Aust. Met. Mag. 40 (1992) 41–46

Predicting changes in intensity of tropical cyclones using a Markov chain technique

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(Manuscript received June 1991; revised November 1991)

At present no skilful, quantitative technique exists for the operational prediction of changes in tropical cyclone intensity. Here we describe the application of a Markov chain technique to this difficult problem. The method predicts transitional probabilities between five discrete categories of intensity and these probabilities are applied to short-period (24 hours) forecasting of tropical cyclones in the Australian region.

When tested on independent data, the Markov technique out-performed a standard 'zero-skill' climatology-persistence (CLIPER) intensity forecast technique by up to 22 per cent, out to 24 hours. The greatest gains were found in the 6 to 18-hour range. In addition, the Markov predictions show a degree of improvement of between 25 and 40 per cent over the Dvorak method, which is the current operational objective technique used by the Australian Bureau of Meteorology.

The effectiveness of the method under operational conditions is illustrated by applying it to four tropical cyclones that caused operational forecast difficulties. We suggest that this approach complements the traditional methods where position and intensity are forecast directly, largely based on information provided by persistence, climatology, satellite data and synoptic interpretation.

Introduction

From both a community response and a meteorological viewpoint, tropical cyclone forecasts may be broadly separated into two distinct time periods: short-term forecasts, up to 24 hours; and medium-range forecasts, beyond 24 hours.

The medium-range forecasts provide planning and guidance advice and an opportunity for local community awareness of the potential threat. As a tropical cyclone approaches the coast or other fixed installations, the short-term forecasts become very important. Most communities require 12 to 24 hours notice to respond to a tropical cyclone warning with industrial shutdowns, evacuations, and so on; and the last 12 hours before landfall are used for civil defence authorities both to fine-tune the community response and to prepare for the storm aftermath.

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At present, *intensity* forecasts consist mainly of combining climatology and persistence of the trend over all time-scales, together with some empirical and pattern recognition approaches to differentiate rapid versus slow development (e.g. Dvorak 1975; Jarvinen and Neumann 1979; Pike 1985; Elsberry et al. 1988). Tropical cyclone *motion* forecasts for the first 24 hours are also dominated by persistence and climatology, especially in low latitudes (Neumann and Pelissier 1981; Keenan 1981; Elsberry et al. 1988). Dynamical and statistical-dynamical techniques, which incorporate forecast changes in the large-scale flow, are most effective at longer times.

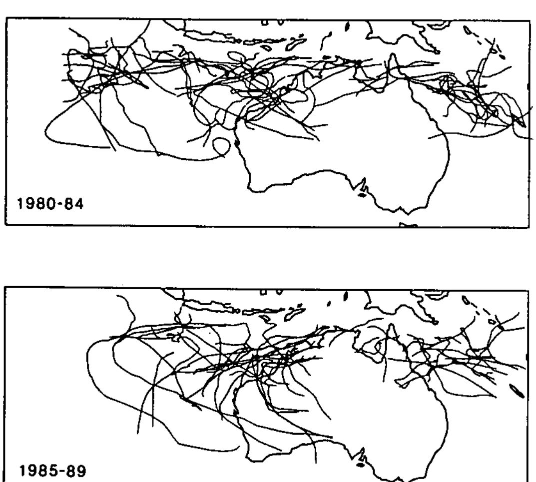
Two major causes of error may therefore be identified in short-term forecasts: initial analysis errors that degrade the persistence forecasts (Jarrell et al. 1978; Neumann 1983), and sharp changes of intensity or motion that cannot be captured by persistence or climatological techniques. The sharp changes are a problem, especially in the

Australian region. As shown in Fig. 1, tropical cyclones off northwestern Australia frequently track parallel to and just off the coast, then recurve to cross the coast within several hours. Short-term forecasts of such recurvature are therefore crucial to the community warning process. The proportion of erratic cyclones over the Australian region in general, and particularly in the eastern region (see Fig. 1), is the highest in the world (Pike and Neumann 1987), so that short-term track change is a major contributor to forecast error.

