The Height Assignment of Cloud Motion Vectors: Infrared Window Channel Method and Case Analyses of Forecasting the Tracks of Two Typhoons

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ABSTRACT

Current progress of the retrievals of cloud motion vectors (CMVs) and the use of the infrared window channel method to assign the heights of the CMVs are detailed in this article. The importance of applying the CMVs to aid the short-term subjective forecast of typhoon tracks was examined via two case studies. It turned out that typhoon Sam of 1999 moved along the edge of a mid-level (700-400 mb) high pressure circulation revealed by the CMVs. On the other hand, the tracks of Sam were not adequately predicted by the typhoon forecast system of the CWB owing to improperly simulating the movement of the existing mid-level high pressure system. As the mid-level high-pressure system retreated eastward Sam then turned northwestward, which was consistent to the flow pattern indicated by the CMVs. For the case of typhoon Wendy, a dominant upper-level (400-100 mb) anti-cyclonic flow residing on top of the Wendy suggested a limited intensification of Wendy.

1. Background

The derivation and application of cloud motion vectors (CMVs) based on geosynchronous satellite observations have gained notable progress in recent years in the United States and European Union as a result of the abundance of the CMVs and the increased accuracy in the associated CMV height assignments (Nieman *et al.* 1993 and 1997). It is found that the importance of CMVs is to advance the present knowledge of the evolution of the weather systems undetectable by the conventional observational network. High-density water-vapor winds further enhance the capability of analyzing the upper-level air motions in both cloudy and cloud-free areas. Impact studies of the CMVs on the subjective and short-term hurricane track forecasts was demonstrated by Velden *et al.* (1998). Improved model's capability to describe the movements of tropical cyclones as well as the predictions of synoptic weather systems due to the assimilation of the CMVs was justified by Goerss *et al.* (1998). The meteorological satellite center of the Central Weather Bureau (CWB) began her first approach to the derivation of CMVs based on the remote sensing digital data from the Japanese Geostationary Meteorological Satellite (GMS-5) as late as 1997, owing to the increasing need of the CMVs for aiding the forecasts of typhoon tracks in data-void (e.g. oceanic) area. The CMV retrieving process and preliminary case studies of the application of CMVs, using the infrared window (IRW) channel method to assign the cloud-top heights, are the main purposes of this article.

2. Target selection

After the correction of the navigation error, the selection of the target for tracking, to get the CMV, can then proceed. In this study, an area of 7 × 7 pixels in the first IRW channel (wavelength: 10.5-11.5 micrometer) of the GMS-5 is set for the tracking. Each IRW pixel of the GMS-5 covers a domain of approximately 5×5 km^2. A potential target area (49 pixels) with a zero standard deviation of the observed IR radiance (Tbb), such as the cloud-free and uniform cirrus-covered areas, is ruled out in the following tracking procedure in order to save the computer time. A potential target area with a none-zero standard deviation, on the other hand, is taken as a designated target and is used for the subsequent tracking procedure.

3. Tracking --- the retrieval of the preliminary

CMV

Three consecutive satellite imageries of 30 min apart are used to procure the CMV of each designated target. Once a 7 X 7-pixel area in the second (30 min later) satellite observation is "regarded" as the same area to the one in the first imagery, the moving speed and direction of the specific designated target in the first imagery can then be calculated. This is the first preliminary CMV for the specific designated target in the first imagery. Next, the same searching procedure is applied to locate a 7 X 7-pixel area in the third satellite imagery, which is the most "similar" to the target in the second imagery. The second preliminary CMV for the specific designated target in the first imagery can then be calculated. An acceleration check is performed to ensure the initial quality of the CMV. When the wind speed difference between the first and second preliminary CMV is less than 5.1 m/s, the preliminary CMV of the designated target in the first image is the vector mean of the first and second preliminary CMVs. Otherwise, there would be no preliminary CMV for that specific target in the first image (Nieman *et al*, 1997).

The tracking procedure in this research fundamentally follows the one used by the Cooperated Institute for Meteorological Satellite Studies (CIMSS), however, some adjustments are made to ensure a higher initial quality of the preliminary CMV. Firstly, the designated target area is set to 7×7 pixels to avoid the complexity of discerning non-uniform cloud-tops in the target area, which would cause the ambiguity of assigning height of the designated target or, equivalently, the height of the CMV (Nieman *et al.*, 1997). Secondly, no nearby wind fields of the designated target in the first imagery (TGT1, hereafter) from the NWP model is referred in this study, such that the dependence of the preliminary CMVs on the model is relieved. Thirdly, two supplementary criteria are applied to seek the most "similar" target area in the search domain in the second and third imageries.

