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A TRIAL OF AN EMPIRICAL METHOD OF PREDICTING TROPICAL CYCLONE MOTION IN THE WESTERN AUSTRALIAN REGION

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ABSTRACT

An empirical method of forecasting tropical cyclone motion by examining the distribution of vorticity in the surrounding low-level flow is described. The results of applying the method to six cyclones that occurred in the Western Australian region are given. The prediction position errors compare favourably with those for other methods currently in use in Australia and overseas.

INTRODUCTION

A trial of the method of tropical cyclone movement prediction to be described in this article arose from the combination of the results of an investigation into the surface wind fields in northwestern Western Australia with the observation, made by many forecasters, that tropical cyclones often but not always move into MSL troughs. This observation prompted the question of whether there is some characteristic distinguishing those occasions when the cyclone moved into the trough from those when it did not, and which could be used as a prognostic tool. The results of the surface wind investigation indicated that an answer to this question was more likely to be found in 900 m isobaric charts than in MSL charts, for reasons given in the Appendix.

The upshot of the investigation of the records of five tropical cyclones was the development of a method of forecasting movement that depends on the location of relative vorticity maxima in the 900 m flow. The method has been used to make hindcasts for one cyclone, and forecasts for six cyclones that occurred during the 1974-75 and 1975-76 seasons.

METHOD

There are two main steps in the method:

(a) the reduction of MSL pressure to 900 m pressure, and

(b) the calculation of the vorticity at various points on the 900 m isobaric chart.

The data used are the surface temperatures and MSL pressures reported by observing stations and ships in the Northern Territory and Western Australian regions, and the 930 mb temperature from those stations at which radiosonde flights are made.

The reduction of pressure to 900 m above MSL for each station is done by first reversing the reduction from station level to MSL pressure, which has been performed by each observer, and then calculating the 900 m pressure by use of the hydrostatic equation in the form

$$\ell n(p_0/p_1) = g(900 - Z)/(RT)$$

where p_0 is station level pressure, p_1 is 900 m pressure, g is the acceleration due to gravity, R is the gas constant for dry air, Z is the height above MSL of the barometer, and T is the mean temperature of the air column between the surface and 900 m, assumed to be equal to the mean of the screen dry-bulb temperature and the 930 mb temperature at the nearest radiosonde station.

After this reduction has been done for all available stations the 900 m pressures are plotted and isobars are drawn at 2 mb intervals. The vorticity at various points on the chart is calculated on the assumption that the wind is geostrophic; that is, the vorticity is defined to be

$$\xi = VK - \Delta V/\Delta n$$

where V is the geostrophic wind speed, K is the curvature of the isobars (assumed to be also streamlines), and $\Delta V/\Delta n$ is the wind shear across the isobars. K is positive for cyclonic curvature, and $\Delta V/\Delta n$ is positive for speed increasing to the left looking downstream. The units used are latitude degrees for distances and knots for wind speeds. K and V are estimated with the use of plastic overlays constructed for the task.

The rule that has been used for forecasting the position of the cyclone 24 hours after chart time is that it will move towards the area of maximum cyclonic vorticity and the distance travelled in 24 hours is given by

$$|\Delta S| = {\frac{\xi_8 + \xi_5}{2}}^{\frac{1}{2}} \quad \text{lat. deg.}$$

where ξ_8 and ξ_5 are the vorticity at eight and five latitude degrees respectively from the cyclone centre along the predicted line of movement. The rule was developed purely empirically from inspection of 900 m isobaric patterns. Subsequently work by Kuo (1969) describing conditions under which cyclonic vortices are driven towards high vorticity regions has been noted. Experience accumulated since 1974 indicates that better results can be obtained by a modification of the rule that predicts an acceleration, rather than a velocity, in the direction of the vorticity maximum; that is, the current movement of the cyclone ought to be taken into account. This is consistent with the results of a theoretical investigation, which is to be described in a later paper. The theory also indicates that a constant level pressure chart is a better prognostic tool than a streamline chart would be.

In practice, the number of points for which the vorticity is calculated is usually less than three. It is not necessary, for example, to do the calculation for an area of the chart where both the curvature and shear are obviously anticyclonic.

The curvature term is largest in the trough (if there is one), and so the vorticity maximum is frequently found there. However, it is not uncommon to find that the shear term in a trough gives an anticyclonic contribution to ξ, which counteracts the effect of the cyclonic curvature. In such cases, the vorticity maximum may lie outside the trough.

An example of a chart with the area of maximum vorticity indicated is given in Fig 1.