Keenan (1982) showed that intensity forecasts based on a combination of synoptic reasoning and the Dvorak technique contained no skill relative to persistence. In this paper, we present an alternative method of forecasting intensity changes using Markov chain techniques. As far as the authors are aware, only one other study (Wang and Neumann 1985) has used transitional probabilities for tropical cyclone predictions. However, their work focussed on track prediction, not intensity forecasts.

In this study tropical cyclones in the Australian region are grouped into five classes of intensity. The Markov technique is then used to predict the probability of transitions between the classes. Previous work with short-range Markov predictions suggests that this approach is particularly suited to the 6 to 18-hour period (Miller and Leslie 1984; Hess et al. 1989).

Fig. 1 **(a) Tropical cyclones over the Australian region for the years 1980–84. (b) As for (a) except for the years 1985–89.**



Methodology

Markov technique

The method used in this study is a hybrid Markov chain-regression technique developed by Miller and Leslie (1984, 1985). The Markov part of the model uses knowledge of the present state (in this case the tropical cyclone central pressure) and a previously observed state (at time $t - \Delta t$) to predict future states, by using climatological probabilities that a particular state will occur (for example that the central pressure, P, will be between 990.0 hPa and 999.9 hPa) given various present states. We approximate these transitional probabilities by employing multilinear regression over a number of covariates.

The probability that a particular intensity state will occur is found by performing linear least squares regression on eleven covariates: previous weather state i, where i has a value of between 1–5; present latitude; present longitude; 1000 hPa minus present pressure; latitude six hours previously; longitude six hours previously; 1000 hPa minus pressure six hours previously; present speed; speed six hours previously; the change in pressure in the last six hours; and the month. No attempt has been made to investigate the effect of choosing different states, more states, or alternative covariates (such as distance from the coast).

We can write the probability Pr of state s as a function of the current state j and the forecast period h (the number of hours ahead for which the forecast is valid):

$$Pr_s(j, h) = a_s(j, h) + \sum_{k=1}^{11} b_{sk}(j, h) X_{sk} \quad \ldots 1$$

where $a_s(j, h)$ is the intercept, $b_{sk}(j, h)$ are the regression coefficients, and X_{sk} are the covariates.

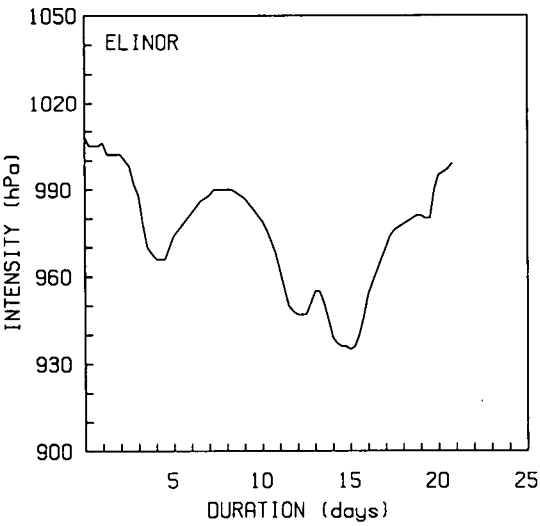
With a linear model it is possible to calculate probabilities less than zero or greater than unity. To exclude this possibility we explicitly set negative probabilities equal to zero and probabilities greater than unity equal to unity. We have also examined the use of logistic models (e.g. Miller and Leslie 1985), but found that they greatly increased the computational burden but did not significantly improve the skill.

Data

A reliable, best-track data base for tropical cyclone position and intensity in the Australian region is available for the years 1958–1989. Data prior to 1958 are not sufficiently reliable for use in this study (Holland 1981). Data for the 20 years 1958–1977 were used to construct the covariates and coefficients given in Eqn 1. The data were stratified geographically, corresponding to two regions, the eastern region (Pacific Ocean) and the western region (Indian Ocean). Separate coefficients were determined for each region.

