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OPERATIONAL FORECASTING OF TROPICAL CYCLONES: PAST, PRESENT, AND FUTURE

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ABSTRACT

Forecast errors for two warning centres are presented and it is argued that statistical/synoptic methods of forecasting tropical cyclone movement have now been developed as far as is profitable. The effects of uncertainties in the 'best track' and of the large-scale circulation on the determination of forecast errors is discussed. Data are presented on the relationship between the movement of a tropical cyclone and its size and latitude. The need to look to global models for improved forecasts for periods of 48 hours or more is illustrated, but it is shown that current arrangements for the dissemination of observations and current methods of objective analysis of tropical cyclones are both totally inadequate for making useful forecasts for 48 hours or less. It is suggested that synoptic and off-time high resolution observations should be assimilated into a near continuous objective analysis in a domain nested within a global model before improved forecasts for 36 hours and beyond can be achieved.

INTRODUCTION

Prior to the Second World War the centre of a tropical cyclone was located from reports of wind and pressure. Warnings gave the probable location of the centre at a particular time and the velocity with which it was then judged to be moving. As the tropical cyclone approached land, low-cloud movement - often judged by nephoscope - and pressure tendencies were critical for determining probable landfall and intensity. The practice had not changed when I became involved just after the Second World War, but there were three new developments, two of them attributable to US military initiatives. First, aerial reconnaissance had begun; second, networks of upper air soundings were established, and third, 24-h forecasts of storm position were introduced. The latter was a highly controversial issue. Most meteorologists considered that there were neither adequate data nor an accepted methodology on which to base forecasts and that to publicly indicate a future position was, therefore, misleading. Others argued that ships had to be navigated and plans had to be made on the basis of an estimated future storm position and that the meteorologist was best placed to make this estimate. Furthermore, the need to provide such information was expected to stimulate a search for the means.

The first operational technique for forecasting the movement of tropical cyclones was introduced by Riehl et al. (1956) just before the excellent Brisbane Symposium of December 1956. Remarkably, Sasaki and Miyakoda (1954) had already introduced a numerical method for path prediction, but electronic computers were not then generally available to make the method operationally useful. During the next 15 years there came a flood of methods, many of which are still in use today, thereby indicating that no one method is universally satisfactory. It is generally recognised that statistical/synoptic methods have now been developed about as far as is profitable. They have been reviewed in a number of papers, in national handbooks, and in the excellent World Meteorological Organization (WMO) Publication No. 528 (WMO 1979).

FORECAST ERRORS

In 1961 I gave the first analysis of the errors associated with forecast methods (Bell 1962). This exercise has since been voluminously and, in some cases, most sophisticatedly developed, but much of this work is academic and of little value for the operational forecaster. Of course, performance must be assessed but the errors of present forecast methods do not merit extensive sophisticated treatment. My reasons for adopting this view are threefold.

First, forecast errors are determined as departures from a storm's 'best track', which itself suffers from an average uncertainty of about 40 km as shown in Table 1. This average error is about the same as that attributable to fixes from geostationary satellites (WMO 1979) and will alone give rise to maximum 24-h errors of 80 km.

Second, the average forecast error of individual methods is of secondary importance to operational forecasters. Reliability is paramount. A method free from large errors would do more to save a forecaster's reputation - and all that depends on it - than a method that shows a small average error but includes some large ones.

Third, forecast errors are currently influenced more by characteristics of the large-scale circulation patterns than by the choice of forecast method. Most methods and warning centres perform well when the flow pattern in a storm's environment is well-defined and steady. All perform poorly when the environmental flow is ill-defined or unsteady. For this reason, the interannual variability of the annual average errors for any warning centre or for any method are greater than the differences between methods or centres. For example, although Guam and Hong Kong forecasters had near equal errors in both 1977 and 1978 (Fig. 1) the annual average errors for these years differed by 100 km (260 to 160 km).

There has been very little improvement, if any, in average forecast errors over the last decade (Fig. 1). Figure 2 shows that warning centres are still hard pressed to beat forecasts obtained from a simple combination of persistence and climatology (Bell 1962).

