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ON THE DIRECTION OF MOVEMENT OF TROPICAL CYCLONES

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ABSTRACT

Analysis of a sample of independent data consisting of 68 satellite cloud photographs of tropical cyclones in the north Australian region has confirmed the general validity of the forecasting guidelines suggested by Lajoie and Nicholls (1974). The asymmetric cloud distribution around the storm with respect to the cyclone centre and its direction of movement is shown to agree with the mean low-level divergence pattern around the cyclone. A method for forecasting the direction of motion of a tropical cyclone from satellite cloud pictures is discussed.

INTRODUCTION

In a preliminary study of high-quality television satellite pictures of well-defined cloud vortices associated with tropical cyclones operating in the northern Australian region, Lajoie and Nicholls (1974) found that outside the central cloudmass surrounding the vortex centre, cyclone cloud systems contain characteristic features that can be used for short-term forecasting of the direction of movement of the storm centre. These significant cloud features, 200 to 600 km away from the vortex centre, are illustrated schematically in Fig 1. For the definition and detailed description of the cloud features the reader is referred to Lajoie and Nicholls's paper. Their main conclusions are summarised. The outer cloudbands are entities separate from the central cloudmass, abruptly end, in general, in one of the southern quadrants, and have more developed cumulonimbus clouds at or near their downstream ends. Three short-term forecasting guidelines were suggested. First, a tropical cyclone does not continue to move, or curve, towards any direction within a cumulonimbus-free sector; if moving in such a direction at or just prior to picture time it will curve away from that direction within twelve hours of picture time. Second, a tropical cyclone centre moves or curves within twelve hours of picture time, towards a direction given by a line joining the current position of the vortex centre to the current position of the most developed cumulonimbus cluster at or near the DEOC (downstream end of the outer cloudband). Third, when a tropical cyclone has two outer cloudbands and is moving at, or just prior to, picture time roughly towards the most developed cumulonimbus cluster near the downstream end of one outer cloudband it will curve within twelve hours of picture time towards the most developed cluster of the other outer cloudband.

The purpose of this paper is to discuss the results of the analysis of a sample of independent data, to present some evidence for the validity of the empirically determined cloud model of Fig 1, and to suggest an operational method for the short-term forecasting of the direction of motion of a tropical cyclone from satellite pictures.

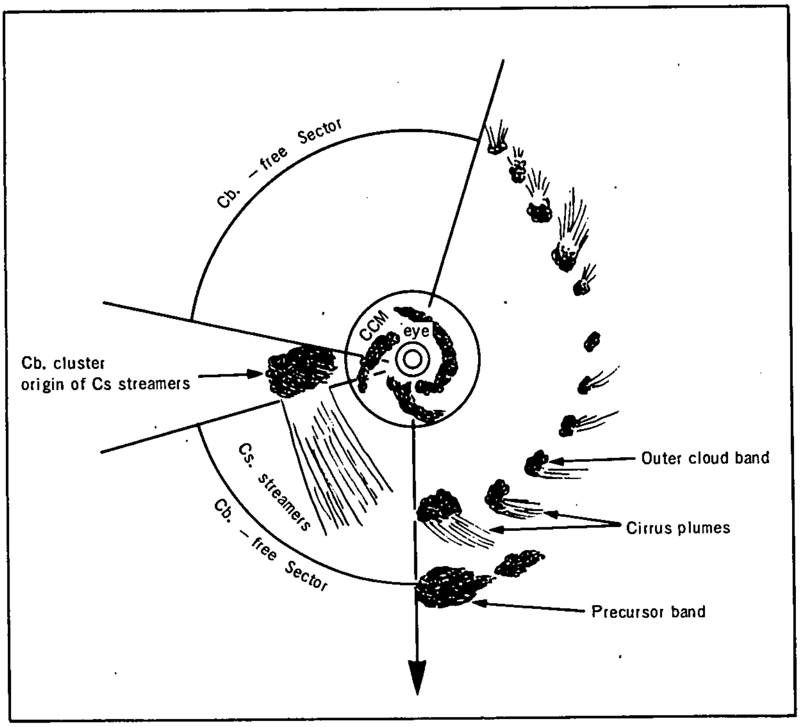


Fig 1 Model cloud structure of a tropical cyclone moving towards the direction shown by the arrow (after Lajoie and Nicholls (1974)). Principal features are:

(a) central cloud mass, CCM (diameter 100 to 200 km, changes configuration with time and from one picture to the next)