RESULTS

The prediction rule was formulated after study of five cyclones that are listed in Table 1. These cases represented a variety of tracks, including some cases of recurvature. The rule was then tested on another cyclone, Glynis, the track of

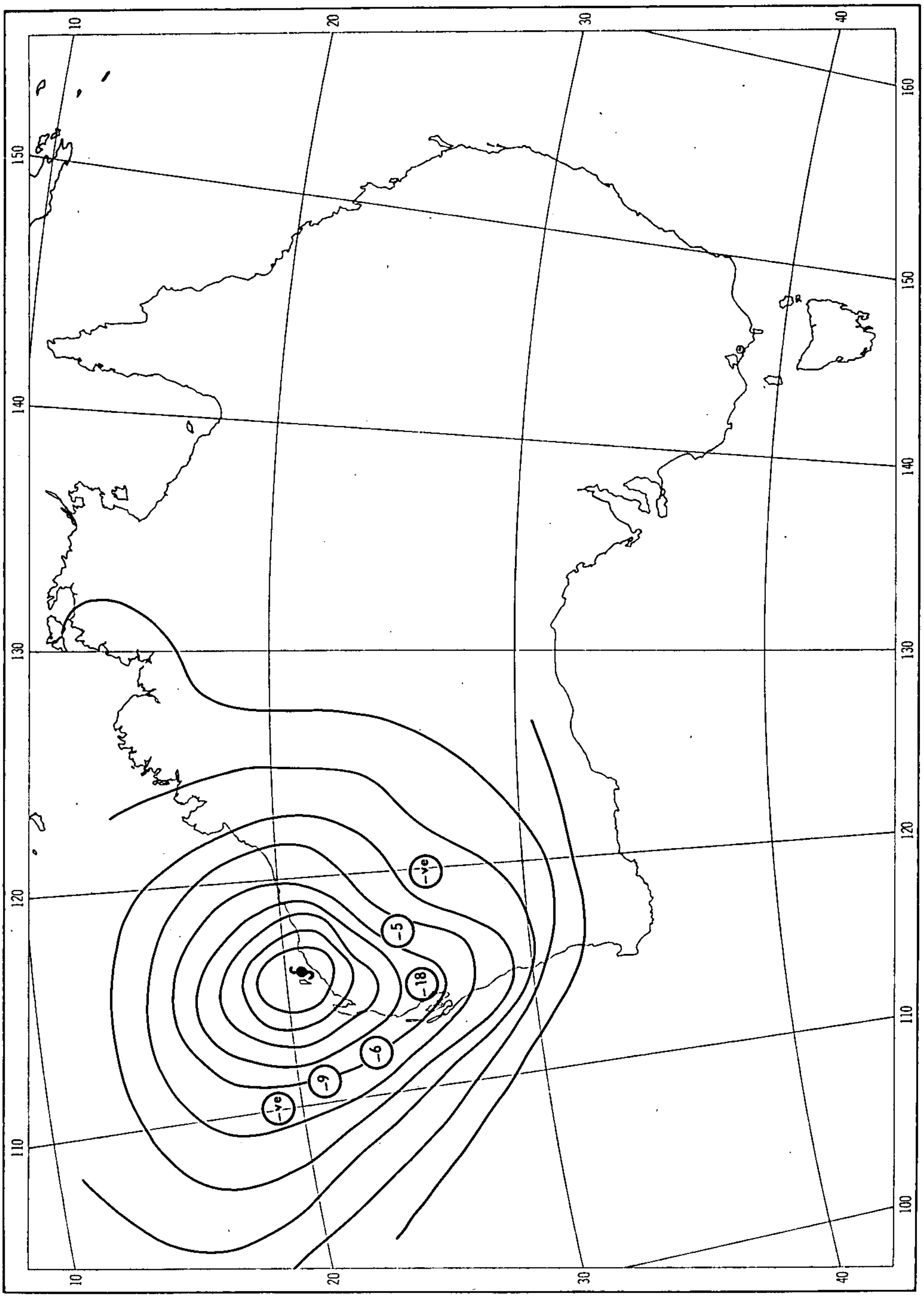

Fig 1 Cyclone Trixie, 900 m chart for 0100 GMT 19 February 1975, isobars at 2 mb intervals. Circled figures are estimated vorticities.

which was not known beforehand by the tester. Glynis was one of the cyclones used in a forecasting game played in Perth as part of the study of a proposed scheme for cyclone reconnaissance by light aircraft. Table 2 shows the actual movement of the cyclone, the 24-hour hindcast made using the vorticity method, and the 12-hour hindcasts made by one of the players in the game. The errors associated with the vorticity method compare favourably with those of the shorter period game hindcasts that were made with the benefit of simulated reconnaissance data.

The vorticity method has been put 'into action' to forecast the tracks of six cyclones during the 1974-75 and 1975-76 seasons. The results, in terms of the errors in the 24-hour forecast positions, are shown in Table 3. The errors are prediction errors, that is, they include the contribution due to the initial position error (Annette 1976). The mean error was 70 n mi, and the standard deviation was 39.6 n mi. The median error was 60 n mi. Table 3 also shows the errors expressed as a fraction of the distance travelled by the cyclone in 24 hours. The mean error, when expressed in this fashion, is 0.44.

