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Automated extraction of cloud motion vectors from INSAT-1 B imagery

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सार — इसशोध पत्र में, भारतीय प्रायद्वीप के आस-पास महासागरीय क्षेत्रों में इन्सैट-1 बी दृष्टव्य और अवरक्त बिम्बावली से मेघ गतिक सदिश निष्कर्षण के लिए स्वनिर्मित तकनीक का वर्णन किया गया है। यह तकनीक पैटर्न अनुकूलन प्रक्रिया पर आधारित है जिसमें उभयनुखी सहसंबंध के स्थान पर दो ग्रे शेड वितरण के मध्य बिंदु दर बिंदु समानता को ढूंढने की कोशिश की गई है। समुद्री क्षेत्रों में पवन आंकड़ों के संवर्धन में मेघ गतिक सदिश बहुत उपयोगी पाये गये हैं। और ये एक दूसरे के साथ तथा आस-पास के रेडियोसौंदे पवनों के अनुकूल हैं। इस शोध पत्र में अति-उच्च विभेदन रेडियोमीटर विभेदन और पवन व्युत्पन्न प्रक्रिया द्वारा उत्पन्न अशुद्धियों और अनिश्चितताओं के स्रोतों पर भी विचार विमर्श किया गया है।

ABSTRACT. The paper describes an automated technique for cloud motion vector extraction from INSAT-1B visible and infra-red imagery over the oceanic areas around the Indian Peninsula. The technique is based on a pattern matching procedure which attempts to search for a pixel-to-pixel equality between two grey shade distributions instead of cross-correlation. The CMVs are found to be very useful in augmenting the wind data over the oceanic areas and are consistent with each other and neighbouring radiosonde winds. The paper also discusses the sources of errors and uncertainties caused by the VHRR resolution and the wind derivation procedure.

1. Introduction

The ATS series of geostationary satellites, launched in the late sixties, provided for the first time, an opportunity to determine wind velocities by tracing cloud movements over a time-series of satellite pictures (Fujita 1969, Ninomiya 1971). Since then, cloud motion vector (CMV) extraction techniques have undergone considerable refinement and CMVs are now being derived operationally over extensive areas within the GOES, METEOSAT and GMS coverages.

Although satellite-derived CMVs continue to have a certain degree of error or uncertainty, they constitute virtually the only source of data over oceanic and inaccessible areas of the globe. Around the Indian Peninsula, in particular, the only radiosonde stations are on the Lakshadweep, Andaman and Maldive Islands. Satellite CMVs, therefore, appear to be the best means of augmenting conventional data in the analysis of wind-flow patterns over the Indian Ocean on a day-to-day basis.

With the operationalisation of INSAT-1B in October 1983, extraction of CMVs from half-hourly INSAT pictures was taken up on an experimental basis. By mid-1984, CMV extraction had become part of the routine activities of the INSAT Meteorological Data Utilisation Centre (MDUC), New Delhi. The technique used was an interactive one, in which the tracer selection was done manually, but its movement was determined by a cross-correlation procedure.

To reduce the degree of operator involvement and to speed up the CMV extraction process, the authors have devised a largely automated technique and have written the software to implement it on a PDP 11/70 computer linked to a COMTAL Vision one/20. Since November 1984 this technique is being used at MDUC to derive CMVs twice a day (03 and 06 GMT) over the Arabian Sea, Bay of Bengal and north-central Indian Ocean. The present paper describes the methodology adopted by the authors, discusses its relative merits and sources of error, and considers with illustrative examples the utility of the CMVs as a supplement to conventional wind field analysis.

