The Basic Relationship between Tropical Cyclone Intensity and the Depth of the Environmental Steering Layer in the Australian Region

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ABSTRACT

A simple barotropic model is employed to investigate relative impacts on tropical cyclone motion forecasts in the Australian region when wind analyses from different tropospheric levels or layers are used as the input to the model. The model is initialized with selected horizontal wind analyses from individual pressure levels, and vertical averages of several pressure levels (layer-means).

The 48-h mean forecast errors (MFE) from this model are analyzed for 300 tropical cyclone cases that cover a wide range of intensities. A significant reduction in the track forecast errors results when the depth of the vertically-averaged initial wind analysis depends upon the initial storm intensity. Mean forecast errors show that the traditionally-utilized 1000–100-hPa deep layer-mean (DLM) analysis is a good approximation of future motion only in cases of very intense tropical cyclones. Shallower, lower-tropospheric layer-means consistently outperform single-level analyses, and are best correlated with future motion in weak and moderate intensity cases.

These results suggest that barotropic track forecasting in the Australian region can be significantly improved if the depth of the vertically-averaged initial wind analysis is based upon the tropical cyclone intensity.

1. Introduction

There is little question that the environmental flow accounts for a large fraction of tropical cyclone motion (Elsberry et al. 1987). Previous studies of the steering concept concluded that tropical cyclone motion could best be approximated by either a mid-tropospheric level (500 or 700 hPa), or a mass-weighted deep layer-mean (DLM) flow field such as the vertically-averaged wind over the 1000–100-hPa layer. However, operational hurricane forecasters know from experience that, in general, weaker tropical cyclones move with a shallow lower-tropospheric flow while the more well-developed systems move with a deep-layer flow (Simpson 1971). The background on the development of environmental steering concepts is summarized in Elsberry et al. (1987).

The question pertaining to the optimum level, or layer, which best approximates tropical cyclone motion was quantitatively addressed by Dong and Neumann (1986). They found that the optimum depth of the deep layer for steering Atlantic hurricanes is greater than that for weaker tropical storms, and that deep-layer steering is generally better than single-level steering (in agreement with Pike 1987). Chan and Gray (1982) examined cases from three tropical cyclone basins including the Australian region, in which they documented the deviations of storm motion from selected levels/layers of environmental steering. Deep-layer steering was found to be a good descriptor of cyclone movement. These studies suffered somewhat from generality in that only broad intensity classes (tropical storm and hurricane) were considered.

In this paper we expand on this general approach in an attempt to identify the *specific* relationship between tropical cyclone intensity and barotropic motion in the Australian region tropical cyclone basin. The physical reasoning behind this suspected relationship is based on the hypothesis that an increase in intensity is generally associated with greater vertical development of the cyclonic vortex, which in turn is advected by an environmental flow of greater depth. A proper and detailed identification of the optimum steering layer will not only be useful for subjective predictions by operational forecasters, but can provide improved initial analysis input for statistical and barotropic track forecast models which initialize on layer-mean wind analyses (such as the operational barotropic model employed in Australia which uses a 1000–100-hPa deep

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layer-mean). These findings should also contribute to further studies of the environmental influences on tropical cyclone motion in the Australian region, through a more proper identification of the basic flow.

A nondivergent barotropic model is employed in this study to investigate the effects on track forecast errors by varying the initial wind analyses (environmental steering flow) based on current storm intensity. The results will allow for an assessment of the importance of the initial analysis and intensity information in barotropic track forecasting.

2. Data sample

Tropical cyclone "best track" data from Australian region storms are on archive at the Australian Bureau of Meteorology. This data set consists of 6-h information that includes the storm date/time, and observations/estimates of current position, central pressure, speed, and direction. Also on archive are the objective, operational mandatory-level wind analyses over the Australian region for the period 1971 to the present (Mills and Seaman 1990). Input to the nondivergent barotropic track-forecast model utilized in this study (discussed in the next section) is provided from a selection of these individual mandatory-level wind analyses, and mass-weighted layer-means derived from these horizontal analyses (Pike 1985). The selection process was based on subjective reasoning and previous studies (e.g., Dong and Neumann 1986; Pike 1987).