(b) one or two outer cloudbands (separate from central cloud mass, cumulonimbi more developed at downstream end, pattern remains unchanged for several hours)

(c) precursor band (downstream end occurs along the same outward radius as that of the outer cloudband)

(d) one or more cirrostratus streamers

(e) cumulonimbus–free sectors

DATA AND METHOD OF ANALYSIS

Satellite pictures for the 1969-70 and 1970-71 cyclone seasons were not used by Lajoie and Nicholls (1974) and hence were used as a sample of independent data to test the general validity of their results. In these two cyclone seasons there were in the north Australian region 68 well-defined satellite pictures of cloud vortices associated with sixteen tropical cyclones. The pictures were analysed in a manner similar to that described in the previous paper. The bearing relative to the vortex centre of the most developed cumulonimbus cluster at or near the DEOC was measured to the nearest five degrees. The directions of motion of the tropical cyclones at various times were obtained from published tracks, prepared after careful post-analysis of all available data.

RESULTS

Cumulonimbus-free sector systems

Many of the 68 cloud systems had cumulonimbus-free sectors. In 28 cases the sectors were clearly defined, with practically no clouds from the edge of the central cloudmass to about 600 km from the vortex centre. In none of these 28 cases did the tropical cyclone move or curve within twelve hours of picture time towards a direction within the cumulonimbus-free sector, in good agreement with the first forecasting guideline.

Single outer-cloudband systems

There were 63 cloud systems with single outer cloudband. In 32 cases the cyclone was moving along a straight track in the 12-hour interval following picture time. Angular deviations between the direction of motion and the measured bearing of the most developed cumulonimbus cluster at or near the DEOC were within ±15 degrees, the RMS angular deviation being 6.4 degrees.

Of the remaining 31 cases, 28 cyclones curved from their direction of motion at picture time to move in a direction parallel, within 10 to 15 degrees, of the measured bearing within 12 hours. In the three other cases the change in direction of motion was quite large, 50 to 125 degrees, and occurred 12 to 16 hours after picture time. Data for the 31 cases are shown in Fig 2. The direction of motion at picture time (circles) and that 12 hours later (squares) (16 hours later for the three cases mentioned above) were plotted against the respective bearing relative to the vortex centre of the most developed cumulonimbus cluster at or near the DEOC. Points plotted on the 45° line correspond to data when the direction of motion was exactly parallel to the measured bearing. Arrows joining the circles to the squares indicate the magnitude and sense of the changes in direction of motion in the 12-hour period following picture time. The change in direction of motion towards the measured bearing is particularly striking. There was only one case (measured bearing 240°) in which there was a reversal of the general trend; but the change was rather small, only 10 degrees. For these 31 cases, the r.m.s. angular deviations and correlation coefficients between the measured bearings and the respective directions of motion were 39.5 degrees and 0.77 for motion at picture time and 8.0 degrees and 0.97 for motion 12 hours after picture time. Within the limits of accuracy of the data this result is in good agreement with the second forecasting guideline.

An example is now given, the case with the largest change in direction of motion in Fig 2, measured bearing 130 degrees, being chosen. It corresponds to data for tropical cyclone Mavis, which operated in the vicinity of the northwest Australian coast in March 1971. Its cloud system at 0126 GMT on 26 March and its track are shown in Fig 3. At picture time Mavis had a well-defined outer cloudband and a percursor band, the bearings of the downstream ends of both bands being 130 degrees. At picture time the cyclone was moving along 245 degrees but 12 to 16 hours after picture time it curved sharply to move along 120 degrees.