2. Methodology

The automated CMV extraction procedure requires three full-resolution, sectorised, navigated and registered images, of which two are visible images for time T and $T+\triangle T$, and the third is an infra-red image for time T. Generally, $\triangle T$ is 30 minutes. Since the resolution of the INSAT VHRR at the sub-satellite point is 2.75 km in the visible channel and 11 km in the infra-red channel, the visible images are preferred for detecting cloud displacements. The infra-red image, however, has to be used for getting the cloud top temperature for wind

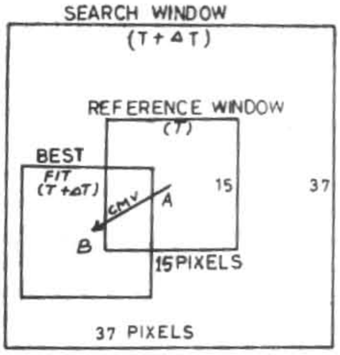
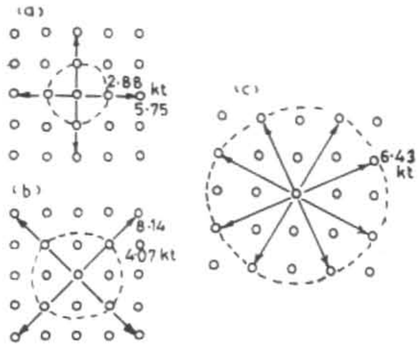
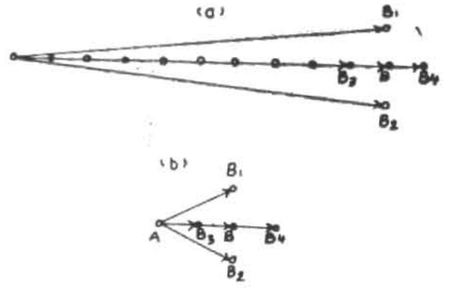


Fig. 1. Reference and search windows



Figs. 2(a-c). CMVs in relation to VHRR resolution



Figs. 3(a & b). Errors due to 1 pixel mis-location

height assignment. Registration of the images is necessary to eliminate the generation of spurious CMVs not representing actual cloud motion.

In the automated procedure, 225 locations (15 × 15 matrix) in image T are examined for the presence of cloud tracers in a reference window of 15 × 15 pixels around each location (Fig. 1). In a full resolution image sector of 512 × 512 pixels, this would correspond to a possibility of deriving a CMV per 1 degree latitude/longitude square approximately. At the beginning of the CMV extraction process, the operator specifies a minimum gray shade threshold for the cloud tracer. The software is so designed as to extract CMVs only for those locations where the reference window contains 5 to 210 pixels of grey shade above this threshold. In this manner, reference windows comprising large cloud patches or clear skies are rejected from further processing.

The search window from image $T+\triangle T$ is assigned a size of 37×37 pixels for low clouds or 61×61 pixels in the case of medium or high clouds. The centres of both the reference and search windows are identical. The smaller size of the search window for low clouds has been chosen to save computer time in view of the generally lighter winds prevailing at low levels.

The pattern matching technique adopted is to take the absolute difference of grey shade between corresponding pixels of the reference window (a_n) and a subset of the search window (b_n) of the same size as the reference window. These differences are summed up to arrive at a mean value for each subset i of the search window.

$$\overline{X_i} = \left[\sum_{n=1}^{225} \left| a_n - b_n \right| \right] \Big/ 225$$

The centre of the particular subset in which $\overline{X_i}$ is the smallest of all, is taken as the end-point B of the cloud motion vector, its origin A being of course at the centre of the reference window.

The wind speed and direction are obtained from the relative pixel shifts (north-south and east-west) between points B and A in time $\triangle T$, and the wind is located at point A. For assigning the height, the surface temperature is input by the operator and a standard lapse-rate of 6.5°C/km is thereafter applied.

After all the 225 possible locations of the image T have been scanned and the CMVs derived wherever conditions permit, two types of quality control options are provided to the operator He may either choose to examine each CMV individually and then accept or reject it. Alternatively, he can define acceptable maximum wind speeds for low, medium and high winds, and ask the software to automatically ignore those CMVs which are above these limits.

Finally, the software outputs in a tabular form the latitude, longitude, speed, direction and height of the CMVs which satisfy the quality check, grouped under the categories of low, medium and high winds (<3, 3–8, >8 km).