For the present study, 300 cases from 1971–1990 over the Australian region tropical cyclone basin (roughly 0–40°S and 100–170°E; see Fig. 1) were selected that cover a wide, but evenly-distributed range of intensities from depressions to very strong cyclones. The selection process only required each case to have 48 h of subsequent storm track for model forecast verification, and a 24-h separation between cases to help minimize serial correlations. The Australian region basin offers a severe test of environmental steering concepts since it is characterized by relatively strong vertical shear zones, early track recurvatures and poleward movement, and frequent continental influences (Peak and Elsberry 1984). These effects quite often result in nonpersistent, nonclimatological tracks (Holland 1984) and difficult forecasts (Pike and Neumann 1987).

3. Model description

The procedures for analyzing the wind field and predicting the forecast track are: 1) the removal of the tropical cyclone vortex from the initial wind analysis and replacement with the environmental flow; 2) a nondivergent barotropic forecast of the environmental flow field; and 3) a point (storm center) trajectory forecast based on the barotropic forecast of the environmental flow. This methodology was chosen to minimize the variance of the tropical cyclone motion due to the vortex specification and interaction, and to focus

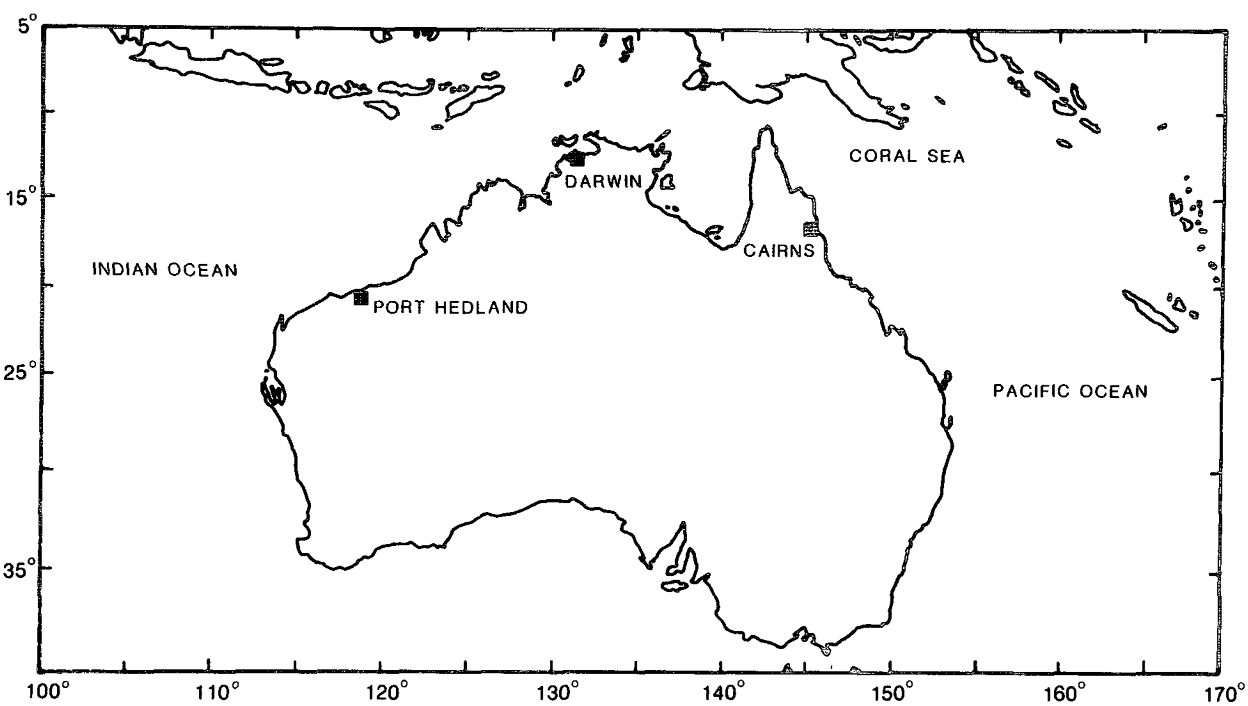

FIG. 1. Australian region tropical cyclone domain.

specifically on the effects of varying the environmental flow field.