STORM MOTION

At the Brisbane conference the influence on storm motion of the constant beta effect was in dispute. The Rossby effect (1948) being a poleward influence while Bjerknes and Holmboe (1944) derived a westward influence. Ramage there reported that he found no significant correlation between storm size and poleward movement and concluded that any effect must be well hidden. Since that time much more information on tropical cyclones and their environment has been acquired but our understanding of the mechanisms determining the movement and intensity of these storms has changed little. There are still many cases in which the causes for the movement or weakening of storms are not clear. After

Table 1 Differences between 'best track' positions of tropical cyclones in the western north Pacific as published by JTWC Guam, the Japan Meteorological Agency, and the Royal Observatory, Hong Kong

Period and time	Total number of observations		Guam - JMA			Guam - RO			JMA - RO		
			Lat.	Long.		Lat.	Long.		Lat.	Long.	
			$\Delta\phi$	$\Delta\lambda$	$[(\Delta\phi)^2 + (\Delta\lambda)^2]^{\frac{1}{2}}$	$\Delta\phi$	$\Delta\lambda$	$[(\Delta\phi)^2 + (\Delta\lambda)^2]^{\frac{1}{2}}$	$\Delta\phi$	$\Delta\lambda$	$[(\Delta\phi)^2 + (\Delta\lambda)^2]^{\frac{1}{2}}$
1977 00GMT	106	Mean	-0.032	-0.108	0.468	0.036	-0.050	0.410	0.068	0.058	0.398
		Standard deviation	0.458	0.552	0.553	0.342	0.511	0.461	0.379	0.436	0.426
		Number of observations greater than 1^o			9			9			7
1978 00GMT	164	Mean	0.012	-0.058	0.313	0.018	0.006	0.321	0.006	0.064	0.314
		Standard deviation	0.250	0.320	0.265	0.313	0.349	0.341	0.269	0.306	0.265
		Number of observations greater than 1^o			3			4			5
1977-78 00GMT	270	Mean	-0.006	-0.074	0.371	0.025	-0.016	0.356	0.030	0.058	0.344
		Standard deviation	0.347	0.414	0.399	0.324	0.420	0.394	0.317	0.354	0.334
		Number of observations greater than 1^o			12			13			11
1977-78 12GMT	274	Mean	0.010	-0.027	0.407	0.009	-0.001	0.378	-0.001	0.026	0.329
		Standard deviation	0.346	0.431	0.374	0.338	0.413	0.376	0.276	0.330	0.278
		Number of observations greater than 1^o			16			16			8
1977-78 00 and 12 GMT	544	Mean	0.003	-0.050	0.389	0.017	-0.008	0.367	0.014	0.041	0.335
		Standard deviation	0.346	0.423	0.387	0.331	0.416	0.385	0.297	0.342	0.307
		Number of observations greater than 1^o			28			29			19

