Reduction of Tropical Cyclone Position Errors Using an Optimal Combination of Independent Forecasts

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ABSTRACT

It is shown that an optimal linear combination of independent forecasts of tropical cyclone tracks significantly reduces the mean forecast-position errors. In this study the independent forecasts are provided by a statistical scheme (CLIPER) and a numerical weather prediction (NWP) model operating over the Australian tropics.

A comparison is made between the optimal linear combination and four other forecast techniques, over the five Australian tropical cyclone seasons 1984/85–1987/88. The combination method gave a mean position error of 157 km at 24 h using independent "best track" data, an improvement of 15% over the next most accurate method. At 48 h, the mean position error of 312 km was 17% less than the next most accurate scheme.

The combination method was assessed further in a real-time trial on operational data during the 1988/89 Australian tropical cyclone season. The results of this trial confirmed the superiority of the combination technique over the other methods. It will be used operationally in the next Australian tropical cyclone season (1989/90) either in its present form or as part of an integrated "expert" system being developed specifically for tropical cyclone motion prediction.

1. Introduction

The accurate prediction of tropical cyclone tracks has proven to be an extremely difficult problem. This is especially true of the Australian region, which possibly is the most difficult of all for obtaining skillful forecasts of tropical cyclone motion (see, for example, Pike and Neumann 1987). Currently, a number of operational and research methods are used by the Australian Bureau of Meteorology in the prediction of tropical cyclone motion. These may be grouped in four main categories: *numerical weather prediction* (NWP) models, including the operational Australian region primitive equations model, the European Centre for Medium-range Weather Forecasts (ECMWF), and UK global models; a *statistical,* synoptic model, based on regression procedures (Keenan 1986); a *quasi-analytical* model which uses advection and propagation by the mean 850–200-mb-deep layer wind (Holland and Evans 1988); and the subjective (manual) Bureau of Meteorology forecasts.

Up to the present, none of the above methods has provided forecasts of tropical cyclone motion in the Australian region with long-term operational mean position errors below 200 km at 24 h. NWP models also have not performed well primarily due to the lack of resolution and inadequate representation of physical processes in the tropics. These poor results have prompted a major NWP effort by the Bureau of Meteorology Research Centre (BMRC) in the Australian tropics.

The usual procedure for tropical cyclone forecasting is to use each method in isolation. However, it has been shown by Thompson (1977) and Fraedrich and Leslie (1987) that two independent forecast schemes may be combined linearly in such a manner that the accuracy of the combination is greater than that of both schemes used individually. The present study is the most recent in a series of investigations by the present authors, demonstrating that the optimal linear combination technique is a powerful tool for increasing forecast skill in a wide range of problems (Fraedrich and Leslie 1987, 1988; Fraedrich and Smith 1989).

In this paper an optimal linear combination is made of the BMRC NWP model (Leslie et al. 1985) operating over the Australian tropics and a climatology-persistence (CLIPER) scheme (Neumann 1972) which is based on "best" track archived data. The performance of the combined schemes is assessed on a large number of forecasts of tropical cyclone position. There have been other successful attempts at combining climatological-persistence data with other predictors. These

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include the techniques described by Peak et al. (1986) and Elsberry et al. (1988), which introduce environmental synoptic information as predictors. The present method differs from these approaches in that it combines climatological-persistence data with the output from a numerical model.

2. Methodology

a. The BMRC tropical NWP model

A new tropical numerical weather prediction system has been developed at BMRC over the past 2 ys. Currently the system comprises a univariate optimal interpolation analysis scheme, (with allowance for bogus observations of the tropical cyclone) and a ten-level, semi-implicit primitive equations numerical weather prediction model that can be run over a mercator projection of any part of the earth between 50°N and 50°S. In this study a horizontal resolution of 100 km is used.

b. The CLIPER model

A version of the CLIPER statistical forecasting method has been developed in BMRC and is based on the original approach of Neumann (1972). A total of eight predictors are used. These are initial latitude, initial longitude, initial eastward velocity component, initial northward velocity component, eastward velocity component 12 h previously, northward velocity component 12 h previously, initial central pressure, and initial day of the year. The predictands are the eastward and northward displacements of the tropical cyclone center.

The values of the predictands are obtained from a stepwise screening regression technique in which all possible products of the eight predictors up to third order are used as secondary predictors. Only those predictors that accounted for >1% of the incremental variance reduction were retained.

c. Optimal linear combination of forecasts

It has been demonstrated elsewhere (Thompson 1977; Fraedrich and Leslie 1987) that if two independent forecasts $\phi^{(1)}$ and $\phi^{(2)}$ are available of some quantity, ϕ, then a substantial reduction in forecast errors may be obtained by linearly combining these forecasts in some optimal manner. In the present study, the predictands are the horizontal (zonal and meridional) components of the displacement of the tropical cyclone center and the predictors are the displacements forecast separately by the NWP Model and the CLIPER scheme.

