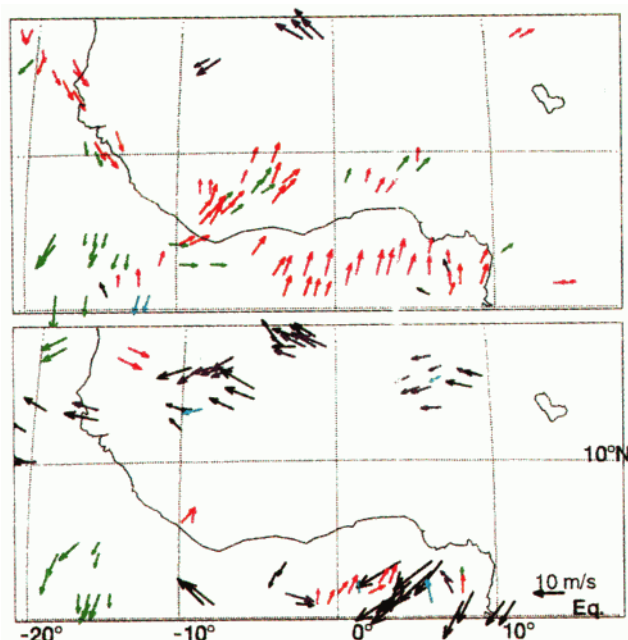


Figure 2. Low consistent CMWs at 12:00 UTC (4 Aug. 1989). Pressure levels higher than 1000 hPa (pink), 925 hPa (red), 850 hPa (green), 700 hPa (turquoise), 600 hPa (blue), 500 hPa (black) deduced from the NCEP analyses. **Top :** VIS field (102) **Bottom :** IR field (87).

vector, the vector V_2 is kept in the "consistent" wind field at 12:00 UTC. Since the flow is submitted to the smooth deviation towards the right by the Coriolis force, this 45° -value is not a severe constraint.

First selection of low CMWs

The IR brightness temperature (BT) can be deduced from the IR radiance which is proportional to the numerical count of the IR picture. The IR BT is computed for the 16×16 pixels of the correlation window centered at that point. The value corresponding to the 10 % coldest pixels BT is labelled as the CMW temperature, as it has already been practised despite possible errors due to the presence of multiple cloud layers or/and semi-transparent clouds. A first selection of the low level winds is then done by keeping only CMWs warmer than 0°C . This threshold has been chosen after several attempts, showing that warmer ones would lead to the suppression of some SW winds in the monsoon area.

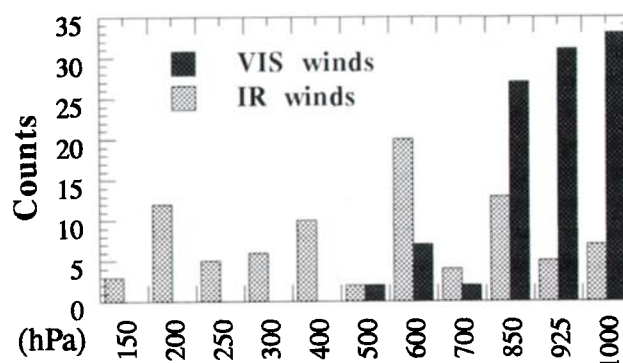


Figure 3. Histograms of the best fit levels between low CMWs and NCEP winds (08:30-17:30 UTC-4 Aug. 1989).

Table 2. Comparison between low CMWs and NCEP analysed winds for the 4 Aug. 1989 at 12:00 UTC.

Low CMWs Mean speed	CMW counts	Rms error ms ⁻¹	Bias ms ⁻¹
VIS 7.1 ms ⁻¹	102	3.3	1.2
IR 9.5 ms ⁻¹	87	4.9	2.1

Note that the large atmospheric absorption mostly due to water vapor of the moist atmosphere which can lead to a deficit in BT of about 2 K for cloud tops at 2 km (Schmetz, 1986) has not been corrected. However, the purpose is not a precise height assignment to clouds but the selection of the lower level clouds.

Table 1 shows the proportion of raw winds successively suppressed to build the low-level consistent field : about 97%.