The commonly used correlation coefficient is used as the first additional criterion as an aid to search for the target in the search domain of the second imagery (TGT2, hereafter). A parameter called "factor of deviation" (FOD, Mihailovic *et al.* 1993) is taken in as the second additional criterion. The FOD is defined as follows:

$$\mathbf{FOD} \equiv \frac{\sum_{n} \left| A_n - B_n \right|}{\sum_{n} \left(\left| A_n \right| + \left| B_n \right| \right)}$$

where **n** is the quantity of variables **A** and **B**. FOD = 1.0 stands for a total discrepancy of **A** with respect to **B**, FOD = 0.0 for a total resemblance of **A** and **B**. In this study, **A** is the Tbb of the TGT1 and **B** is the Tbb of one of the possible targets in the search domain.

A possible target among the many 7×7 pixels areas in the search domain is said to be "similar" to the one in the previous image needs to meet three conditions simultaneously. To become TGT2, a possible target in the search domain needs to meet three conditions: (1) minimum Tbb square difference, (2) maximum Tbb correlation coefficient, and (3) minimum FOD of Tbb with respect to TGT1. By this way, the initial quality of the CMV in this study would be better than that in the CIMSS CMV-retrieving algorithm, which uses only the minimum square difference of Tbb to locate the most "similar" target in the succeeding image.

4. Height assignment of the CMV

The height assignment of the CMV, or equivalently the cloud-top heights, has been a long-lasting challenging task since the origin of the CMV as a result of the uncertainty of satellite observations. Fritz and Winston (1962) developed the IRW method that became the pioneering method of assigning heights to the cloud-tops. The mean value of the coldest 20% pixels of the IRW channel cloud-top Tbb within a target area is defined as the temperature of the target area (Nieman *et al.*, 1997). The vertical temperature profile at the central latitude and longitude of the target is attained by interpolating the temperature fields from a NWP model. In this application the first guess and forecast fields of temperature and wind from the operational regional model of the CWB are used to get the temperature profile at the grids closest to each preliminary CMV. When the four grids enclosing the geographical location of the preliminary CMV are set, a bi-parabolic interpolation scheme (Manning and Haagenson 1992) is used to perform the horizontal interpolation of the temperature and wind fields to the location of the preliminary CMV. The interpolated temperature fields at the two adjacent pressure levels in the model comprising the temperature of the preliminary CMV are used to do the vertical interpolation to get the corresponding pressure level for the preliminary CMV. Additionally, the corresponding interpolated wind vector, from the numerical model, at the spot of the preliminary CMV is obtained in order to execute a simple quality control process to the retrieved preliminary CMV as will be discussed in the following Section. It should be noted that the work of the vertical interpolation is that: (1) the temperature is in linear relationship to the logarithmic pressure (*ln* pressure), (2) the wind vector is linear with respect to the pressure level.

5. A simplified quality control process

The quality control procedure in the CIMSS CMV-retrieving algorithm is rather sophisticated and is well documented (Nieman *et al.*, 1997). A fairly simple quality control procedure by referring the wind fields from the operational regional model of the CWB is applied in this study to provide qualitative CMVs as one of the aids for subjective forecast of typhoon tracks. The preliminary CMV retrieving process and the use of the rather simplified simple quality control procedure applied in this study consume less than 2 hours of computer time in a DEC Alpha machine for an IRW image of 1024 X 1024 pixels covering the eastern Asia.

As discussed in Section 3, an acceleration check of ruling out the CMVs whose first and second preliminary CMV have more than 5.1 m/s of speed difference is the first step of the quality control procedure. The second step of the quality control in this study is that: Once the pressure altitude of a preliminary CMV is specified, the same interpolation scheme is used to obtain the wind vector at the location of that preliminary CMV utilizing the same numerical model's output of the wind fields. A buddy check procedure as used in the objective analysis process for the Penn State/NCAR MM5 model is referred (Manning and Haagenson 1992) to get rid of the preliminary CMV which is too far apart from the wind vector from the numerical model in either the direction or speed. When the absolute difference of wind direction between the retrieved preliminary CMV and the interpolated wind vector is greater than 30 degrees, the retrieved preliminary CMV is discarded. For the case of the CMV below 500 mb: when the absolute difference of wind speed between the CMV and the corresponding interpolated wind vector is greater than 17.5 m/s, the retrieved CMV is discarded; for the case of the CMV above 500 mb: when the absolute difference of wind speed between the CMV and the corresponding interpolated wind vector is greater than 21.0 m/s, the retrieved CMV is discarded.