The axisymmetric tropical cyclone vortex is removed from the initial objective wind analysis by zeroing out all grid point values within a specified radius of the storm center. This radius is determined from the operationally-analyzed outermost closed isobar. Bi-linear interpolation from surrounding grid point values just outside the specified radius is used to re-assign values to all grid points that were zeroed out. This simple procedure, in effect, approximates the environmental flow over the original vortex region.

The environmental flow is assumed to be governed by the nondivergent barotropic vorticity equation, which expresses conservation of the vertical component of absolute vorticity following parcels on a sphere:

$$\frac{\partial \zeta}{\partial t} + \tilde{V} \cdot \tilde{\nabla} (\zeta + f) = 0, \quad (1)$$

where $\tilde{V}$ is the horizontal, nondivergent wind, ζ is the relative vorticity on a sphere, and f is the Coriolis parameter. Since $\tilde{V}$ is nondivergent, we may write its eastward (u) and northward (v) components in terms of a stream function:

$$u = -\frac{\partial \psi}{\partial y}, \quad v = \frac{\partial \psi}{\partial x}. \quad (2)$$

Here, x and y are, respectively, the eastward and northward coordinates along the surface of the sphere. Changing coordinates to latitude (ϕ) and longitude (λ), and making use of (2), the relative vorticity is then:

$$\zeta = \nabla^2 \psi = \frac{1}{r^2 \cos\phi} \frac{\partial}{\partial \phi}\left(\cos\phi \frac{\partial \psi}{\partial \phi}\right) + \frac{1}{r^2 \cos^2\phi} \frac{\partial^2 \psi}{\partial \lambda^2}, \quad (3)$$

where r is the earth radius, and ∇^2 is the Laplacian operator in spherical coordinates. The streamfunction-vorticity tendency equation becomes

$$\frac{\partial \zeta}{\partial t} = \frac{1}{r^2 \cos\phi}\left[\frac{\partial(\zeta + f)}{\partial \lambda} \frac{\partial \psi}{\partial \phi} - \frac{\partial(\zeta + f)}{\partial \phi} \frac{\partial \psi}{\partial \lambda}\right] = (\nabla^2 - R^{-2}) \frac{\partial \psi}{\partial t}, \quad (4)$$

that is,

$$\frac{\partial \psi}{\partial t} = (\nabla^2 - R^{-2})^{-1} \frac{\partial \zeta}{\partial t} \quad (5)$$

where R is the internal Rossby radius of deformation, which we take to be 1000 km. This additional term is included to take into account the first internal mode. Without this term, Cressman (1958) has shown that there is an unrealistic retrogression of long waves in nondivergent barotropic models.

The model equations are solved using leapfrog time differencing and centered spatial differencing on a limited-area, latitude-longitude grid located over the Australian region analysis domain (Fig. 1). The latitude and longitude increments are equal and fixed at one degree. Since the model domain is confined to lower latitudes, numerical problems with this finite-difference scheme at higher latitudes (e.g., convergence of the meridians, singularities at the poles) do not arise. The solution procedure is as follows: the vorticity field is calculated from (3). Then the forcing term is computed from (4). Next, the Hemholtz equation (5) is solved for $\partial\psi/\partial t$. Finally, the streamfunction is updated in time.

Because of the limited model domain, it is necessary to specify horizontal boundary conditions for $\partial\psi/\partial t$ when inverting the Laplacian. The simple boundary condition employed in our sensitivity studies is $\partial\psi/\partial t = 0$. This is applied to the two outermost sets of points. In addition, a Rayleigh-type relaxation term is added to (4) for the next three sets of points inward. This term is proportional to $\partial\psi/\partial t$ and is intended to nudge $\partial\psi/\partial t$ towards zero over this region. The coefficient of the term has a maximum value of $2/r^2 \cos\phi\Delta\lambda\Delta\phi$ and decreases linearly to zero in the interior of the domain. Here, $\Delta\lambda$ and $\Delta\phi$ are the longitude and latitude increments, respectively.