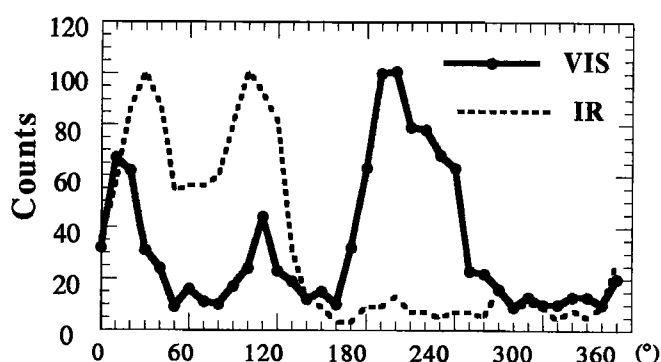
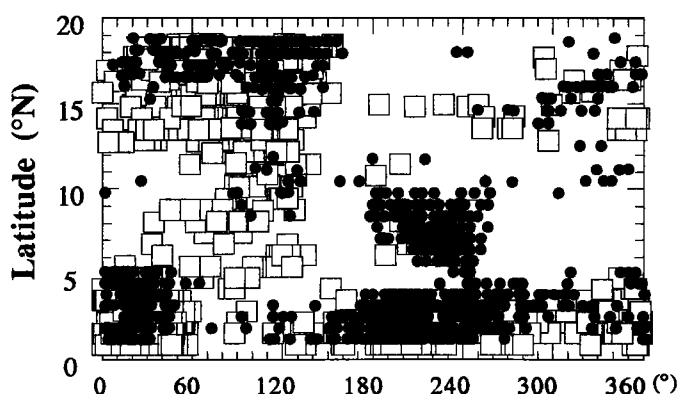
First results

Consistent cloud motion wind fields

Fig. 2 shows VIS and IR consistent wind fields (4 Aug. 1989 at 12:00 UTC) satisfying all the quality tests with a 10% coldest BT higher than 0°C.

The IR field comprises 87 winds with a majority of winds in the easterlies at latitudes higher than 15°N. There is a gap over land between the latitudes 15°N and 5°N by reason of the poor contrast of clouds over land (forest, savannah). In the southeastern and southwestern parts of the map, the overlying flow is well identified by northerly wind vectors.

The VIS field comprises 102 winds with a majority of SW winds over land between 10°N and 5°N and over ocean. A flow originating off the coast of Mauritania passes along the coast of Senegal and Liberia. The SW monsoon flow penetrates the continent between the Fouta-Djalou and Mont-Togo ranges as it can be deduced from the visual observation of the VIS-image animation. In the southern part of the map, the flow lying over the monsoon layer is recognizable by northerly wind vectors, less numerous than in the IR field. The tracking on IR pictures is done on higher clouds because semi-transparent cloud elements can be better detected, and the tracking of low-level clouds is favoured on VIS pictures by a better contrast over the surface.

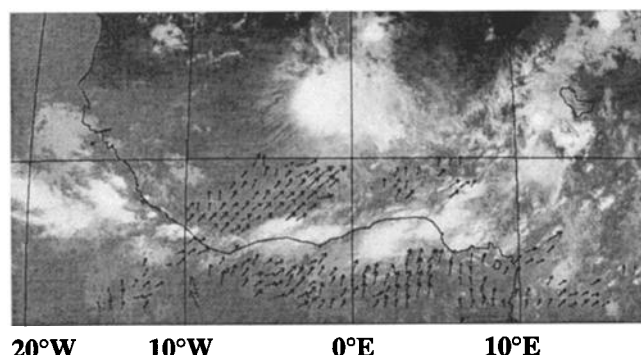
**Figure 4.** Counts of CMWs versus the wind direction from 08:30 to 17:30 UTC (4 Aug. 1989). VIS channel (continuous line), IR channel (broken line).**Figure 5.** Latitude versus CMW direction from 08:30 to 17:30 UTC (4 Aug. 1989).

Comparison between low CMWs and analysed NCEP winds

Analyses of the operational NCEP (National Centre of Environmental Prediction) forecast model available at midday are used in this study and limited to the winds at tropospheric levels (11 levels between 1000 hPa and 150 hPa). They have been interpolated from a grid of 2.5°*2.5° to the grid of the satellite winds (16*16 pixels). For each of the satellite gridpoint, the magnitudes of the vector differences between the satellite wind and the analysed winds are computed. The best fit is obtained for the minimal magnitude of the vector differences, and the corresponding pressure level is assigned to the CMW.

On Fig. 2, red and pink for the lowest levels (1000 and 925 hPa respectively) prevail in the VIS wind field for the SW surface flow whereas other colors (green, turquoise, blue and black) prevail in the IR wind field for the easterlies and over the monsoon layer, indicative of higher levels (850, 700, 600 and 500, respectively). Some partial coverage of the pixel by the very hot surface of the Sahel can explain some red and pink vectors at about 17°N probably linked to divergent cirrus elements of the cumulonimbus anvil that can be clearly observed on the IR picture (Fig. 7).

Histograms of the best fit levels are reported on Fig. 3. For IR winds, no particular level prevails between 150 and 1000 hPa. On the contrary, VIS winds are below 850 hPa with the exception of 10 winds at 600 hPa and 500 hPa.