Denoting the zonal and meridional components of the predicted displacement by (ϕ_x, ϕ_y), the linear combination forecast is

$$\left.\begin{aligned} \phi_x &= a_1\phi_x^{(1)} + a_2\phi_y^{(1)} + a_3\phi_x^{(2)} + a_4\phi_y^{(2)} + a_5 \\ \phi_y &= a_6\phi_x^{(1)} + a_7\phi_y^{(1)} + a_8\phi_x^{(2)} + a_9\phi_y^{(2)} + a_{10} \end{aligned}\right\} . \tag{1}$$

The values of the coefficients a_1–a_{10} are obtained by applying standard multiple linear regression techniques to more than 50 tropical cyclone "best" tracks observed during the tropical cyclone seasons 1979/80–1983/84. The seasons 1984/85–1987/88 were used as an independent dataset to verify the performance of the method. Each cyclone track was divided into 12-h sections and a different set of regression coefficients was obtained for each 12-h period. As might be anticipated, the coefficient weighted the CLIPER forecasts more heavily in the first 12 h, but weighted the NWP model more heavily later in the forecast period.

3. Data

a. BMRC tropical NWP model

The data used in the BMRC tropical NWP model forecasts are taken from the global validated data archived by the Australian Bureau of Meteorology in 10° × 10° latitude/longitude box files. These data are used to create the input numerical analysis for both forecasting and verification purposes. A bogusing scheme also is available in which the bogus- or pseudoobservations are treated as radiosonde observations. The bogused tropical cyclone is based on a composite Australian region tropical cyclone (Holland 1984).

b. CLIPER model

The data for the CLIPER model consist of 6-h "best" track observations/estimations of tropical cyclone date/time, position, central pressure, speed, and direction, and a binary indicator of whether the cyclone center is over land or ocean. These data are available in archived form, from 1958 to the present. Data prior to 1958 also are available but are regarded as too unreliable for use in both modeling and verification purposes.

4. Results

a. Forecast position errors

The combination method has been evaluated in a direct comparison with four other methods over a total of about 40 tropical cyclone tracks in the period 1984/85–1987/88. The other methods are the BMRC tropical NWP and CLIPER models used individually, the ECMWF global model as received by the Australian Bureau of Meteorology, and the current operational Australian Bureau of Meteorology scheme which is the statistical-synoptic-regression technique (REGR) developed by Keenan (1986).

The results of the comparison are summarized in Table 1. The mean tropical cyclone position error at 24 and 48 h has been reduced by the combination scheme. The combination scheme (COMB) recorded mean forecast errors of 157 and 312 km at 24 and 48 h, respectively. These errors were 15% less than the

TABLE 1. Mean tropical-cyclone position errors, based on independent "best track" data, of the five schemes evaluated in a comparison of performance over the four tropical cyclone seasons 1984/85–1987/88.

Method	Forecast interval (h)	Mean error (km)	Std dev. (km)	No. of forecasts
CLIPER	12	86	65	239
BMRC NWP	12	102	73	225
REGR	12	91	59	221
ECMWF	12	—	—	—
COMB	12	69	41	225
CLIPER	24	185	116	221
BMRC NWP	24	217	122	205
REGR	24	189	103	208
ECMWF	24	227	117	196
COMB	24	157	89	205
CLIPER	36	284	189	204
BMRC NWP	36	277	177	187
REGR	36	263	132	182
ECMWF	36	—	—	—
COMB	36	238	117	187
CLIPER	48	379	236	185
BMRC NWP	48	362	215	171
REGR	48	355	179	173
ECMWF	48	369	207	165
COMB	48	312	147	171

next best scheme (CLIPER) at 24 h and 17% less than the next best scheme (REGR) at 48 h.

The significance of the mean error reduction achieved by the combination method was assessed using the standard t-test, with the number of degrees of freedom adjusted to allow for the serial correlation between successive forecasts. The null hypotheses that the combination method had an identical mean error with any of the other techniques were each rejected at the 1% level or lower. In addition, the mean error of the combination method was lower than all the other techniques in every tropical cyclone season to which it was applied.

b. Case study: tropical cyclone Jason

An example of one of the more dramatic improvements in forecast performance obtained from the combination forecast is given in Fig. 1, which shows the "best track" observed cyclone position and the forecast tracks out to 48 h from the BMRC tropical NWP model, the CLIPER scheme, and the optimal linear combination of the BMRC tropical NWP model and CLIPER. The tropical cyclone is cyclone Jason and the initial analysis time is 0000 UTC 10 February 1987. There is little difference between the forecasts at 12 h, but from 24 h onwards the combination forecasts exhibits a clear reduction in forecast position error. At 48 h the position error for the BMRC tropical model forecast is 448 km, for CLIPER it is 407 km, and for the combination the position error has been reduced to 259 km.

c. The 1988/89 Australian tropical cyclone season

A real-time trial of the linear combination method was carried out during the most recent (1988/89) Australian region tropical cyclone season. In this trial, operational data, rather than best-track data, are used. This particular season was notable for a relative absence of tropical cyclones, with only six occurring in the region of interest by early April 1989. The performance of the schemes is summarized in Table 2, and confirms