The results of the forecasts are also shown pictorially in Figs 2 to 5 in an attempt to give some kind of 'feel' for the capacity of the vorticity method to forecast changes in track. In general, the more bizarre a cyclone track, the more striking a successful forecast of it is. For instance, it is thought that the forecasting of the unusually rapid movement of Vida (Fig 2) is strong evidence of the usefulness of the method, although the error in predicted position, 150 n mi, is one of the largest made. The figures also make apparent that the direction of movement is, in general, well forecast, and that most of the error is due to the speed forecast. It is hoped that the revised form of the forecast rule, which takes account of the current movement of the system, will produce better speed forecasts in future.

Table 4 juxtaposes the performance statistics for the vorticity method with those for other methods in use overseas and in Australia. The latter figures were taken from Annette (1976). On the face of it, the vorticity method compares favourably with these other methods. However, one ought not to make too much of the comparisons, since the figures apply to different samples in different regions, and the number of forecasts is too small to justify the application of tests of statistical significance.

Table 1 Cyclones used in development of movement prediction rule

Cyclone name	Dates
-	8-12 February 1961
-	21-24 February 1961
Ella	5- 6 February 1968
Gina	14-15 February 1968
Gladys	16-19 February 1969

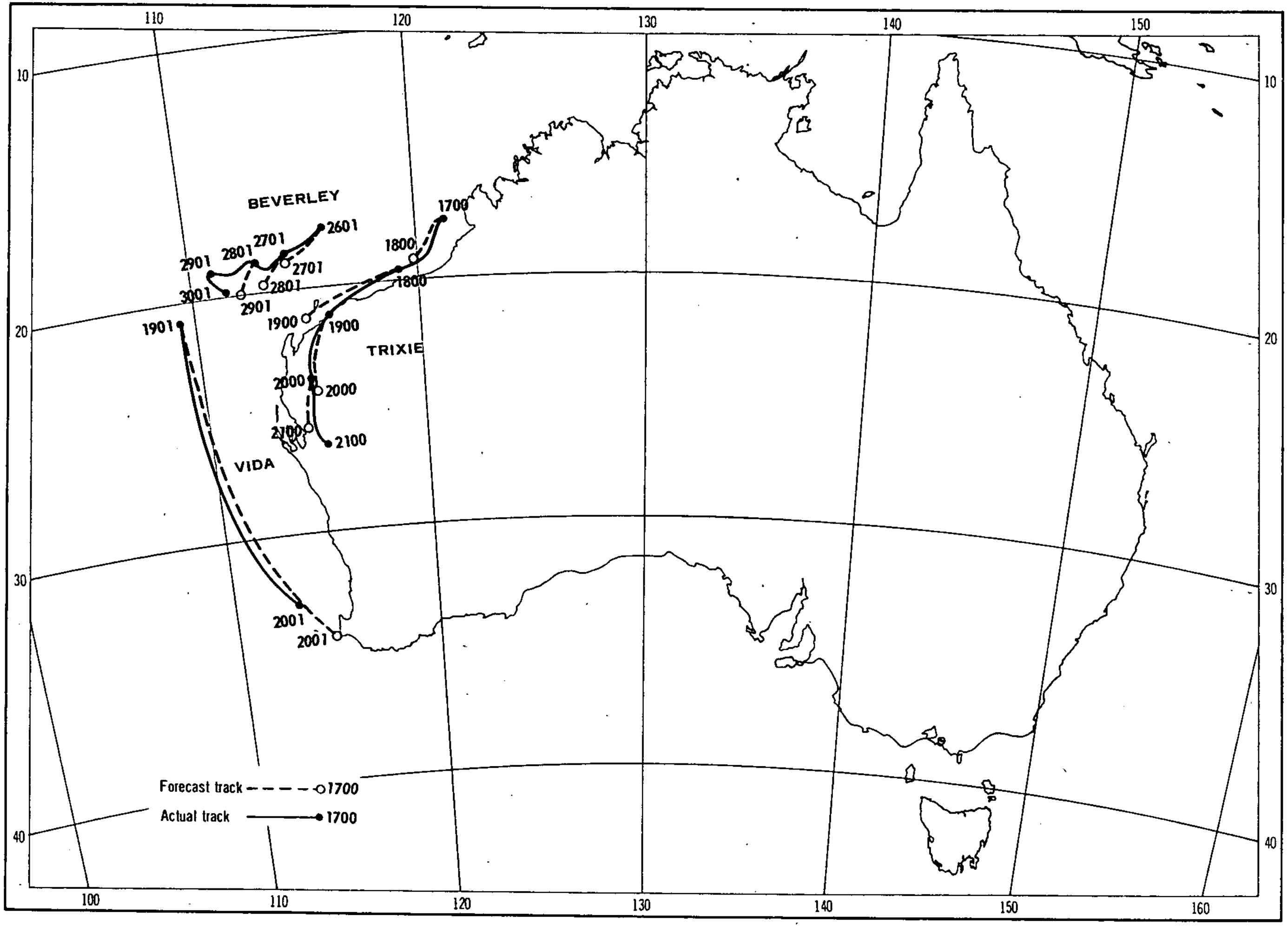

Fig 2 Forecast and actual tracks of cyclones Trixie (February 1975), Vida (March 1975), and Beverley (April 1975). Four–figure groups give date followed by time GMT.

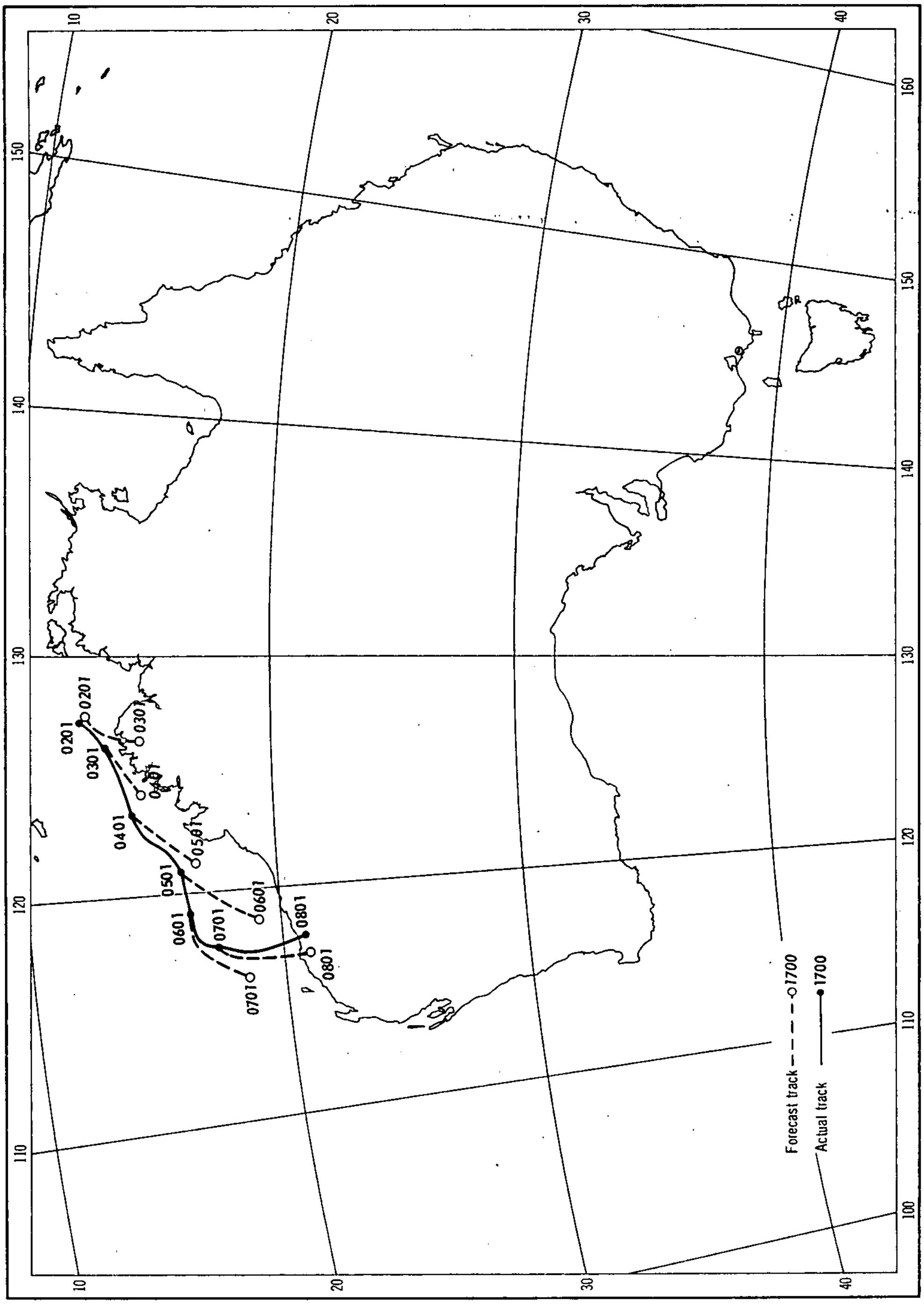

Fig 3 Forecast and actual track of cyclone Joan (December 1975).