3. Merits and limitations

3.1. *Cross-correlation vis-a-vis absolute difference*

The most commonly used method of pattern matching for CMV derivation is the cross-correlation method. Here the pixel array of the reference window X is correlated to a subset of the search window Y to obtain correlation coefficient, σ being the standard deviation.

$$C = \frac{\overline{XY}}{\sigma_x\, \sigma_y} = \frac{\Sigma XY}{N\sigma_x\, \sigma_y}$$

The centre location of the subset of the search window which yields the maximum correlation coefficient gives the end point of the CMV.

The cross-correlation method is not ideally suited for incorporation into a completely automated procedure. In most situations, the shapes and sizes of clouds selected as tracers do not remain invariant with time. If multi-layered clouds are present in the reference window, they would be expected to move along different directions with different speeds. The result is that, in practice, correlation coefficients nearing unity are rarely encountered. It has been our experience and that of others also (Leese & Novak 1971) that maximum cross-correlations are of the order of 0.7 or less, and in many cases two or three maxima of the same order are found, necessitating a judicious selection.

In an automated technique, there is a strong possibility of spurious CMVs being generated (Endlich and Wolf 1981) with high associated correlations, which would pass a quality check. This would happen, for example, if the reference window had all its pixels of a uniform grey shade and the search window also had uniform (but not necessarily same) grey shade. The cross-correlation technique is again likely to yield high but physically doubtful correlations, when the spatial distribution of tracers within the two windows is identical but their grey shades different as may be the case with growing or decaying systems.

The above considerations prompted the authors to adopt the minimum absolute difference technique which aims to obtain a near-perfect match for the overall cloud pattern of the reference window. It does not measure the degree of relationship between two arrays as with the correlation technique, but attempts to search for a pixel-to-pixel equality between two grey shade distributions. It is, therefore, more capable of discerning changes in cloud size and shape and differential motions of multi-layered clouds.

This technique, being much simpler, is also executed faster on the computer. This is a very important factor facilitating CMV derivaton on a near real-time basis.

3.2. *Uncertainties in height assignment*

For most synoptic applications, it is necessary to plot the satellite-derived CMVs on conventional constant pressure charts. The question of assigning proper heights to the CMVs is, therefore, of primary importance and has been the subject of considerable debate.

Even if it became possible to derive very accurate cloud top heights, the problem would still remain whether the CMV is representative of the wind flow at that height or any other. The *in situ* aircraft verification of Hasler *et al.* (1979) showed that cumuliform clouds associated with oceanic trade winds and sub-tropical highs move at speeds representative of winds at the cloud base level rather than the cloud top level. Oceanic cumuli near fronts and high-level cirrus move at a speed which agrees best with the mean wind in the cloud layer. Lee (1979) has described the tendency of CMVs to congregate around the 300 and 900 mb levels. Tsuchiya and Downey (1981) tried to group CMVs by tracer type instead of cloud top temperature, and observed that cellular type tracers represented winds at 900 mb, whereas movement of cirriform tracers agreed well with the winds at 250 and 400 mb.

In the present work, the software picks the highest grey shade from the reference window pattern of infrared image and converts it to temperature by a simple use of Planck's law. Using the input surface temperature, and a standard lapse-rate, the height corresponding to this temperature is interpolated. The fact remains that this height may not exactly correspond to the actual cloud top height because of factors like atmospheric attenuation, partial transmission through the cloud of radiation from underlying surfaces, deviations of the real vertical temperature profile from that assumed, etc. These factors, however, would generally cause the CMV to be assigned a lower height than the actual cloud top level. Our CMVs would, therefore, represent a level within the cloud, which appears to be more realistic as per the observations of various workers cited above.

It must be further stressed that ambiguities in CMV height assignment would matter significantly only in cases of strong vertical wind shear such as in the vicinity of jet streams. Our areas of operational interest are the oceanic regions south of 24°N, where such situations are not encountered very frequently except during the monsoon season.