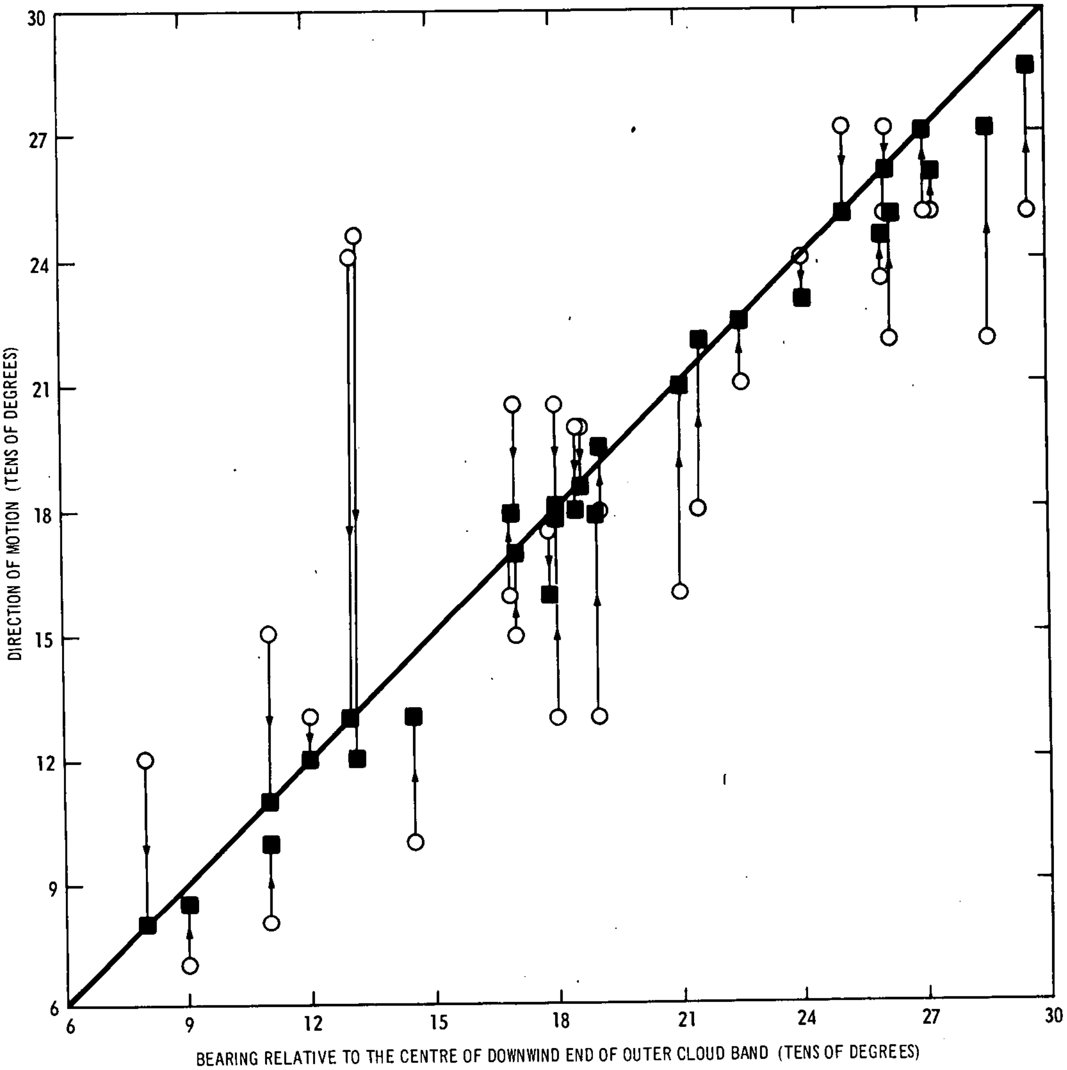


Fig 2 The direction of motion of tropical cyclones at the time of the satellite picture (○) and 12 hours after that time (■) plotted against the respective bearing relative to the vortex centre of the downstream end of the outer cloud band. The straight line is a line of unit slope. Each arrow indicates the change in direction within 12 hours of picture time