**Figure 6.** The IR picture at 12:00 UTC with the VIS monsoon winds from 08:30 to 17:30 UTC (4 Aug. 1989).

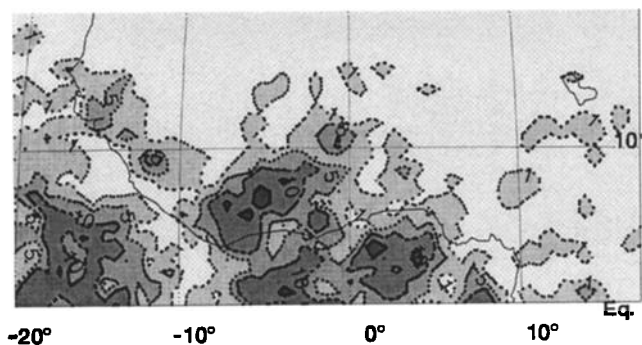


Figure 7. Iso-count lines of VIS monsoon winds for the first ten-day period of August 1989 (08:30-17:30 UTC). Counts up to 5 (light grey), between 6 and 10 (medium grey), between 11 and 20 (dark grey), between 21 and 33 (darker grey).

After checking, these winds are situated at high latitudes ($>15^{\circ}\text{N}$) or near the Equator. In both cases, the semi-transparency of high clouds or partial coverage can explain the relatively high apparent temperature of the clouds. Rms errors and biases are larger for the IR winds than for the VIS (Table 2). Obviously, clouds situated at higher levels are more rapid with higher values of rms errors and biases.

Characterization of CMW directions

Fig. 4 plots the CMW direction in function of the latitude for all winds on the 4 Aug. 1989 from 8:30 to 17:30 UTC. In the IR case (empty squares), SW winds are found only over the ocean. In the VIS case (black circles), the SW flow is identified over water (latitudes \approx between 0° and 5°N) and land (latitudes \approx between 5° and 10°N) showing the better contrast of low clouds over the surface.

The area of penetration over land of small cumuli embedded in the monsoon flow approximately reaches the 10°N latitude; the corresponding wind direction is comprised between 120° and 270° (Fig. 4). The monsoon flow itself can extend more north by about 16°N (≈ 1000 km), but low clouds cannot be found in that area in agreement with Fig. 2 and Fig. 6. SW winds at about 15°N correspond to the motions of cirrus elements diverging from the cumulonimbus anvil, and should be eliminated in the future by the use of the water vapor channel picture.

The limit of the monsoonal area over land

In order to check the above result, we consider now pictures from 08:30 UTC to 17:30 UTC, firstly for one day and secondly for a ten day period.

Fig. 5 represents the number of winds versus CMW direction for the 4 Aug. 1989. Two peaks, one for the easterlies and one for the northerly flow over the monsoon layer, are identified in both channels. An additional peak between directions 150° and 270° is only identified in the VIS histogram.

Fig. 4 and Fig. 5 point out a possible selection for the monsoon flow: wind directions between 150° and 270° , which corresponds also to latitudes lower than 10°N during that day. Small clouds are not found at the level of squall lines nor to the north where the monsoon layer is very thin (Fig. 1 and Fig. 6). Fig. 6 shows VIS vectors reported on

the IR picture (12:00 UTC) which is used for showing the semi-transparent parts of high convective clouds. A huge squall line travelling westwards and cumulonimbii along the Guinean gulf coast are clearly fed at the basis by the monsoon humidity.

VIS CMWs have then been computed for the first ten day period of Aug. 1989 (8:30 to 17:30 UTC) and the resulting iso-count lines have been reported on Fig. 7. The presence of cumuli and stratocumuli illustrates the penetration of the monsoon flow over land. Some privileged areas of more numerous small clouds are obtained over land, for example over the plain at the NE of the Fouta-Djalou range.

Conclusion

An objective method for tracking low clouds on VIS pictures has been devised to analyse the lower-tropospheric monsoonal circulation over West Africa during the rainy season, at the south of the most convective area. The method first selects lower level clouds with the 10% BT of the correlation window, and the analysis of the latitude versus the wind direction allows to define an area where VIS monsoon winds prevail without valuable IR winds. Enhancements are expected with images from Meteosat Second Generation. Higher resolutions (a subsatellite 3km-resolution for all channels, additionally a 1 km-resolution for the VIS channel, a temporal 15-min resolution) will enhance the tracking of small and quickly deforming clouds.

Acknowledgements. Meteosat window images were provided by the European Space Operational Centre (ESOC, Germany) and analysed data by the National Centre of Environmental Prediction (USA).

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(Received July 31, 1998; revised November 6, 1998; accepted November 30, 1998).