3.3. *Limitations related to the VHRR resolution*

Since the INSAT visible pixel has a size of 2.75 x 2.75 km at the sub-satellite point, a north-south or east-west tracer displacement of one visible pixel in 30 minutes corresponds to a wind speed of 5.5 kmph or 2.88 knots, as shown in Fig. 2(a) (In the subsequent discussions, the term "tracer" is used synonymously with the centre of the reference pattern). If the tracer moves diagonally in the pixel matrix [Fig. 2(b)], a displacement of 1 visible pixel in 30 minutes corresponds to a wind speed of $\sqrt{2}$ times 5.5 kmph or 4.07 knots. Hence for northerly, southerly, easterly or westerly flow, the wind speed can have discrete magnitudes of 2.88, 5.75, 8.63, 11.5, 14.4, 17.3....knots. Northwesterly, northeasterly, southwesterly or southeasterly winds will have magnitudes in steps of 4.07, 8.14, 12.21 16.3, 20.3, 24.4....knots. We may, therefore, say that wind speeds derived from INSAT imagery using the tracer displacement technique *by whatever procedure* would have a "least count" of 2.88 knots for zonal and meridional CMVs, increasing to 4.07 knots for NE, NW, SE, and SW'ly CMVs. The least count would be higher for other CMV directions.

An analysis of the directional accuracy of INSAT CMVs at various wind speeds can be made by viewing the situation from the opposite angle. As may be inferred from Fig. 2, winds of 2.88 knots can be detected only if they are along N, S, E or W. To obtain a resolution of 45° in wind direction, the speed must be at least 4.07 knots. A minimum wind speed of 6.43 knots is required to obtain wind directions on a 16-point compass. A wind speed of 10.4 knots would enable the direction to be determined along 32 points of the compass. It must again be mentioned that these limitations hold good *regardless of the procedure* followed in the tracer displacement technique.

3.4. *Procedural errors*

In addition to the inherent errors discussed above, procedural errors or limitations may result in a wrong or ambiguous placement of the end-point of the CMV vector in relation to its origin. Even if the net mislocation is minimised to ± 1 pixel from the real CMV

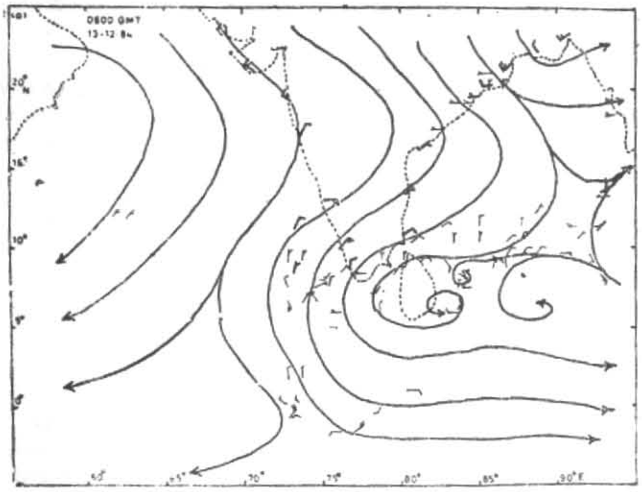


Fig. 4 (a). Comparison of 06 GMT low level CMVs (thin bands) and 12 GMT 850 mb observed winds (thick bands) for 13 December 1984