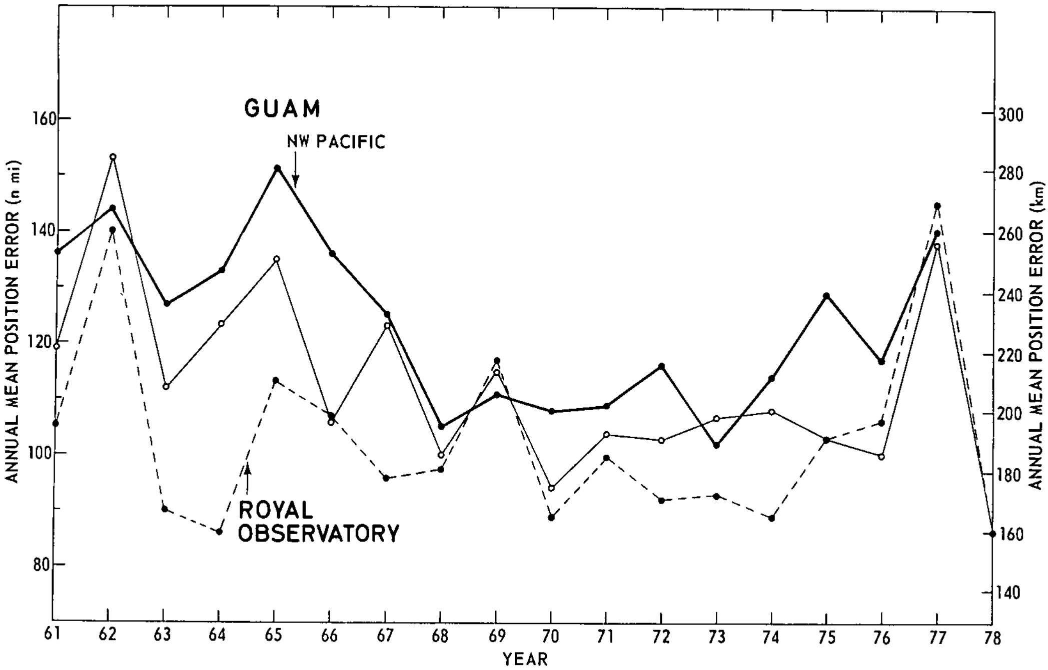

Fig. 1 Position errors in 24h tropical cyclone forecasts in the western North Pacific. The forecasts from Guam are issued earlier than those from Hong Kong.

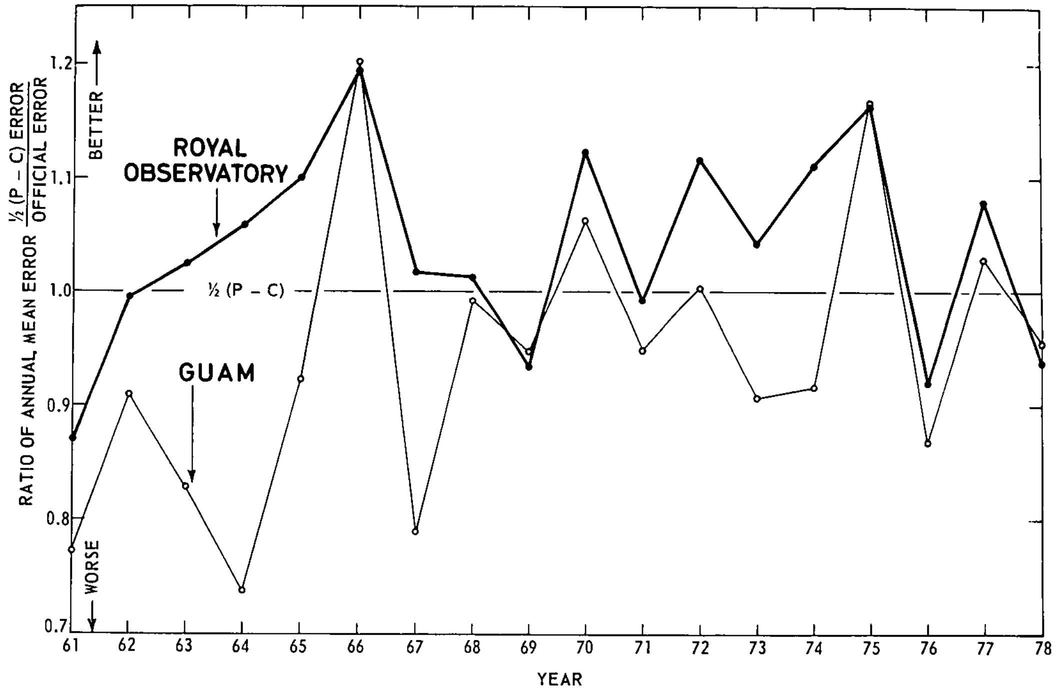

Fig. 2 The ratio of the annual average error of ½ (P – C) to the annual average official errors. The official forecasts are better than ½ (P – C) when the ratio is greater than 1. Area : 10 to 30 N, 105 to 125 E.

the event a level can often be found to provide a 'steering level' but this is a useful concept for forecasting only when the near environment height and wind fields throughout the mid-troposphere are well defined, similar, and stationary. Even then some departure from the steering flow may occur according to storm size, intensity, asymmetry in the inflow and outflow fields of divergence, and interaction. Some of these problems are illustrated in my computer animated film of space-mean wind and height fields around selected typhoons.