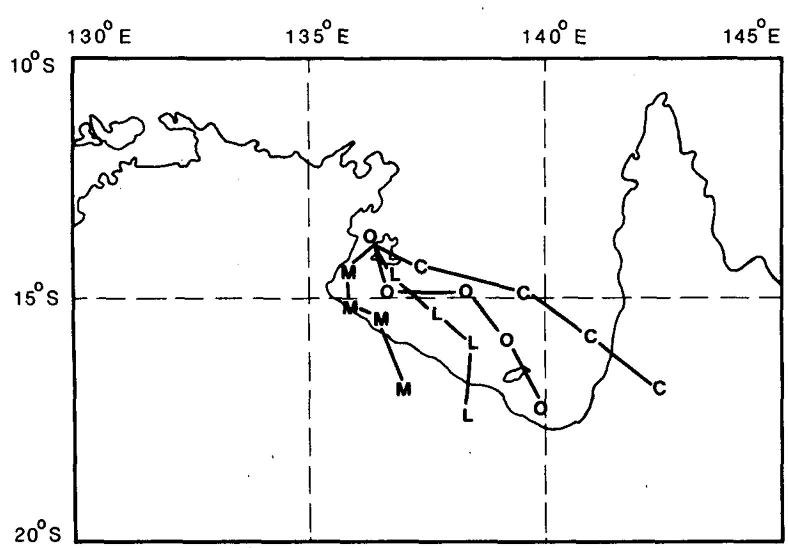

FIG. 1. Comparison of forecast tracks of tropical cyclone JASON for the period 0000 UTC 10 February 1987 to 0000 UTC 12 February 1987. The observed "best track" is denoted by O; the CLIPER scheme by C, the BMRC NWP model by M; and the optimal linear combination of C and M by L, for 12-, 24-, 36- and 48-h forecasts.

the findings of section 4a that, again, the combination method is the best of all those tested.

The most significant of the tropical cyclones in the 1988/89 season was cyclone AIVU which struck the north Queensland coast at about 0900 local time on 4 April 1989. The forecast tracks for a selection of predictive techniques is shown in Fig. 2. The most notable feature of the combination forecast in this case is that it located the landfall position to within 80 km at 48 h. However, the forecast time of land fall was nearly 12 h later than observed.

5. Conclusions

It has been shown that the mean position errors of tropical cyclone forecasts may be reduced significantly, simply by combining independent prediction techniques in an optimal linear manner.

The linear combination of a statistical scheme (an Australian region CLIPER) and a numerical weather prediction model was compared on "best track" data with four other methods available to the Australian Bureau of Meteorology for tropical cyclone track forecasting. It was found that the combination method was superior to all the other methods, and recorded mean-position errors at 24 h and 48 h of 15% and 17%, respectively, lower than the next best method.

The method also was used in real-time trial on operational data during the 1988/1989 Australian tropical cyclone season. Similar reductions in mean position errors were found.

The optimal linear combination of statistical and numerical prediction schemes has proven to be sufficiently superior to existing forecast techniques used by the Australian Bureau of Meteorology for it to be implemented operationally in next tropical cyclone season (1989/1990). It eventually will be part of an integrated tropical cyclone analysis and forecasting package based on an "expert" system now being developed by the Australian Bureau of Meteorology.

TABLE 2. Mean position errors of the five predictive schemes in the real-time trial using operational data for the 1988/1989 Australian region tropical cyclone season. The schemes are the same as in Table 1. A total of only six cyclones occurred during this season up to early April 1989.

	Forecast period			
Scheme	12 h	24 h	36 h	48 h
CLIPER	84	175	262	347
BMRC NWP Model	92	201	257	342
REGR	86	173	258	340
ECMWF Model	—	195	—	364
COMB	61	143	232	309

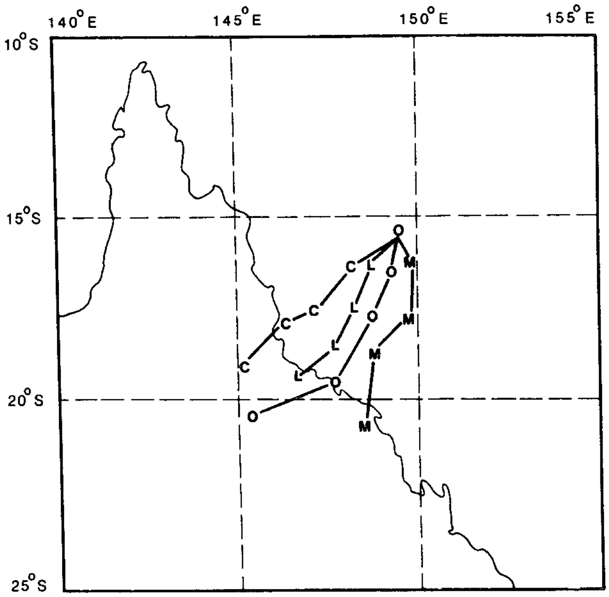

FIG. 2. As in Fig. 1 except for tropical cyclone AIVU, for the period 1200 UTC 2 April 1989–1200 UTC 4 April 1989.

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