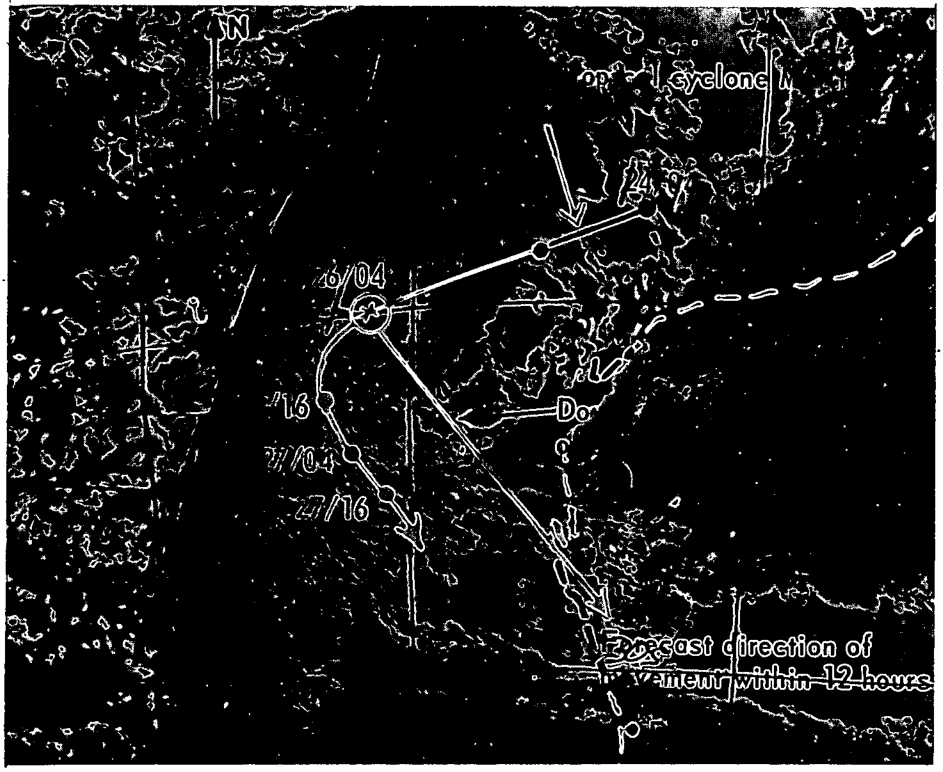


Fig 3 Satellite picture of tropical cyclone Mavis taken on 26 March 1971 at 0126 GMT. The Australian coastline is shown by a broken line. The solid line represents the track of the cyclone from 24 to 27 March, the dates and times along the track are in GMT. At picture time the bearing of the downstream end of the outer cloudband (approximately) 500 km from the cyclone centre) was 130°. The cyclone was then moving towards 245° but changed course 12 to 16 hours later to move along 120°

'Double' outer cloudband systems

There were only five systems that had two outer cloudbands ending in different directions from the vortex centre. In each of these cases the direction of movement of the cyclone was within ±10 degrees of that specified in the third forecasting guideline.

The origins of cirrostratus streamers

Another cloud feature examined in the cloud photographs was the bearing relative to the vortex centre of the origins of cirrostratus streamers. In 44 of the 68 pictures the origins were outside the central cloudmass and hence could be analysed. These were found to be, within 10°, at right angles to and to the right of the bearing relative to the cyclone centre of the downstream end of the outer cloudband, as illustrated in Fig 1. Of the 44 cases there were eight that had two cirrostratus streamers, the second having an origin 120 to 145 degrees to the right of the downstream end of the outer cloudband.

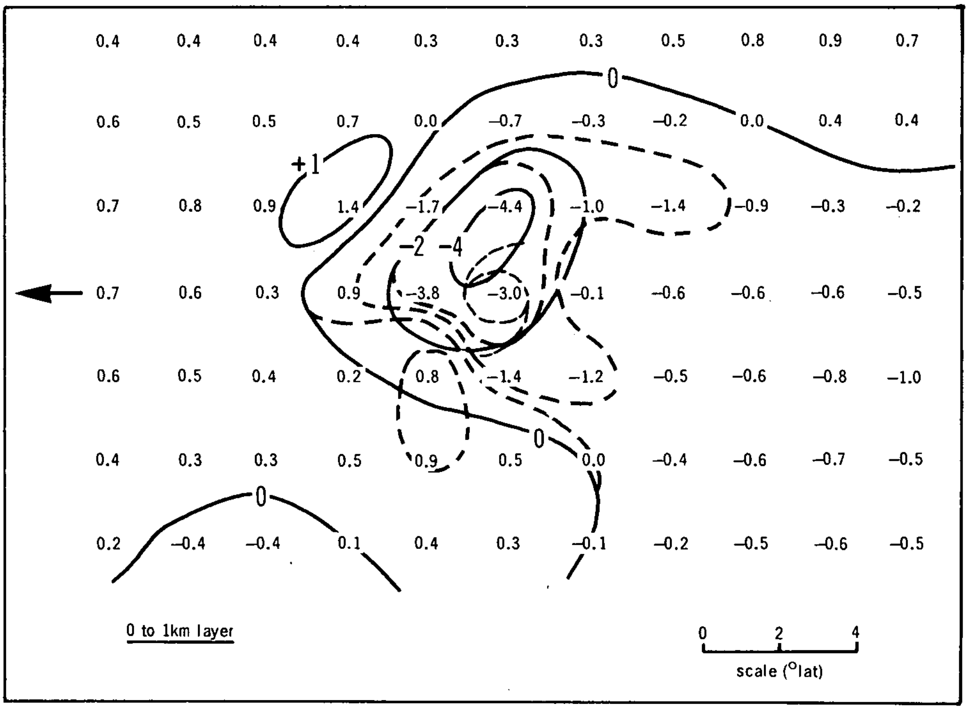
Hence the cirrostratus streamers can provide a useful aid in the identification of the features of the satellite cloud photograph.