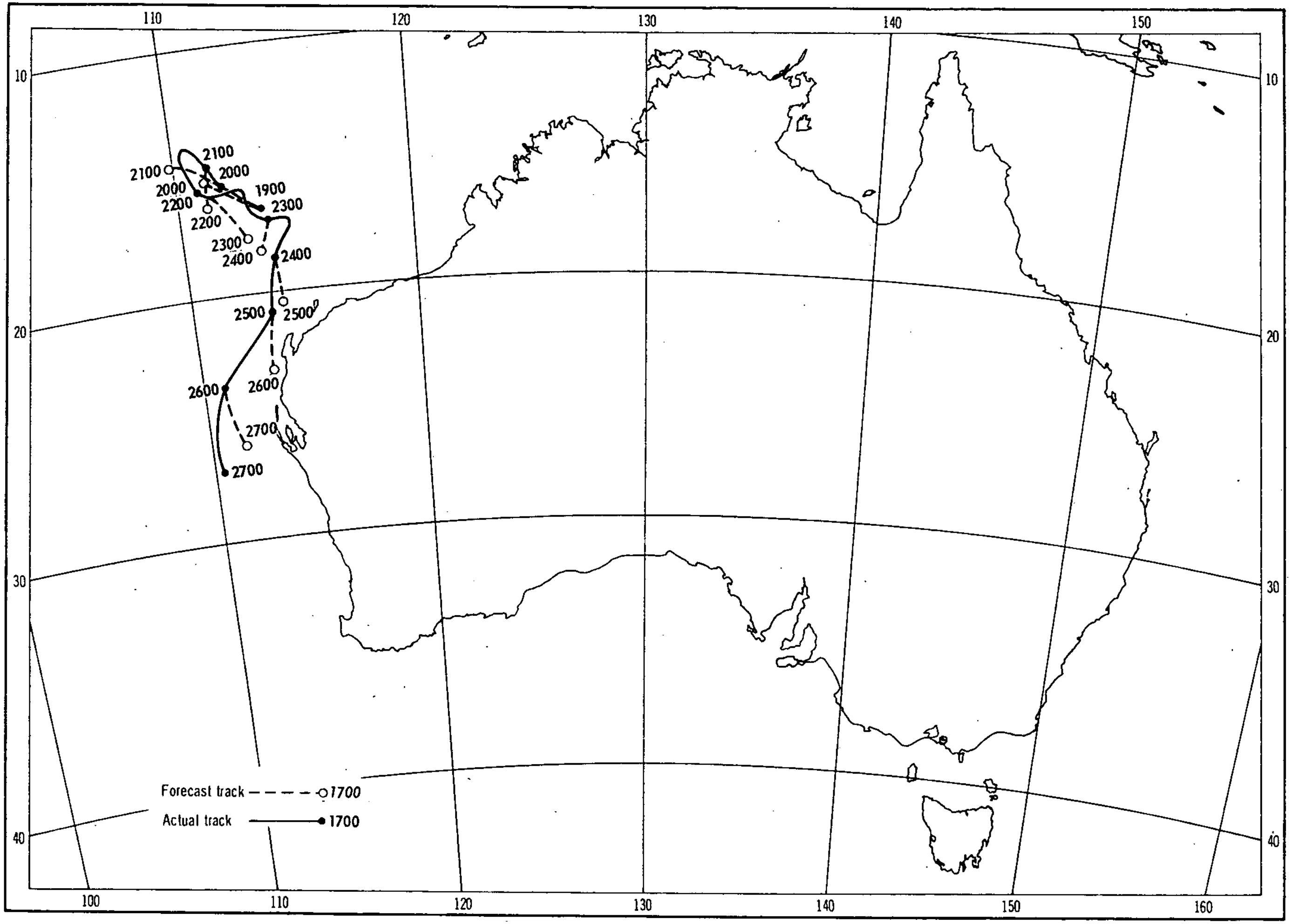

Fig 4 Forecast and actual track of cyclone Vanessa (January 1976).