Figure 1 also shows the cyclone tracks in each region for the ten-year period 1980–1989, which is part of the independent data set used to verify the models. The independent data set covered the twelve-year period 1978–1989. Notice the substantial track variability over time-scales of less than one day. The time series for tropical cyclone intensity shown in Fig. 2 illustrates the short-term variability in this parameter. Holland (1984) has shown that most severe tropical cyclones in the Australian region undergo at least one short period of rapid deepening, which often does not extend beyond six to twelve hours.

Fig. 2 **Time series of the intensity (central pressure) of tropical cyclone *Elinor* for the period 10 February–3 March 1983. Note the high level of short-term variability of the intensity.**



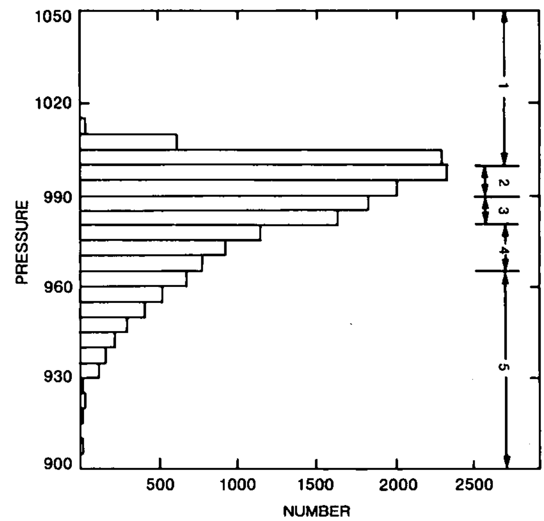
The particular choice of five approximately equally-sized intensity states was made on the basis of the relative frequency histograms shown in Fig. 3. These mutually exclusive states, s, are defined as follows: $\geqslant$1000.0; 990–999.9; 980–989.9; 965–979.9; and $<$965.0 hPa. Selecting more bins might have reduced the total number of events in the bins to unacceptably low levels.

Measures of skill

Zero-skill standard For cyclone intensity forecasting there is no established forecasting technique to act as a standard against which skill can be measured. In this study we use a climatology and persistence (CLIPER) forecast of intensity change based on that of Jarvinen and Neumann (1979).

The predictands are the intensity (central pressure) over the 24-hour forecast period at six-hourly intervals. A total of eight basic predictors is used.

Fig. 3 **Relative frequencies of occurrence of central pressures in 5 hPa ranges for the dependent data set (1958–1977).**



These are: the initial longitude of the tropical cyclone centre; the initial latitude; the initial eastward speed; the eastward speed 12 hours previously; the initial northward speed; the northward speed 12 hours previously; the initial central pressure; and the day (July 1 is day 1).

The values of the predictands are obtained from a stepwise screening regression technique using a standard package. All possible products of the eight primary predictors up to third order were used, which produced a total of 164 predictors after symmetry is taken into account. Other potential predictors such as cyclone size or outer structure were not included because of a lack of data.

The current operational objective method — the Dvorak technique The objective method presently used by the Australian Bureau of Meteorology for intensity determination and prediction is the Dvorak (1975) technique, which specifies procedures that combine meteorological analyses of satellite imagery with a model of tropical cyclone development. The model relates the cloud characteristics of tropical cyclones to changes in intensity of the three kinds of cyclones; typical, slowly developing and rapidly deepening. Full details of the procedure, as used in the Australian region, are available in the Australian Tropical Cyclone Forecasting Manual (Neal and Holland 1978) and only a cursory description needs to be presented here.