JUSTIFICATION FOR THE MODEL CLOUD DISTRIBUTION

Some evidence for the validity of the model cloud distribution of Fig 1 can be found in the distribution of the mean low-level divergence around a tropical cyclone. Because of the lack of data in the southern hemisphere, the mean large-scale low-level divergence field around six North Atlantic hurricanes, determined by Miller (1958), has been considered. This divergence field, Fig 4, was determined from observed winds in the 0 to 1 km layer. Miller's technique was to first transform the wind observations to a coordinate system in which the origin was the hurricane centre and one of the axes lay along the average direction of motion of the storm, the averaging being performed in the period 6 hours before to 6 hours after the time of the wind observation. The resulting winds were then grouped in two-degree latitude squares around the storm centre and averaged. The size of the squares was chosen to exceed that of the average hurricane, in order to obtain the mean flow just outside the vortex circulation in relation to the storm's motion. Since during most of their lifetimes these six hurricanes moved along practically straight tracks, Fig 4 can be regarded as representative of the divergence field associated with a storm moving along straight tracks, or in the context of this paper, for a storm having a single outer cloudband.

According to Riehl (1954, p. 290), the procedure of averaging the winds along a fixed direction of motion of the storm preserves systematic asymmetries introduced by or associated with the storm's motion. The areas of low-level convergence and hence active convective clouds around the storm should therefore show up in the mean divergence field if these areas occur in the same positions with respect to the storm centre and to its direction of motion.

A close examination of the divergence values in Fig 4, however, reveals that two divergence values on the left front quadrant of 0.8 and $0.9 \times 10^{-5}\ s^{-1}$ have been disregarded. Using Miller's average winds, the divergence values have been recomputed and verified. Since in each of the squares of the left front quadrant between 200 and 600 km the number of wind observations ranged from 14 to 43 and the wind persistence varied from 86 to 95 per cent, these two relatively high values of divergence may be real. The large-scale divergence field could therefore be represented by the dashed isopleths in Fig 4, that is, with a marked divergence maximum in the left front quadrant.



0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.5	0.8	0.9	0.7
0.6	0.5	0.5	0.7	0.0	−0.7	−0.3	−0.2	0.0	0.4	0.4
0.7	0.8	0.9	1.4	−1.7	−4.4	−1.0	−1.4	−0.9	−0.3	−0.2
0.7	0.6	0.3	0.9	−3.8	−3.0	−0.1	−0.6	−0.6	−0.6	−0.5
0.6	0.5	0.4	0.2	0.8	−1.4	−1.2	−0.5	−0.6	−0.8	−1.0
0.4	0.3	0.3	0.5	0.9	0.5	0.0	−0.4	−0.6	−0.7	−0.5
0.2	−0.4	−0.4	0.1	0.4	0.3	−0.1	−0.2	−0.5	−0.6	−0.5

Fig 4 Mean large–scale divergence (10^{-5} sec^{-1}) in the 0 to 1 km layer around tropical cyclones in the North Atlantic obtained from average winds along sides of squares 200 x 200 km after Miller (1958). Heavy isopleths represent the large–scale divergence field around the storm with respect to its direction of motion shown by the arrow on the left. A re–analysis of Miller's divergence values by the author is shown by the dashed isopleths

If the revised divergence pattern of Fig 4 is now 'inverted' to correspond to conditions in the southern hemisphere and rotated through 90° to correspond to the divergence field associated with a storm moving south, Fig 5 would result. When the latter is compared with Fig 1 the following features 200 to 600 km from the cyclone centre become evident:

(a) the large area of appreciable convergence in the left front quadrant corresponds to the most frequent relative positions of the outer cloudband and the precursor band, both of which have been observed at distances varying from 200 to 600 km from the cyclone centre;

(b) the abrupt change from strong convergence on the left to appreciable divergence to the right of the direction of motion agrees well with the observed abrupt ending of the outer cloudband and precursor band along the direction of motion;

(c) the appreciable divergence in the right front quadrant occurs in the same relative position as that of the cumulonimbus-free sector.