An unexpected phenomenon clearly shown in the film is that there is a large diurnal pulsation of both the shape and intensity of synoptic features in the wind and pressure fields. It is of interest that the pulsations are little diminished by removing the average diurnal range for the month from each grid point. These variations might sometimes be the cause of a tropical cyclone oscillating about a smoothed track with a near 24-h periodicity as is occasionally observed.

The average poleward movement and acceleration of tropical cyclones of different sizes is shown in Table 2. Acceleration is included as this is expected to be less dependent on contributions from steady steering and interaction. South of 30°N the average poleward acceleration of large storms is about twice that of small ones. Poleward acceleration and storm size are significantly correlated (Table 3) and, in accordance with the Rossby effect, poleward displacement is also strongly correlated with storm intensity. However, acceleration is not correlated with storm intensity. Other interesting phenomena are suggested in Table 3. Although these tables show that the poleward displacement of tropical cyclones is positively correlated with their intensity and size these factors contribute only very little to the variance of the motion and they find no place as inputs to current forecast methods.

NUMERICAL METHODS

The formation, intensity, and movement of tropical cyclones are governed by large-scale circulation patterns. It is therefore to numerical models (NWP) that we must look to predict these patterns for 48 h and more ahead. However, from the operational viewpoint, a regional tropical cyclone forecast model is of little value as its failures and successes will follow those of simpler methods. A forecast for only one level has similar disadvantages. It is therefore necessary to use a three-dimensional moving nested 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° × 40° 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.

Apart from the computing and modelling problems associated with the development of MNG models there are fundamental difficulties associated with data coverage, its timeliness and analysis. The true central pressure of tropical cyclones cannot be included in conventional objective analysis techniques without gross distortions and the uneven distribution of observations around a storm can cause displacements of the vorticity centre by several degrees (Elsberry 1978) as was shown in my film. It is clearly necessary to use all available data, including off-time and off-standard level observations received from satellites and aircraft (especially ASDAR). To achieve this in a timely and satisfactory way requires an objective

Table 2 Subsequent 24 h average movement and acceleration of tropical storms and typhoons by size in different latitude bands (1958-1974)

Latitude of centre ($^{\circ}$N)	Radius of outer isobar in degrees latitude*									
	0.4-1.4	1.5-2.9	3.0-4.4	>4.4	All sizes	0.0-1.4	1.5-2.9	3.0-4.4	>4.4	All sizes
	POLEWARD MOVEMENT ($^{\circ}$lat./24 h)					EASTWARD MOVEMENT ($^{\circ}$lat./24 h)				
0.0-9.9	1.1	1.1	1.6	1.4	1.3	-3.4	-3.6	-4.1	-3.3	-3.7
10.0-19.9	1.4	1.7	1.6	1.9	1.7	-2.5	-2.8	-2.7	-2.9	-2.8
20.0-29.9	2.5	2.5	2.3	2.6	2.5	-1.7	-1.1	-0.5	-0.3	-0.6
⩾30.0	-	2.7	1.6	2.5	2.2	-	1.1	2.6	3.1	2.2
All latitudes	1.6	1.9	1.8	2.1	1.9	-2.3	-2.3	-2.0	-1.9	-2.0
	POLEWARD ACCELERATION ($^{\circ}$lat./24h/24h)					EASTWARD ACCELERATION ($^{\circ}$lat./24h/24h)				
0.0-9.9	-	0.5	0.7	1.0	0.6	-	-0.3	-0.2	-0.8	-0.4
10.0-19.9	-	0.2	0.2	0.5	0.3	0.2	0.6	0.5	0.3	0.4
20.0-29.9	0.5	0.3	0.4	0.7	0.5	0.9	0.8	0.9	1.0	0.9
⩾30.0	-	-0.3	-0.8	0.9	-0.2	-	2.1	1.1	1.3	1.6
All latitudes	0.0	0.3	0.3	0.6	0.4	0.5	0.6	0.6	0.6	0.6

* Isobars are drawn at 2 mb intervals.

A dash indicates that the sample size N is less than 20.

Table 3 Correlation coefficients (r) and their significance (sig.) for the relationships between the 24 h movement and acceleration of typhoons and their size and intensity. Number of pairs N.