The Dvorak technique allows intensity forecasts to be made from satellite-observed cloud pictures in two basic steps. The first step is to obtain the initial intensity by satellite imagery analysis. Then the intensity forecast is made simply by extrapolating empirically-derived curves based on the cyclone model. In operations, the extrapolation frequently is refined during the life cycle of the cyclone. This occurs if, for example, changes occur in the environmental flow pattern or the cyclone approaches or moves away from the influence of a land mass.

Skill score The accuracy of the probability forecasts is judged by the half-Brier score (Brier 1950), defined as

$$Br(h) = (1/N) \sum_{m=1}^{N} (\delta_m - Pr_m)^2 \qquad \ldots 2$$

where δ is the observed probability for the mth period of observation ($\delta = 1$ if the predictand was in state s at the end of the forecast period; otherwise $\delta = 0$), Pr the forecast probability for the mth period, and N the total number of periods. Half-Brier scores can be computed for the Markov model, CLIPER and the Dvorak method by substituting the appropriate values of probability into Eqn 2.

The half-Brier score can be interpreted as the mean square error of the probabilistic forecasts. Lower scores indicate more skill; the scores range from zero (perfect score) to unity (all forecasts incorrect).

Results and discussions

The Markov chain model was applied to the data set previously described and the performance of the model will now be discussed.

Summary of model results

Figure 4 is a plot of the skill of the Markov chain model presented in terms of the percentage improvement of half-Brier scores compared to CLIPER at 6, 12, 18 and 24 hours. For simplicity of presentation we have combined the results for the two regions. The improvement of Markov over CLIPER is 22 per cent at six hours diminishing to 18 per cent at 24 hours. These improvements indicate a highly significant level of skill as they are comparable to the gains over CLIPER achieved by the best quantitative methods for predicting tropical cyclone motion.

To further illustrate the skill of the Markov technique the intensity forecasts obtained from the Australian region Dvorak method are also shown in Fig. 4. Here the Dvorak method is four per cent less accurate than the CLIPER method at six hours, dropping to 21 per cent less accurate at 24 hours.

The reliability diagrams for intensity are shown in Fig. 5. The diagonal lines indicate perfect forecasts. The predicted results therefore show that the technique is very reliable over almost the entire probability scale. The only exceptions are at six hours, between 30 and 50 per cent, and at 24 hours, at the top 10 to 20 per cent of the scale, which show some deterioration.

Fig. 4 **A plot of the percentage improvement in half-Brier scores of the Markov model and the operational Dvorak technique relative to CLIPER intensity forecasts at 6, 12, 18 and 24 hours using the independent data set (1978–1989).**