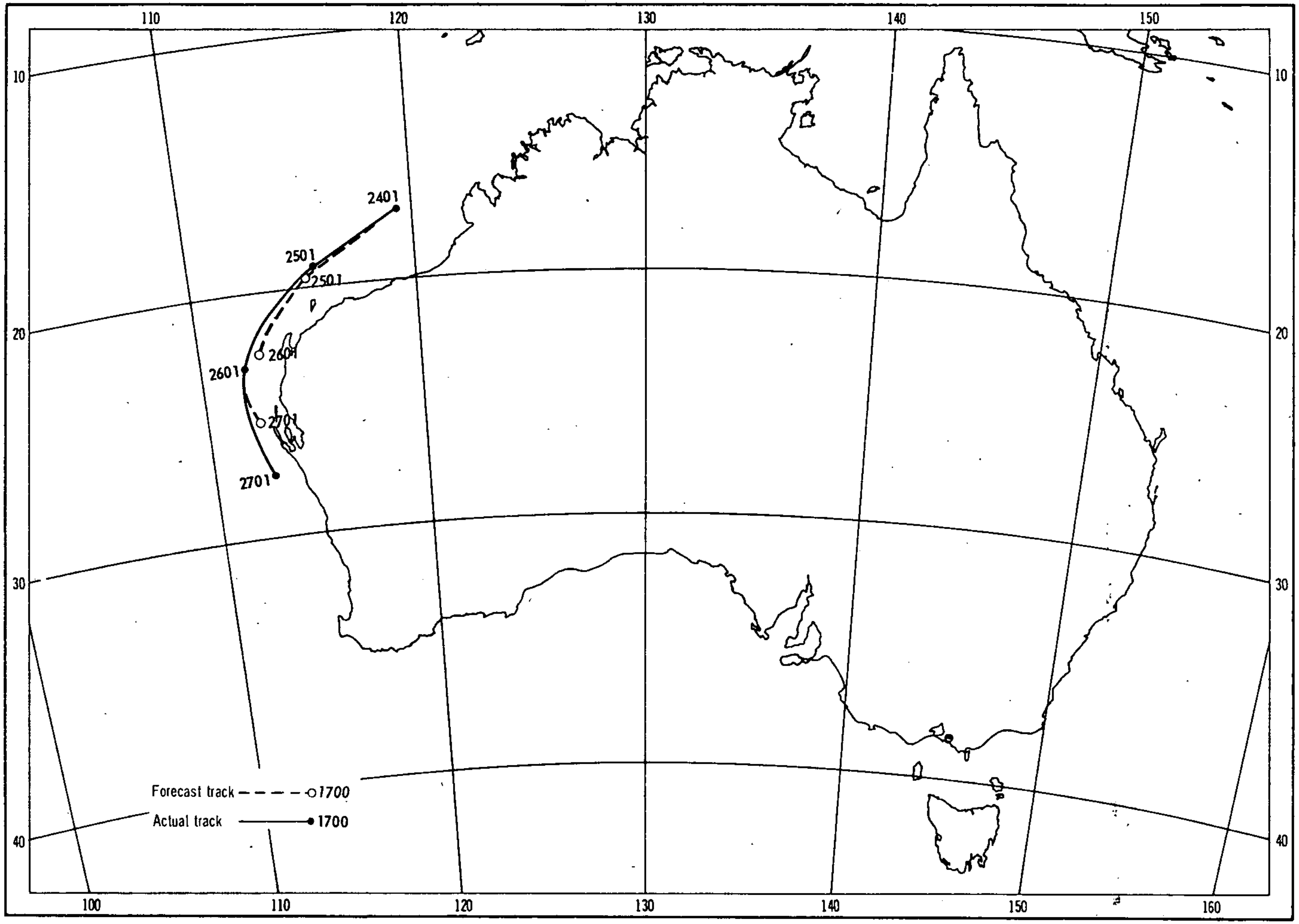

Fig 5 Forecast and actual track of cyclone Wally (February 1976).

Table 2 Predicted and actual movement in 24 hours of cyclone Glynis, errors in 24-hour forecasts, and errors in 12-hour forecasts made in cyclone game

Day	Predicted direction	Actual direction	Predicted 24-hour distance (deg. lat.)	Actual 24-hour distance (deg. lat.)	Error (n mi)	'Game' 12-hour error (n mi)
27/1	SW	WSW	3.6	3	60	35
28/1	WSW	W	4.3	4.5	35	40
29/1	SW/WSW	WSW	2	3.5	86	75
30/1	WSW	WSW	3.1	2.8	18	140
31/1	S	S/SSW	1.1	3	120	40
1/2	SSW	SSW/SW	4.5	5.5	60	200

Table 3 Errors in 24-hour predicted position for six cyclones during 1975 and 1976

Cyclone	Position error (n mi)	Position error / Distance travelled
Beverley April 1975	18	0.17
	65	0.67
	100	0.87
Joan December 1975	78	0.72
	40	0.22
	49	0.27
	165	1.83
	119	0.99
	60	0.28
Trixie February 1975	19	0.11
	60	0.28
	60	0.36
	17	0.14
	68	0.45
Vanessa January 1975	19	0.16
	37	0.61
	76	0.42
	47	0.22
	17	0.11
	124	0.89
	72	0.32
	90	0.44
Vida March 1975	150	0.20
Wally February 1976	35	0.14
	55	0.18
	140	0.52
Mean	70	0.44
Median	60	
S.D.	39.6	

Table 4 Comparison of errors in vorticity method forecasts with errors in forecasts by other methods (from Annette 1976). Forecast period is 24 hours