It seems also that a 'tongue' of appreciable convergence exists 100 to 200 km from the storm centre at right angles to and to the right of the direction of motion in a position corresponding to that of the origin of the cirrostratus streamers.

OPERATIONAL APPLICATIONS

A rather large and high-quality picture is required to perform the detailed cloud analysis. The size of the picture should preferably be such that five degrees of latitude has a span of at least 3 cm. A high quality picture can be obtained by careful photographic processing or by printing a number of copies of the same picture with different exposure times and selecting the one with optimal contrast between clouds of different types. Then, using a transparent overlay, the following features are determined and outlined:

(a) the vortex centre;

(b) the boundary of the central cloudmass (this must not exceed 200 km in diameter);

(c) the positions of all the individual cumulonimbus clusters from the edge of the central cloudmass to about 600 km from the centre;

(d) the positions of the cirrostratus streamers and their origins;

(e) the position of the outer cloudband (see the various patterns of outer cloudbands in Fig 2 of Lajoie and Nicholls (1974));

(f) the position of the most developed cumulonimbus cluster at or near the DEOC (note the downstream end of a precursor band often helps in determining the DEOC);

(g) all cumulonimbus-free sectors;

(h) check that items (f) and (d) fit the cloud model of Fig 1, that is, whether the origin of the cirrostratus streamer, when this can be located, is roughly at right angles to, and to the right (in the southern hemisphere) of the downstream end of the outer cloudband;

(i) check that the cloud analysis of the previous picture and the updated trajectory satisfy the forecasting guidelines - if it does not either the previous cloud analysis or the direction of motion is incorrect, resolve this difference before proceeding further;

Fig 5 Pattern of low-level divergence around a tropical cyclone in the southern hemisphere with respect to its direction of motion shown by the arrow. This pattern was obtained after inverting the revised divergence field of Fig 4 and rotating it through 90°

(j) note the changes if any in cloud features (c) to (g) that have occurred since the previous picture;

(k) use the forecasting guidelines to forecast the direction of motion.

The above forecasting method should give reliable results when the cyclone centre can be accurately located and the detailed cloud analysis can be performed. However, some skill in cloud interpretation and analysis must be developed if the method is to be used successfully. Until an objective method of cloud analysis is available it is suggested that the method be used to supplement other methods currently employed and results given such weight as may be considered appropriate in the light of all relevant data.

CONCLUDING REMARKS

This investigation has provided general support for the short-term forecasting guidelines of Lajoie and Nicholls (1974), namely that a tropical cyclone does not move or curve in any direction within a cumulonimbus-free sector, but moves or curves within 12 hours of the time of the satellite picture in a direction given by the bearing of the DEOC relative to the vortex centre. The independent data sample indicates that the bearing of the DEOC gives the direction of movement within ±15 degrees. There were also three cyclones which recurved 12 to 16 hours after picture time but because of uncertainties in the accuracy of the tracks it is not possible to discuss this difference.

The asymmetric cloud distribution around the tropical cyclone with respect to its direction of movement corroborates well the revised version of the mean divergence field around a tropical cyclone. Outer cloudbands, and the cumulonimbus clusters originating the cirrostratus streamers, are associated with appreciable low-level convergence while the cumulonimbus-free sector is associated with low-level divergence. Strong convergence to the left and divergence to the right of the direction of motion (in the southern hemisphere) confirm that the bearing of the DEOC relative to the cyclone centre coincides with the direction of motion of the cyclone centre.

Even though the guidelines can reliably be used only for a short-term prediction, their importance can be of great assistance operationally. For example, on 29 March 1975 tropical cyclone Beverley was 540 km northwest of Exmouth on the northwest Australian coast and was moving west, that is, away from the coast. But because the satellite picture received later on that day indicated a DEOC southeast of the vortex centre, the Perth Tropical Cyclone Warning Centre forecast a sharp recurvature and immediately warned the township of Exmouth of the imminent danger. The cyclone did curve sharply to a southeasterly direction a few hours later and passed over Exmouth on the following day with a maximum sustained wind of 117 km/h and maximum gusts of 152 km/h. This was the first operational success of the forecasting guidelines, the use of which gave more time for the township to prepare itself and to take more precautionary measures than would have been possible otherwise.

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