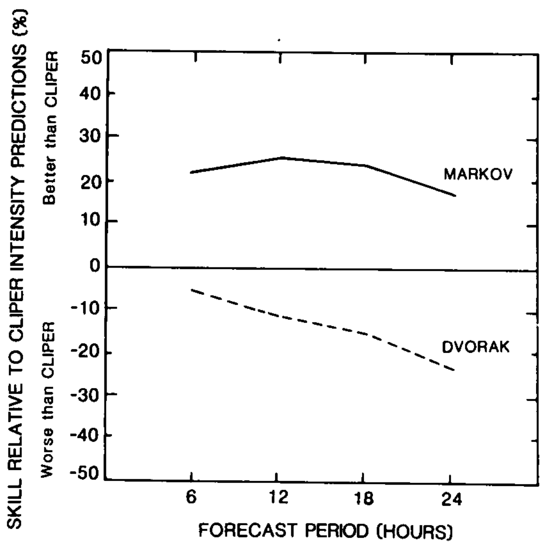


Fig. 5 **Reliability diagrams for the Markov model at 6, 12, 18 and 24 hours.**

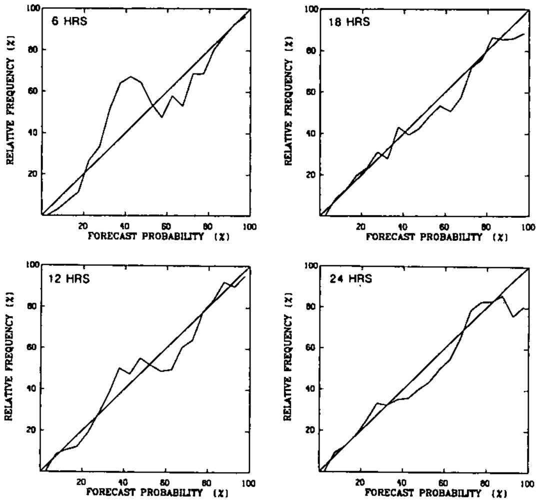


Table 1 shows some sample values of Student-t scores for each covariate used in predicting the cyclone intensity. The most significant covariates in the particular transition are previous state, present and previous latitudes, present and previous longitudes, and change in pressure.

Case studies

To illustrate the application of the Markov chain method to particular cyclones, a selection of individual tropical cyclones was made. The cyclones

Table 1. An example of Student-t scores of the covariates for predicting tropical cyclone intensity (predicting state 3 given state 5 for the Western region). Absolute values of t scores ⩾ ~2 indicate significant covariates at the 5 per cent level.

Forecast period	*Previous state*	*Present latitude*	*Present longitude*	*Present pressure*	*Previous latitude*	*Previous longitude*	*Previous pressure*	*Present speed*	*Previous speed*	*Change in pressure*	*Month*
6	5.65	−2.50	−2.69	0.16	2.75	2.72	−1.49	−0.16	0.25	9.36	0.74
12	2.14	−3.32	−3.20	−0.56	3.59	3.14	−1.39	1.14	−1.09	6.38	0.40
18	0.42	−3.99	−0.52	−0.27	4.19	0.45	−0.84	2.17	−1.31	4.09	−1.52
24	0.14	−4.61	0.42	0.33	4.81	−0.51	−1.03	2.38	−0.93	1.81	−2.34

were chosen on the basis of being locally very well known for the difficulties that they presented to operational forecasters at the time of their occurrence. Time series of the tropical cyclone intensities (hPa) are shown in Fig. 6 for cyclones *Alby* (27 March to 4 April 1978), *Kerry* (12 February to 4 March 1979), *Lena* (2 April to 9 April 1983), and *Winifred* (27 January to 5 February 1986). Note that all four cyclones are from the independent data set.

Table 2 summarises the model performance for the case studies. Note that on every occasion the Markov chain method outperforms both the other methods. The improvement in accuracy over CLIPER is between 10 and 30 per cent for all four cyclones at most of the forecast periods, as shown in Fig. 7. The improvement over the Dvorak technique is even greater, but more variable. For example for *Winifred*, the improvement is around 10 per cent whereas for *Kerry* it is between 30 and 35 per cent.

Table 2. Average half-Brier scores for each tropical cyclone track compared with climatology for the four cases considered.

Model	*Cyclone*			
	Alby	*Kerry*	*Lena*	*Winifred*
6-hour forecast				
Markov	0.034	0.037	0.035	0.062
CLIPER	0.045	0.048	0.074	0.069
Dvorak	0.053	0.052	0.046	0.084
12-hour forecast				
Markov	0.055	0.058	0.066	0.090
CLIPER	0.073	0.070	0.075	0.098
Dvorak	0.097	0.081	0.083	0.124
18-hour forecast				
Markov	0.078	0.072	0.097	0.106
CLIPER	0.098	0.082	0.109	0.118
Dvorak	0.116	0.101	0.124	0.149
24-hour forecast				
Markov	0.086	0.080	0.123	0.121
CLIPER	0.108	0.093	0.135	0.132
Dvorak	0.128	0.114	0.156	0.176

Fig. 6 Times series of intensity (hPa) for tropical cyclones *Alby*, *Kerry*, *Lena* and *Winifred* used in the case studies.