Latitude of centre (°N)	Movement						Acceleration					
	Poleward			Eastward			Poleward			Eastward		
	r	N	sig.	r	N	sig.	r	N	sig.	r	N	sig.
						STORM RADIUS						
0-9.9	0.13	352	2%	0.042	352	n.s.	0.18	197	1%	-0.24	197	<0.1%
10-19.9	0.078	2552	<0.1%	-0.019	2552	n.s.	0.098	1889	<0.1%	-0.065	1889	1%
20-29.9	0.053	1383	5%	0.12	1383	<0.1%	0.13	1229	<0.1%	0.063	1229	5%
>30	0.017	128	n.s.	0.19	128	5%	0.23	119	1%	-0.15	119	n.s.
All latitudes	0.079	4415	<0.1%	0.054	4415	<0.1%	0.12	3434	<0.1%	-0.010	3434	n.s.
						STORM INTENSITY*						
0-9.9	-0.31	80	1%	-0.30	80	1%	-0.029	65	n.s.	-0.25	65	5%
10-19.9	-0.14	993	<0.1%	0.047	993	n.s.	0.022	915	n.s.	-0.066	915	5%
20-29.9	-0.16	893	<0.1%	0.037	893	n.s.	-0.047	863	n.s.	-0.12	863	<0.1%
>30	-0.40	93	<0.1%	0.029	93	n.s.	-0.28	90	1%	-0.21	90	5%
All latitudes	-0.15	2059	<0.1%	0.056	2059	2%	-0.028	1933	n.s.	-0.083	1933	<0.1%

* Storm central pressure ⩽ 980 mb.

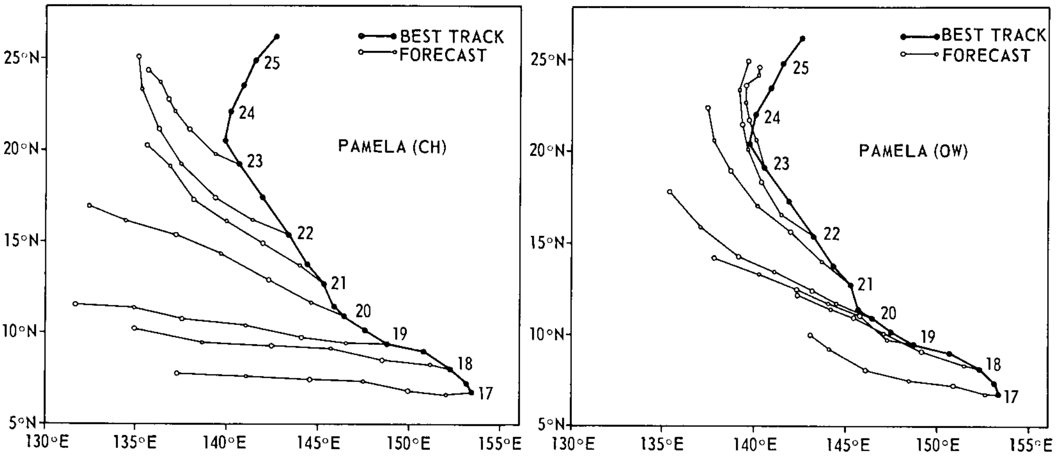

Fig. 3 Forecast positions at 12h intervals up to 72h for typhoon Pamela 1976 made with nested grid models having channel (CH) type cyclic and one-way (OW) interactive, boundary conditions (from Hodur and Burk 1978).