Forecast		No. of forecasts	Mean error (n mi)
US forecasts within 24 hours of landfall in USA			
	1970	34	76
	1971	46	99
US forecasts regardless of distance from coast			
	1971	275	129
Brisbane forecasts within 360 n mi of coast			
	1967-72	20	109
Perth forecasts			
	1973-74	80	180
Vorticity method forecasts within 600 n mi of coast			
	1975-76	26	70

LIMITATIONS OF THE METHOD

An obvious drawback of the method is that, for the present, it depends on the drawing of a chart by hand so that a degree of subjectivity is introduced. An attempt to assess the seriousness of this effect was made on several occasions by having two meteorologists draw charts for the same situations independently. It was found that they invariably agreed on the position of the vorticity maximum but frequently disagreed on its magnitude. The speed forecasts are a function of the magnitude and so are at the mercy of the subjectivity of its estimate.

The problem of the dearth of data over oceans is always with us. The obtaining of sufficient data to produce reasonably accurate vorticity fields over the Indian Ocean depends on the number of reporting ships in the area and this number is almost always small. Consequently, the vorticity technique is not suitable for cyclones in the western half of the Perth region of responsibility, and may fail to predict westward movement of cyclones in the eastern half. It may be that this situation can be improved by information about the vorticity field obtained from satellite pictures.

CONCLUSION

The number of cyclones for which genuine forecasts (as opposed to hindcasts using data from the archives) have been made is small, but it is suggested that the degree of success has been sufficient to warrant further trials. It would be interesting to find how the method performs in areas other than the Western Australian region. As far as is known, there is no reason why it should not be applicable to the Queensland and Northern Territory regions.

ACKNOWLEDGMENTS

Mr K.P. Lynch of the Perth Regional Office of the Bureau of Meteorology was the first to suggest that clues to the apparently anomalous surface winds on the northwest coast and to tropical cyclone movement might be found in the pressure field at a level between 500 and 900 m, rather than at the surface.

This work was begun while the author was employed at the Perth Regional Office of the Bureau of Meteorology. Since that time, the Regional Director and his staff have made available facilities and data for further testing of the method, for which I am grateful.

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APPENDIX

On the Reduction of Pressures to MSL

The MSL synoptic charts for the Western Australian region in summer frequently display an extensive area of low pressure over the northwest of the State. It has been observed that on many occasions the gradient and surface winds blow in an anticlockwise direction around the low pressure centre, with a speed significantly higher than that consistent with the weak pressure gradient. An example of this kind of apparently anomalous flow is given in Fig 6. Forecast failures have occurred as a consequence of forecasters dismissing such winds as observational errors, and so an explanation of the phenomenon was sought. It was found in the method used to reduce station level pressures to MSL.

The form of the hydrostatic equation used in the reduction of observed station level pressures to a common level is

$$\ell n(p_0/p_1) = g\Delta h/(R\bar{T}) \qquad \ldots 1$$

where $p_0 \equiv$ pressure at height z_0

$p_1 \equiv$ pressure at height z_1

$\Delta h \equiv z_1 - z_0$

$\bar{T} \equiv$ mean temperature of column of air between z_1 and z_0, in deg. K

$g \equiv$ acceleration due to gravity

$R \equiv$ gas constant for dry air.

Until 1972, the reduction of station level pressure p_1 to MSL pressure p_0 was done by specifying a positive lapse-rate for the imaginary column of air beneath the station which, in combination with the observed temperature at the station, permits the calculation of $\bar{T}$. In 1972 the procedure was simplified by replacing the observed temperature by the mean temperature for the particular month. In either case, the following argument is valid.

Many of the observing stations in the northwestern inland of Western Australia are more than 300 m above MSL, but usually they record dry-bulb temperatures similar to those observed at less-elevated northwestern stations. This is not astonishing since the heating of air near the ground is affected to a large degree by the diffusion of heat upwards from the ground, but a consequence is that $\bar{T}$ is usually much higher for an elevated station than for a station near MSL. Inspection of Eqn 1 will show that the effect of a relatively high $\bar{T}$ is to produce a relatively low p_0. That is, the MSL pressures associated with elevated stations are in general lower than those associated with the lower (mostly coastal) stations, and so a low pressure area appears on the MSL synoptic chart.

If the reduction of pressure to a common level is done by applying Eqn 1 to the real column of air above each station, then the resulting pressure pattern is often quite different from the MSL pattern, with the 'heat low' much weaker or even replaced by a high pressure centre or ridge.

A 600 m chart corresponding to the MSL chart of Fig 6 is shown in Fig 7. It will be seen that the agreement between pressure and wind fields is much closer on the higher level chart.