The final step is a simple trajectory procedure which follows a point (storm center) in the fluid (environmental flow) during the barotropic model integration (Velden et al. 1984). This step is necessary because of the elimination of the vortex (and associated vorticity center) as described above. The trajectory begins at the specified storm center location, and is calculated after each time step based on the barotropic forecast of the environmental flow.

TABLE 1. Mean track forecast errors (km) from various wind analyses used to initialize the barotropic track forecast model. The number of cases is 300. The lowest MFE for each period is underlined.

	Forecast interval (h)			
	12	24	36	48
Single levels (hPa)				
850	108	211	280	381
700	106	209	272	375
500	111	216	286	389
400	117	226	297	415
Single-level combinations (hPa)				
850, 200	125	239	311	437
850, 500, 200	117	221	293	412
850, 400, 200	118	228	305	427
Layer-means (hPa)				
1000–100	93	193	267	359
850–200	89	189	249	346
850–300	<u>85</u>	183	242	<u>336</u>
850–400	87	<u>182</u>	<u>240</u>	338
850–500	89	186	246	341
700–400	94	197	251	351
700–500	96	202	254	356

TABLE 2. 48-h mean track forecast errors (km) from various layer-mean wind analyses used to initialize the barotropic track forecast model for specified tropical cyclone intensity classes. The total number of cases is 300, which are fairly evenly distributed among intensity classes. The lowest forecast error for each intensity class is underlined.

Intensity class (hPa)	>1005	995–1005	985–995	975–985	965–975	955–965	945–955	935–945	<935
No. of cases	25	25	25	25	50	50	25	25	50
Layer-means (hPa)									
1000–100	389	374	367	364	367	364	347	338	324
850–200	383	365	357	355	348	339	328	326	313
850–300	371	362	355	351	331	332	310	304	302
850–400	343	341	349	344	322	316	334	341	339
850–500	332	331	332	337	332	329	356	360	356
700–400	348	338	347	342	345	341	361	365	368
700–500	342	331	340	346	359	367	372	377	372

This forecast procedure is both simple and economical, and has been employed in previous sensitivity/impact studies (Velden et al. 1984; Velden 1990). It is appropriate for use in our analysis as it provides for a forecast based purely on the specified environmental steering current. The results presented in the next section are based upon 48-h forecasts from this model.

4. Results

We first consider the relative performance of selected single-level wind analyses, single-level combinations (with individual levels given weights determined by regression equations provided by the ERL-Hurricane Research Division), and vertically averaged (mass-weighted) tropospheric layer-means as input to the model for the entire sample, before stratifying by storm intensity. Mean forecast errors (MFEs) for the 300 cases are shown in Table 1. Care must be taken in the interpretation of this table. As we will show later in the text, storms with different intensities move with different flow regimes and inherent forecast difficulty levels. Since we deliberately chose a sample with an evenly-distributed range of intensities, and not a climatological intensity distribution, generalizations about Australian region tropical cyclone steering cannot be gleaned from this particular table. The focus is on the relative differences between the MFEs for a sample with evenly-distributed intensities.

Table 1 shows 12, 24, 36, and 48-h forecasts (km) from the barotropic model initialized with selected wind analyses. Considering first the single-level analyses, the results show that the MFEs for 700 hPas are slightly lower than 850 hPa, moderately lower than 500 hPa, and significantly lower (student-t test 95% significance level will be used throughout the paper) than the 400-hPa MFE. The MFE from the selected single-level combinations are generally higher than the single-level MFE, which suggests that adding upper-tropospheric (outflow region) information is detrimental to approximating the steering current, at least in the context of barotropic track forecasting.