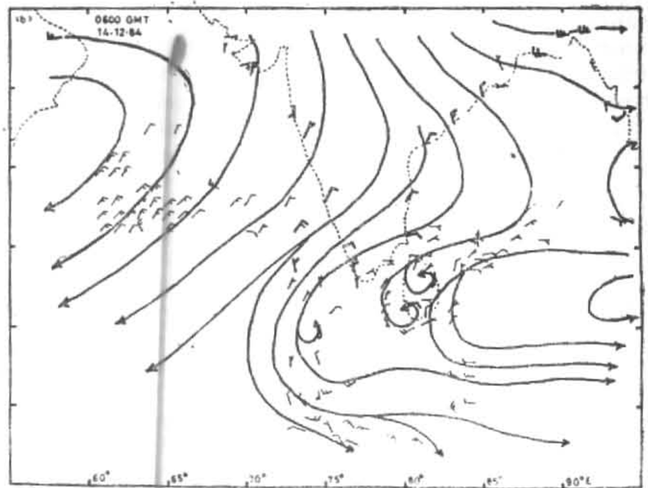


Fig. 4 (b). Same as Fig. 4(a), but for 14 December 1984

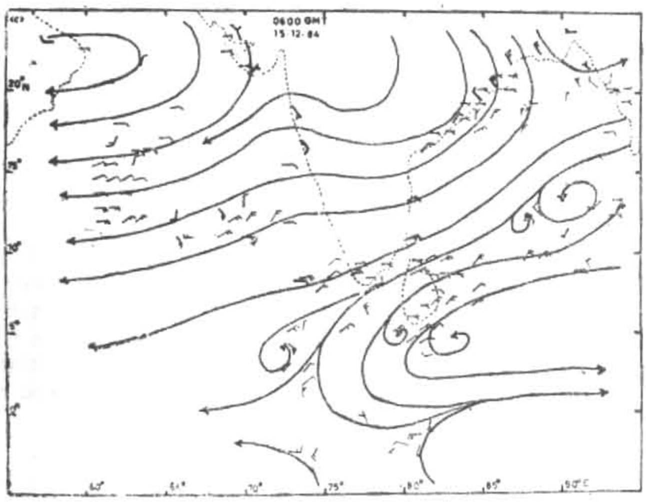


Fig. 4 (c). Same as Fig. 4(a) but for 15 December 1984

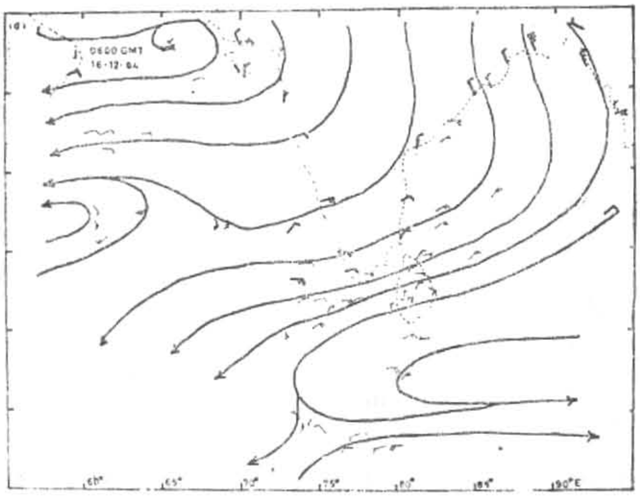


Fig. 4 (d). Same as Fig. 4(a) but for 16 December 1984 end-point (by accurate navigation, registration and pattern-matching) the effect in terms of wind speed and direction may be negligible or significant depending upon the CMV itself.

For example, consider a tracer displacement of 10 pixels from point A to point B (Fig. 3a) amounting to a westerly wind of 28.8 knots. Now if the point B is mislocated to B_3 or B_4 the wind direction would remain unaffected, but the wind speed would be determined as 28.8 ± 2.88 knots. On the other hand, had the point B been placed at B_1 or B_2, the wind speed would not have changed, while the direction would have been slightly different from the pure westerly course.

With still stronger winds, ± 1 pixel location error will be of hardly any consequence to the wind direction, while the ± 2.88 knots error in wind speed will appear relatively less significant.

Lighter winds would be affected much more by mislocation errors. For example, if the tracer is displaced from point A to B by 2 pixels (Fig. 3b) the wind is westerly 5.75 knots. If point B is wrongly placed at B_1 or B_2, the wind speed would be 6.43 knots and the direction WSW or WNW instead of W. Whereas, at B_3 or B_4, the speed would be 2.88 or 8.63 knots instead of 5.75 with no change in direction.

4. Comparison of CMVs with upper air observations

The extent of agreement of the low-level CMVs with 850 mb wind observations was assessed over four consecutive days, 13 to 16 December 1984, on which there was a predominance of low-level cloud tracers (Figs. 4a to 4d). The 06 GMT oceanic CMVs with assigned heights upto 3 km and 12 GMT wind observations at 850 mb over coastal and island stations were plotted on a common chart and streamlines were drawn considering both the data sets. The two data sets are seen to merge with each other very well, enabling a much finer streamline analysis to be made than with conventional data alone.