This observation, that some MSL troughs and lows are artifacts of the pressure reduction method, suggested that the search for connections between tropical cyclone movement and low-level pressure fields was more likely to be profitable if such spurious features were first removed; hence before analysis the data were reduced to the common level of 900 m, which was found to be more satisfactory than the 600 m level used at the beginning of the investigation.

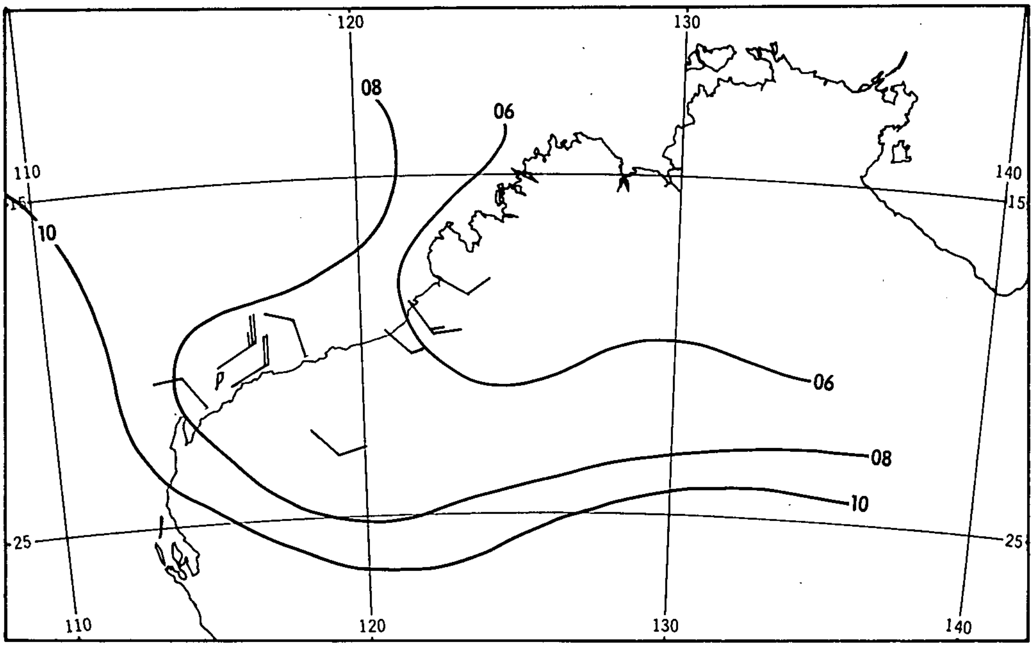

Fig. 6 MSL isobars and surface winds 0400 GMT 6 November 1973.

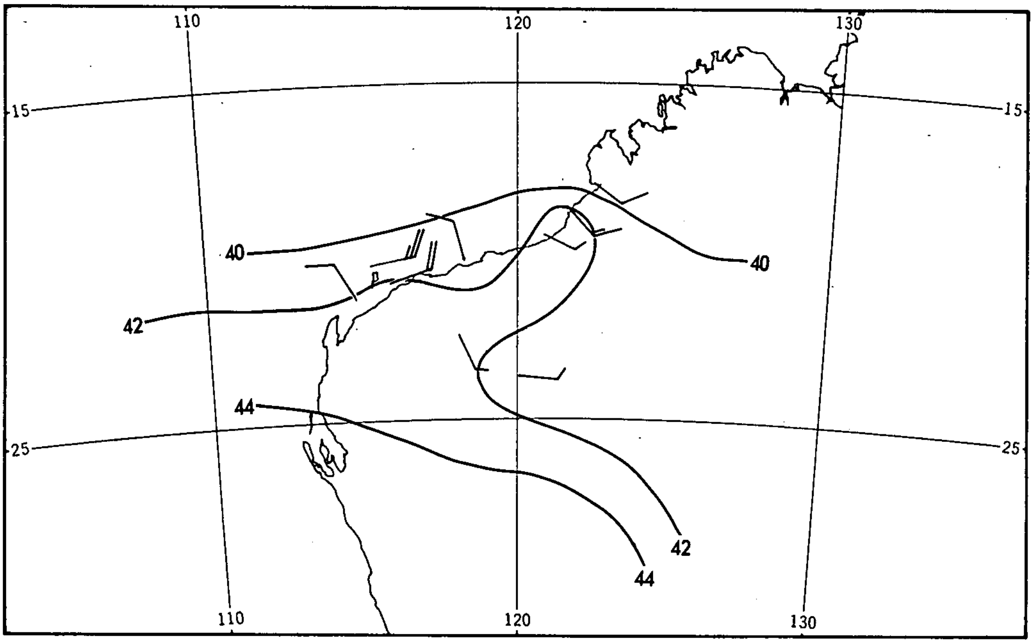

Fig. 7 600m isobars and surface winds 0400 GMT 6 November 1973 (later in the investigation 900m was adopted as the common level for pressure reduction).