6. Case studies

Two case analyses to examine the quality and usefulness of the retrieved CMVs are performed. More cases of typhoons will be collected and the relationship between the CMVs and the tracks of typhoons will be analyzed in this continuing study.

a. Typhoon **Sam** (12UTC August 19 to 12UTC August 21, 1999)

The CWB issued the first sea warning of typhoon Sam at 12UTC of August 19 forecasting a northwest movement of Sam. The corresponding CMVs at 12UTC of August 19 are shown in Fig. 1a. In this figure the CMVs between surface and 700.0 mb (low-level) are shown in red; the CMVs between 700.1 and 400.0 mb (mid-level) are shown in yellow; the CMVs between 400.1 and 100.0 mb (high-level) are shown in blue. Sam was not intensive enough (intensity of tropical storm only), such that the steering flow of Sam should reside in the mid-level (Velden *et al.*, 1998). There was a mid-level anti-cyclonic flow prevailing north of Sam, which would prevent Sam from a northward movement. One also notices that the low- and mid-level CMVs above Taiwan island were easterlies. These all suggested that the short-term moving direction of Sam after 12UTC of August 19 would be the west. For the purpose of comparison, the CMVs derived by the CIMSS at the same time are in Fig. 1b, which covered the entire north Pacific. It is noted that the flow patterns close to Sam shown in Fig. 1a were essentially comparable to those in Fig. 1b. The mid-level anti-cyclonic flow centered at the ocean east of Japan at 12UTC of August 19 moved westward at 00UTC August 20 with the center of Sam being in southern Taiwan Straight. The low- and mid-level CMVs north of Sam principally remained easterlies, such that Sam kept moving toward the west. The mid-level anti-cyclonic flow at the ocean east of Japan retrograded at 12UTC August 20. Subsequently, the steering flows of Sam became southeasterlies. This indicated that the short-term moving direction of Sam would turn to be northwest. The flow patterns ahead of Sam varied very much at 00UTC August 21. An anti-cyclonic circulation appeared to the northeast of Sam. The mid-level flow features revealed by the CMVs just north of Sam suggested that Sam could move either to the west or southwest at this moment and had no possibility of intensification. In the meantime, a systematic forecast error of recurring paths of Sam by the typhoon forecast system (TFS) is clearly shown due to a much weaker and retrogressive prediction of the mid-level anti-cyclonic flow located north of Sam.

b. Typhoon **Wendy** (00UTC September 3 to 00UTC September 4, 1999)

Wendy was a very short-lived typhoon, lasting for less than 24 hr. Before 00UTC September 3, Wendy was a tropical depression (TD_W, hereafter) moving northwestward, along the edge of a mid-level ridge crossing the Taiwan island, as shown by the CMVs valid at 00UTC September 1 (Fig. 2). One also recognizes that there was an upper-level high-pressure system dominated on top of the TD_W at 12UTC September 1. Moreover, there were vertical wind shear zones surrounding the TD_W. These all revealed that the intensification of the TD_W would be limited. The mid-level ridge still prevailed to the north of the TD_W at 00UTC September 2, such that the possibility of a further northwestward movement of the TD_W was slim. The mid-level wind fields north of the TD_W continued to be easterlies or east-north-easterlies at 12UTC September 2, therefore, the moving direction of the TD_W, centered on the Bashi Channel, tended to be west or west-southwest. The TD_W was upgraded as typhoon Wendy at 00UTC September 3 with ambient mid-level wind fields of easterlies. The mid-level steering flow of Wendy went on to be easterlies at 12UTC September 2. As a result, Wendy kept moving to the west and landed Hong Kong approximately at 12UTC September 2.

7. Summary and conclusions

It is the first effort in the CWB to develop a CMV-retrieving system as one of the useful tools to forecast the tracks of typhoons. The present state of using the IRW method to assign the heights of the CMVs is outlined in this article. Two cases of typhoon track analyses utilizing the retrieved CMVs are shown to reveal the practical, successful but qualitative application of the CMVs.