To the south of 7°N latitude, on all the days, the CMVs provide a clear indication of the reversal of wind direction from easterly to westerly, which would otherwise have to be located on a largely subjective basis. Likewise, to the west of 70°E longitude, the CMVs are seen to define very well the anticyclonic flow pattern over an area not having any observational data. The INSAT CMVs would thus appear to add details to and improve the objectivity of the wind analysis over the oceanic area around the Indian Peninsula.

In the streamline analysis of Figs. 4(a) to 4(d), only a few CMVs had to be overlooked, and the intra-consistency of the CMVs is very good.

If one examines the streamline patterns of the four days together, they exhibit the desired continuity in time. The ITCZ, for example, shows a gradual southward progression from 7°N on 13 December to 1°N on 16 December.

As good cloud tracers are generally distributed unevenly, the CMVs tend to be derived in clusters. Many of the neighbouring CMVs have identical speeds and direction, but some of the clusters have CMV alignments which strongly suggest the presence of mesoscale circulations. There is no ground truth available to confirm or disprove their existence, but in Figs. 4(a) to 4(c), such circulation have been drawn only where supported by two or more CMVs. These interesting features cannot be identified on conventional wind charts and deserve to be studied with greater attention with a larger volume of CMVs data.

The number of coincident INSAT CMVs and upper air observations was too small to enable a statistical comparison between them to be made. However, a comparison of CMVs and radiosonde winds within 1° latitude/longitude of each other revealed that out of 28 such pairs, 6 pairs had identical directions, 5 had identical speeds and 4 had same speeds as well as directions. This must be viewed against the possible errors and uncertainties of the CMV derivation process, particularly with light winds, as described in the preceding section. It must also be noted that there is a time difference of 6 hours in the two data sets. Further, CMVs with heights upto 3 km have all been plotted on the 850 mb chart, neglecting any vertical wind shears in the 3 km layer above the surface.

Bauer (1976) in his comparison over North America of CMVs with coinciding radiosonde winds, first made an intercomparison between neighbouring radiosonde winds themselves. He found that a CMV and a neighbouring radiosonde wind had a mean absolute difference of 8.3 knots in the u-component and 8.6 knots in the v-component. Bauer also found no systematic bias with respect to latitude, height or distance from the sub-satellite point. But it is worthwhile to consider Bauer's finding that between a radiosonde wind and another nearby radiosonde wind, the mean absolute difference was 7.9 knots in the u-component and 9.6 knots in the v-component. In other words, the intra-variability of radiosonde winds is of the same order as the difference between CMVs and radiosonde winds.

5. Concluding remarks

(*i*) The cloud motion vectors generated by the automated technique described in this paper have been found to be useful and generally acceptable. There are some situations, however, which merit some comment. In the case of very low-level clouds, the infra-red brightness temperature may be of the same order as that of the sea surface. In the visible image also, these clouds may not appear very bright. For eliminating the derivation of spurious CMVs, the operator is asked to input a suitable threshold visible grey shade value. The software checks whether in a box there is a sufficient number of visible pixels brighter than this threshold, otherwise CMV extraction in that box is not attempted.

(*ii*) In the present stage of development of the technique, multi-layered cloud tracers have not been used as such, the CMV being attributed to the highest cloud top in a box. A further refinement is possible by dividing the cloud pixels in a box into subsets according to the temperature and then performing pattern-matching subsetwise. The feasibility of such an approach is under the consideration of the authors.

(*iii*) A systematic comparison of satellite CMVs and radiosonde winds is not practicable for many reasons. There are only a few stations along the Indian coastline and these report at 00 and 12 GMT, while the CMVs are derived at 06 GMT. Moreover, finding a suitable cloud tracer just over a station is a matter of chance. Besides, as discussed earlier, the upper wind observations themselves are not free from errors.

A better way of validating the CMVs is to take a long sequence of half-hourly images and derive the CMVs with every successive image pairs. The degree of consistency among the CMV patterns so generated would be a measure of the quality of the CMVs. The authors are already engaged in such an exercise and propose to present the results in a subsequent paper.

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