A substantial reduction in MFE occurs when layer-mean fields are used as input to the model. Overall, the 850–300 and 850–400-hPa layer-means yield the lowest MFE, and are significantly lower than the MFE from the optimum single-level (700 hPa) and the 1000–100-hPa DLM commonly utilized in operational models that incorporate layer-mean wind analyses as input. This supports the findings of previous studies (e.g., Dong and Neumann 1986; Pike 1987) that tropospheric layer-means, as opposed to single-levels, should be used to provide the best approximation to environmental steering. However, at least in the Australian region, the traditional 1000–100-hPa DLM is not the optimal layer. This supports our previous observation and the contention by Holland (1984) that boundary and outflow layer asymmetries do not contribute to the basic current, and may even introduce variance, at least in the context of barotropic environmental steering. [Upper-tropospheric synoptic-scale circulations such as TUTT cells (Sadler 1976, 1978),

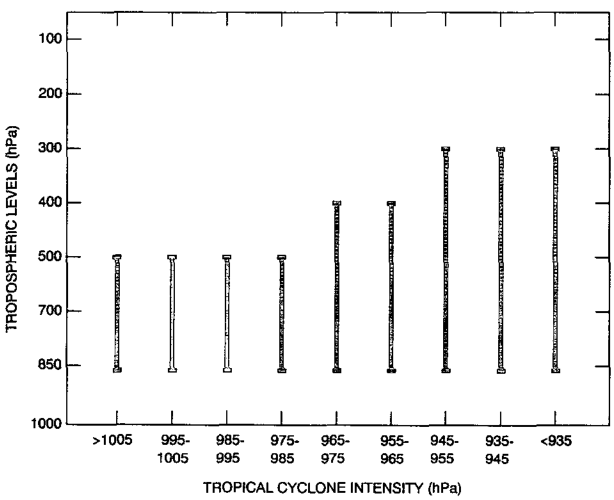

FIG. 2. The relationship between tropical cyclone intensity (MSLP) and the depth of the steering layer in the Australian region. The thick bars indicate the layer-mean wind analysis that provides the optimum 48-h track forecast in each intensity category. (Note: as indicated in Table 2, there was a tie between the 850-500- and 700-500-hPa layer-means for the 995-1005-hPa intensity category).

or mobile, mid-latitude troughs (Velden 1987) can influence the cyclone path, but these baroclinic interactions are not considered here.] Holland (1984) also suggests the general use of the 850–300-hPa layer for approximating the basic current in Australian tropical cyclones. As discussed later, this layer is valid for intense systems, but is not optimum for weaker storms.

Given the results shown in Table 1, only the layer-mean fields are examined further. The MFE differences between the "best" three or four layer-means are quite small, and an optimal layer-mean is not obvious. This is especially true given the evidence presented later in the text that intense storms (in which the 850–300-hPa layer-mean is optimum) exhibit lower overall MFE than weaker storms. It is emphasized that these results should not be interpreted as a general finding for the Australian region basin, since our sample intensities are intentionally evenly-distributed, and not based on climatology.

To investigate the influence of intensity (*defined as the current minimum sea level pressure,* MSLP) on the selection of the optimum steering layer, the sample is stratified into 10-hPa intensity classes shown in Table 2 (while only the 48-h MFEs are shown, similar results were found at other forecast intervals). From Table 2, our objective results seem to confirm intuitive reasoning that the motion of weaker storms is best approximated by shallow layer-means, and intense storms by deep layer-means. Figure 2 graphically represents the relationship between the optimum steering layer (lowest MFE) and intensity. It is clear that a general relationship exists, although due to the somewhat narrow intensity stratification, the differences in MFEs in Table 2 are generally not significant. This may, in part, be due to the variance in the best track intensity estimates that were derived almost solely from satellite techniques that were evolving during the period of this study (Holland 1981).

It is suggested from Fig. 2 that a re-stratification into three broader intensity classes (>975, 955–975, <955 hPa) would adequately represent the steering/intensity relationship. This broader intensity stratification will also reduce the likelihood of variance due to unrepresentative intensity estimates. The MFEs (48-h) are presented in Table 3, and show that the 850–500-hPa layer is optimal for less intense storms with central pressures higher than 975 hPa; the 850–400-hPa layer is optimal for storms with central pressures between 955 and 975 hPa; and the 850–300-hPa layer is optimal for the most intense storms with central pressures lower than 955 hPa. The 850–200-hPa layer provided the lowest MFE for storms with central pressures lower than 925 hPa. However, the very small number of cases prevented this result from being significant, and is not shown. Differences in the MFE between the layer with the lowest and next lowest values are significant for each intensity category. Table 4 presents a summary of the variability of these results. Shown for each layer-mean are the number of forecasts that yielded the best (and worst) 48-h position errors relative to the other layer-means, for each intensity category. The highest number of optimal forecasts in each intensity category corresponds to the layer-mean with the lowest MFE shown in Table 3, suggesting a strong degree of consistency in the results.

