SOME ASPECTS OF TROPICAL CYCLONE MOVEMENT
AND FORECASTING

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I.  INTRODUCTION

At the Brisbane conference on tropical cyclones in 1956 there was considerable
discussion on the factors influencing the movement of tropical cyclones. Even the
influence of the $\beta$ - effect was in dispute. Rossby (1948) derived a poleward tendency
from this cause whilst Bjerknes and Holmboe (1944) derived a westward influence.
Ramage (1956) reported that he found no significant correlation between tropical
cyclone size and poleward movement. In the intervening 25 years much more information
on tropical cyclones and their environment has been acquired but our understanding of
the mechanisms determining the movement of these storms has changed little. At the
Perth conference on tropical cyclones in 1979, Anthes (1979) summarised the conclusions
from asymmetric hurricane models in the words "The effect of the variation of Coriolis
parameter with latitude ( $\beta$ -effect) is to cause a northwestward drift of the storm
at a speed of 1-2 m/s".

It is the purpose of this paper to point to some factors that influence
tropical cyclone motion. In addition, some of the limitations that currently
impede progress in tropical cyclone movement forecasting are highlighted and, in
some cases, methods to overcome them are suggested.

II.  LOCATING THE TROPICAL CYCLONE

It is often thought that the problem of locating a tropical cyclone
was solved by the introduction of satellites. However, the accuracy of fixes from
gestationaly satellites is considered to be about 40 km (WMO 1979) - an error
of this magnitude will itself give rise to maximum 24 h forecast errors of 80 km!
It has been shown that the average error between fixes in best tracks published
by JTWC Guam and the Japanese Meteorological Agency, was 45 km for 274 positions at
1200 GMT during 1977-78. Over 5% of "best" positions differed by more than 110 km
(Bell 1979).

Further errors arise when objective analysis techniques are applied to
tropical cyclones to produce the initial chart for numerical prediction (NWP)
models. Observed central pressure and contour values in tropical cyclones cannot be
included in conventional objective analysis techniques without causing gross
distortions of the fields over a wide area. In addition, the uneven distribution
of observations around a cyclone centre can cause displacement of the vorticity
centre by several degrees (Elsberry 1978, Bell 1979) as is shown in my film of
computer animated charts. The problem is exacerbated insofar as the Global
Telecommunications System (GTS) does not currently carry to the major computing
centres all the observations in the cyclone environment which are both available
and necessary to define the circulation. This point is dramatically illustrated
in Fig. 1.
Fig. 1. Tropical-cyclone-centred composite 500 mbar height analyses for (a) 999 fields (1946-69) hand-drawn or objectively analysed by a successive-correction scheme and (b) 78 fields from the U.S. National Meteorological Centre 1978 operational computer files. (Redrawn from originals by P.W. Leftwich in Lawrence 1979.)

III. STORM MOTION

The motion of more than 2000 tropical cyclones in the western Pacific was examined to see if it showed evidence of any dependence on size and intensity such as would occur in a symmetrical vortex due to the $\beta$-effect. There is, in general, a contribution to storm displacement due to the broad scale flow, tropical cyclone acceleration has therefore been considered, in addition to displacement, as it is expected to be less dependent on contributions from steady steering and interaction. South of $30^\circ$N the average poleward acceleration of large cyclones ($r > 4.4^\circ$) is $0.73^\circ$ lat/24 h/24 h or more than twice that of small cyclones ($r < 1.4^\circ$). Poleward acceleration and cyclone size are significantly correlated (Table 1) in the sense indicated by the Rossby effect. Poleward displacement is also strongly correlated with cyclone intensity. However, the data do not show poleward acceleration to be correlated with cyclone intensity. These and other interesting facts are illustrated in Table 1. Although the significance of some of the correlations shown is very high the correlation coefficients are small so that these factors contribute little to the variance of tropical cyclone motion and find no place as inputs to current forecast methods.

There are significant departures of storm motion from the volume averaged steering current (Bell 1979). This subject is pursued in another paper but the film illustrates these departures and also shows the strong diurnal variation in fields of geopotential which sometimes may be reflected in storm tracks.
Table 1. Correlation coefficients (r) and their significance (sig.) for the relationships between the 24-hour movement and acceleration of typhoons and their size and intensity. Number of pairs N.