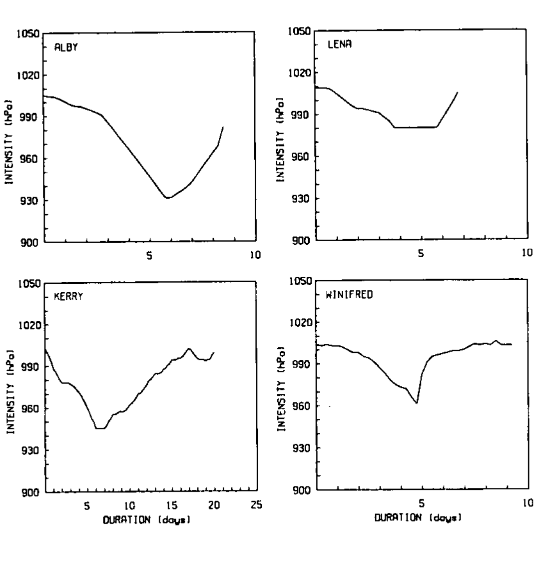
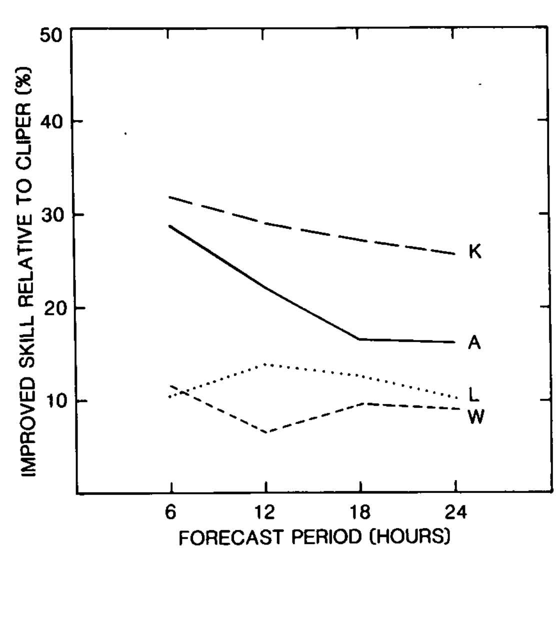


Fig. 7 Improved accuracy of Markov model intensity forecasts over CLIPER intensity forecasts for tropical cyclones *Alby* (A), *Kerry* (K), *Lena* (L) and *Winifred* (W), at six-hourly intervals.



Concluding remarks

We have presented a method for predicting short-period changes in tropical cyclone intensity. The range of intensity values for Australian region tropical cyclones is grouped into five states of approximately equal numbers. A Markov chain technique is then used to predict the transition probabilities from the current state to all possible future states, based on a 20-year data set from 1958–1977.

Using a twelve-year independent data set from 1978–1989, the technique consistently performed better than the 'zero-skill' climatology-persistence (CLIPER) out to 24 hours, but the relative improvement dropped slightly after 18 hours. The skill level compared with the Australian Bureau of Meteorology's operational Dvorak technique was even greater and increased steadily over the 24-hour period. Applications of the technique to four tropical cyclones that were difficult to forecast confirmed its performance, not only in mean statistics but also for particular cases.

Although there are many techniques available for predicting cyclone parameters, as far as we are aware there are no operational techniques being used successfully to predict *changes* from the current state. The Markov chain method, as described in this study, is simple and efficient, and can be implemented on a personal computer. Moreover, it outperformed the operational Dvorak method to such an extent (up to 40 per cent improvement, see Fig. 4) that it has been incorporated in the Australian Tropical Cyclone Workstation.

Finally we suggest that this technique can be used to complement other methods, such as numerical weather predictions, for forecasting changes in tropical cyclone intensity during the first 24 hours.

Acknowledgments

The authors would like to thank Ana Gestakovski and Lily Goa for typing the manuscript and David Pike for drafting the figures. This work is partially supported by the US office of Naval Research under grant No. N-00014-89-J-1737.

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