To ensure a better initial quality of the CMVs, the mean square difference, FOD and correlation coefficient are used to determine the similarity between the TGT1 and TGT2. In this study the IRW method is utilized to assign the heights of the CMVs. The temperature and wind fields from the first guess of the operational regional model in the CWB are referred to assign the pressure altitudes of the CMVs. A simple quality control procedure is designed, such that the CMVs with questionable speeds or directions are removed according to the wind fields of the regional model of the CWB. Two cases of typhoons are presented to qualitatively study the feasibility of using the CMVs to aid the analyses of typhoon paths. It showed that the CMVs were good at specifying the mid-level steering flows of the typhoons Sam and Wendy of 1999. It turned out that the variation of CMVs with time became a very important guidance for the judgement of the short-term path of Sam. For these two typhoons of tropical storm intensity, the mid-level steering flow (Velden *et al.*, 1997) were fundamentally easterlies. This suggested that the typhoons would primarily move toward the west. Viewing the subsequent imageries, one did find the westward movement of the typhoons. With large-scale anti-cyclonic flows dominating in the upper-level atmosphere, which are prohibitive to the further intensification of typhoon, it then can be certain that there was limited possibility for the further growth of the typhoon Sam and Wendy. By examining the following imageries, this argument was proved to be true. The above discussion indicates the qualitative correctness and usefulness of the CMVs retrieved in this study to the short-term prediction of the typhoon tracks.

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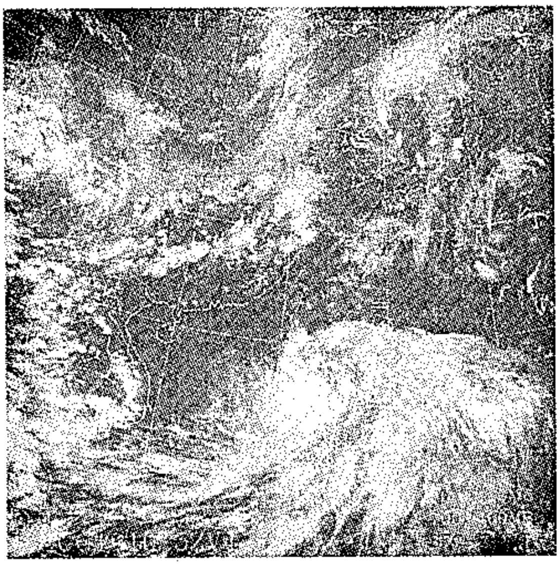

Fig. 1a The CMVs retrieved in this study covering the eastern Asia, valid at 12UTC August 19, 1999.

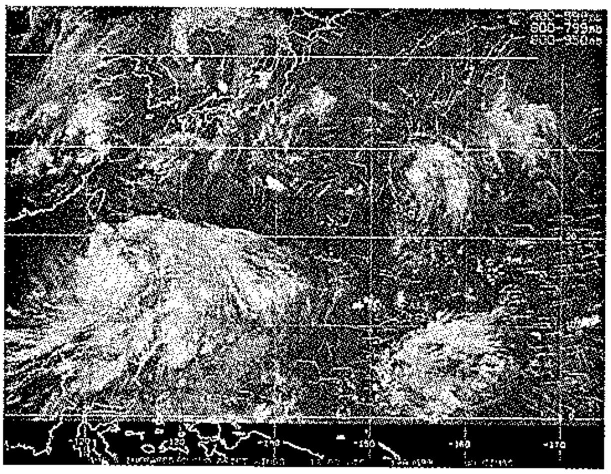

Fig. 1b The CMVs retrieved by the CIMSS covering the north Pacific Ocean, valid also at 12UTC August 19, 1999.

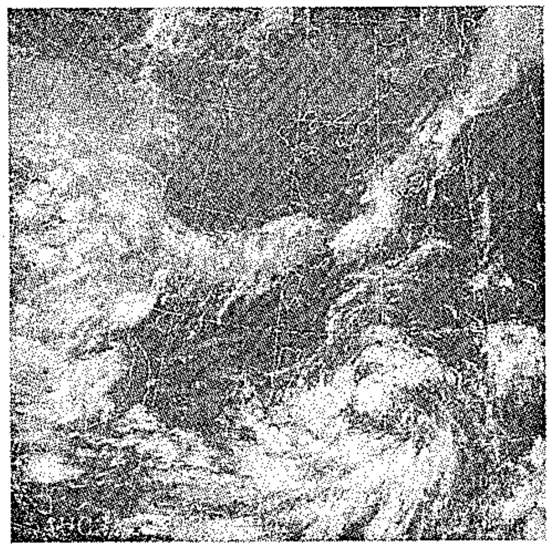

Fig. 2 The CMVs retrieved in this study covering the eastern Asia, valid at 00UTC September 1, 1999.