<table>
<thead>
<tr>
<th>Latitude of centre</th>
<th>MOVEMENT</th>
<th>ACCELERATION</th>
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<tbody>
<tr>
<td></td>
<td>Poleward</td>
<td>Eastward</td>
</tr>
<tr>
<td></td>
<td>r</td>
<td>N</td>
</tr>
<tr>
<td>0-9.9</td>
<td>0.13</td>
<td>352</td>
</tr>
<tr>
<td>10-19.9</td>
<td>0.076</td>
<td>2552</td>
</tr>
<tr>
<td>STORM RADIUS</td>
<td>0.053</td>
<td>1383</td>
</tr>
<tr>
<td>20-29.9</td>
<td>0.017</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All lat.</td>
<td>0.079</td>
<td>4415</td>
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</tbody>
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| STORM INTENSITY*  |          |     |      |          |     |      |          |     |      |
|                   | -0.31    | 80  | %    | -0.30    | 80  | %    | -0.029   | 65  | n.s. | -0.25    | 65  | 5%   |
| 20-29.9           | -0.14    | 993 | <0.1%| 0.047    | 993 | n.s. | 0.022    | 915 | n.s. | -0.066   | 915 | 5%   |
|                   | -0.16    | 893 | <0.1%| 0.037    | 893 | n.s. | -0.047   | 865 | n.s. | -0.12    | 865 | <0.1% |
| 330               | -0.40    | 93  | <0.1%| 0.029    | 93  | n.s. | -0.28    | 90  | 1%   | -0.21    | 90  | 5%   |
| All lat.          | -0.15    | 2059| <0.1%| 0.056    | 2059| 2%   | -0.026   | 1933| n.s. | -0.058   | 1933| <0.1% |

* Storm central pressure less than or equal to 980 mbar.

IV. NUMERICAL METHODS

The formation, intensity and movement of tropical cyclones are governed by large-scale circulation patterns. It is therefore to the numerical prediction of these patterns that we must look to improve forecasts for 48 h or more ahead. Indeed, these patterns also control 24-h forecast errors. For this reason, the interannual variability of the annual average forecast errors for any warning centre or for any method are greater than the differences between methods or centres (Bell 1979). For example, although the JTWC at Guam and the Royal Observatory, Hong Kong had nearly equal errors in 1977 and 1978 (Fig. 2) the annual averages for these years differed by 100 km (260-160 km). The control of the large scale circulation patterns does not usually show up well in monthly or seasonal averages. Nevertheless, the Japanese index of the zonal circulation (90° - 170°E) in the relatively high latitude band of 40° to 60°N when averaged over the months July to September correlates (r = 0.53 significant at the 5% confidence level) with the average Hong Kong forecast errors for the same months over the 17-year period 1963-1979.

There has been very little improvement, if any, in average forecast errors over the last decade and warning centres are still hard pressed to improve on the forecasts given by a simple combination of persistence and climatological movement (Bell 1962).
Fig. 2. Position errors in 24 h tropical-cyclone forecasts in the western North Pacific. The forecasts from Guam are issued earlier than those from Hong Kong.

From the operational viewpoint, regional NWP tropical-cyclone forecast models are of little value as their failures and successes follow those of simpler and more timely methods. A forecast for only one level has similar disadvantages. It is therefore necessary to use a three-dimensional moving grid (MNG) in a global model with interaction at the boundaries. The need for this approach is illustrated by Fig. 3 which shows how the forecast track of typhoon Pamela 1976, in a $60^\circ \times 40^\circ$ domain, was improved when a one-way (OW) interactive model replaced one with cyclic (CH) boundary conditions. Boundary values were interpolated from 0000 and 1200 GMT analyses. Pamela recurved on interacting with an approaching mid-latitude trough - a feature not observed in the domain of the CH model.

Fig. 3. Forecast positions at 12 h intervals up to 72 h for typhoon Pamela 1976 made with nested grid models having channel (CH) type cyclic and one-way (OW) interactive, boundary conditions (From Hodur and Burk 1978).
V. CONCLUSION

It has been indicated that:-

1) There is still an uncertainty in the precise location of a tropical cyclone centre;
2) There are departures from geostrophic steering; and
3) The broadscale flow pattern and steering change over a 24 h period.

For these and other reasons conventional synoptic/statistical 24 h forecast methods are difficult to improve further and are generally considered to be at or near their limit.

NWP methods are unlikely to improve on conventional ones over a 24 h forecast period because of:-

1) The uncertainty of the initial position;
2) Objective analysis distortions;
3) Lack of relevant data at NWP centres; and
4) Lack of timeliness.

There are indications that at 48 h and longer a moving fine mesh grid nested in a global model could provide forecasts significantly better than those currently available.

However, means must first be found to:-

1) Get all data from within and around tropical cyclones to the major NWP centres; and
2) Assimilate the off-time, off-level information provided by SATEM, ASDAR, satellite winds and aircraft reconnaissance.

Only in this way can the tropical cyclone be adequately defined and resolved (Fig. 1). To achieve assimilation in a timely and satisfactory way requires that a dynamic initialisation system be used on both the global and fine mesh grid scales. In such systems first guess fields at time \( t_0 - \Delta t \), where \( \Delta t \) is of the order 12 h, are integrated to time \( t_0 \) during which period off-time and off-level observations are used to nudge the forecast model towards reality. Not only does such a system incorporate all observations but it also reduces imbalances at the start of the forecast period thereby improving the quality of short-period forecasts. Such a system is used in the U.K. Meteorological Office's Global Model and was described for the hurricane case by Anthes (1974). Because such models can only be run on high-powered computers they will be found only at major NWP centres. Arrangements must therefore be made to pass all the relevant data over the GTS to these centres.
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