TABLE 3. As in Table 2, except for different intensity classes.

Intensity class (hPa)	>975	955–975	<955
No. of cases	100	100	100
Layer-means (hPa)			
1000–100	374	365	336
850–200	365	344	322
850–300	360	332	305
850–400	345	318	338
850–500	333	330	357
700–400	344	343	365
700–500	340	356	374

TABLE 4. A summary of the variability of the results in Table 3. The numbers indicate how many times each particular layer-mean yielded the best (worst) forecast for each intensity category.

Intensity class (hPa)	>975	955–975	<955
No. of cases	100	100	100
Layer-means (hPa)			
1000–100	6 (32)	8 (16)	16 (8)
850–200	5 (27)	10 (8)	23 (5)
850–300	6 (17)	20 (9)	34 (2)
850–400	21 (8)	31 (4)	17 (12)
850–500	36 (4)	13 (11)	3 (24)
700–400	12 (7)	14 (20)	4 (22)
700–500	14 (5)	4 (32)	3 (27)

Similar results are also found with the 12-, 24-, and 36-h MFE (not shown), and specifically identify the greater depth of the optimal deep-layer environmental steering relative to increasing tropical cyclone intensity in the Australian region. This information should be very useful to operational forecasters for subjective purposes, and can be employed to more appropriately initialize operational statistical and barotropic numerical track forecast models.

To illustrate further the varying flow regimes and resulting track forecasts depending on layer-mean depth and storm intensity, two examples of individual cases are presented. These examples were deliberately chosen to show a typical case, and a dramatic one. The first case involves a weak storm and shows the typical differences in track forecasts that occur depending on which layer-mean wind analysis is used to initialize the model. The second case highlights a strong storm, and shows the dramatic differences in track forecasts that can occur.

a. Tropical cyclone Lena (1983)

Lena developed from a weak tropical low on 1 April and initially moved southwestward (Fig. 3). The storm