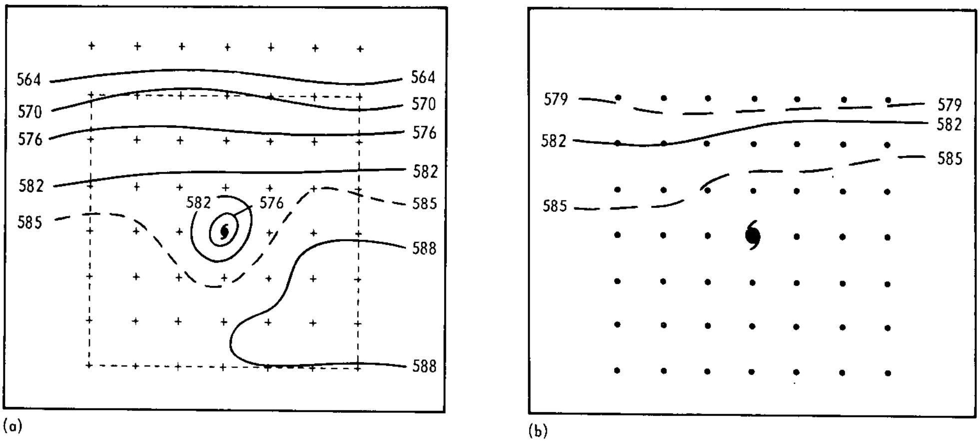

Fig. 4 Tropical-cyclone-centred composite 500 mb height analyses for (a) 999 fields (1946-1969) hand-drawn or objectively analysed by a successive-correction scheme and (b) 78 fields from the US National Meteorological Centre 1978 operational computer files. (Redrawn from originals by P.W. Leftwich in Lawrence 1979.)

analysis system running continually using data to nudge the model towards reality as in the UK Meteorological Office's global model. The high computer power required for such models will limit their use to major centres; means must then be found for them to receive the necessary high resolution data without delay. The severity of this data and analysis problem is illustrated by Fig. 4.

OUTLOOK

In recent years there has been an increase in the number of tropical cyclone related phenomena for which warnings are expected. In addition to storm movement, maximum wind speed, and rainfall it is now necessary to warn of such terrestrial and oceanographic responses as floods, landslips, wave heights, and storm surges. The magnitude of these events at a given location is critically dependent on storm movement and intensity. However, these two factors cannot currently be forecast beyond 24 h with an accuracy sufficient to permit the associated responses to be predicted at an acceptable level of probability. This deficiency, coupled with the growth of capital intensive developments and operations near coasts in tropical cyclone areas, has now put increasing pressure on warning centres to improve the accuracy of their predictions over 48 h to 72 h.

In conclusion, I believe that conventional synoptic/statistical type 24 h forecasts are now at the limits of their development imposed by positioning errors, storm asymmetries, and unsteadiness in the broadscale flow patterns. Developments of MNG forecasts for 36 to 48 h ahead may help to reduce the frequency of gross errors at 24 h. The MNG 24-h forecasts will be too late to be of operational use and will continue to be limited by data and analysis deficiencies. However, for periods of 48 h and more I see the possibility of considerable improvement in forecasts of storm movement and intensity as fine mesh, moving-grid systems are further developed and fed almost continuously with high-resolution data while nested in a global model that also assimilates data on a nearly continuous basis.

REFERENCES

Bell, G.J. 1962. Predicting the movement of tropical cyclones in the region of the South China Sea. *Proc. Inter-Regional Seminar on Tropical Cyclones.* Japanese Met. Agency, Tokyo.

Bjerknes, J. and Holmboe, J. 1944. On the theory of cyclones. *J. Met., 1,* 1-21.

Elsberry, R.L. 1978. Applications of tropical cyclone models. *Proc. 8th Tech. Exch. Conf.* Air Force Academy, Colo, 48-61.

Hodur, R.M. and Burk, S.D. 1978. The Fleet Numerical Weather Central Tropical Cyclone Model: comparison of cyclic and one way interactive boundary conditions. *Mon. Weath. Rev., 106,* 1665.

Lawrence, M.B. 1979. Atlantic hurricane season of 1978. *Mon. Weath. Rev., 107,* 477-91.

Riehl, H., Haggard, W.H., and Sanborn, W.R. 1956. On the prediction of 24-hour hurricane movement. *J. appl. Met., 13,* 415-20.

Rossby, C.-G. 1948. On the displacement and intensity changes of atmospheric vortices. *J. Mar. Res., 7,* 175-96.

Sasaki, Y. and Miyakoda, K. 1954. Numerical forecasting of the movement of cyclones. *J. Met. Soc. Japan, 32,* 325-35.

WMO. 1979. Operational techniques for forecasting tropical cyclone intensity and movement. *WMO Publication No. 528.* Geneva.