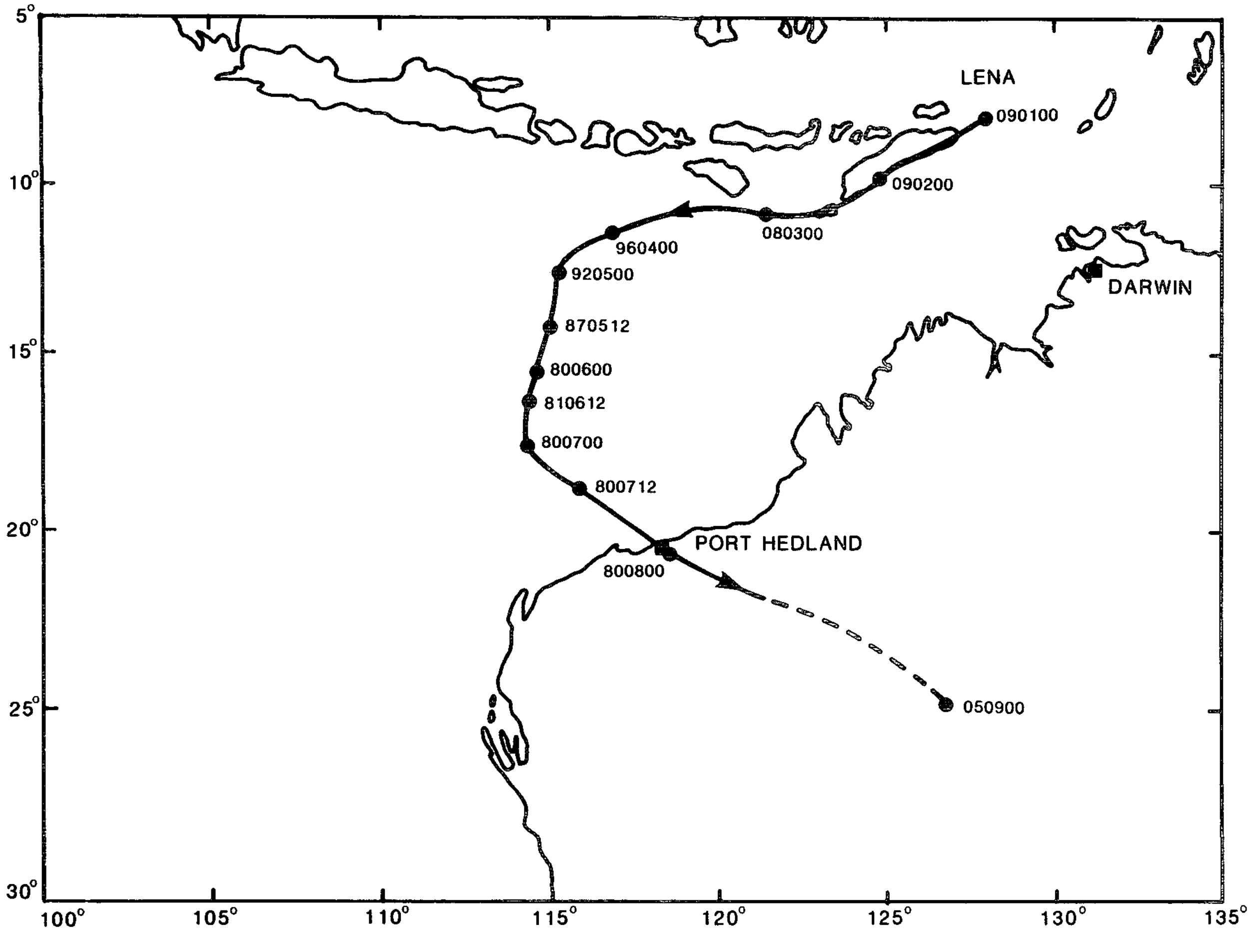

FIG. 3. Track of tropical cyclone Lena during April 1983. The numbers indicate MSLP (87 = 987 hPa), date (01 = 1 April) and time (12 = 1200 UTC), respectively.

then tracked in a westerly direction until 4 April, at which time it reached tropical cyclone status with an estimated central pressure of 994 hPa. Lena then turned southward and deepened to 980 hPa before recurving on 7 April and moving rapidly to the southeast, crossing the Australian coastline near 0000 UTC 8 April. Throughout its lifetime, Lena was a relatively weak system.

To show the impact of properly initializing the barotropic forecast model with a shallow layer-mean wind analysis in a weak cyclone event (as found in our results above), 48-h track forecasts from 1200 UTC 5 April initialized with the 850–500-, 850–300-, and 1000–100-hPa layer-mean wind analyses are presented. The forecast tracks are shown in Fig. 4, while the track forecast errors are given in Table 5. Although the forecast track differences in this case are not dramatic, the shallower layer-mean clearly yields the best results. The track forecast errors of the model initialized with the 850–500-hPa layer-mean are 20–30% lower than with the 1000–100-hPa layer-mean, and illustrate the fact that the motion of this relatively weak cyclone is best approximated by the lower-tropospheric flow, which in this case has more of a component towards the west than its deep-layer counterpart.

It should be noted that a considerable track forecast error still exists even with the use of the "optimal" 850–500-hPa layer-mean initial analysis. While we considered a reasonable number of layer-mean combinations, it is possible that in some individual cases such as this one, the optimal steering level or layer-mean is one we did not consider (e.g., perhaps in this case the 850–700-hPa layer-mean would be "optimal"). The forecast errors could also be due to analysis uncertainties, model errors, and the fact that we are not considering the beta effect. However, the point is clear in this case and in other more dramatic cases we examined, that in general the weaker intensity systems are steered by the lower-tropospheric flow identified in this study as the 850–500-hPa layer-mean wind.

b. Tropical cyclone Kerry (1979)

The second case involves a very intense storm which occurred during February–March 1979, with an aircraft

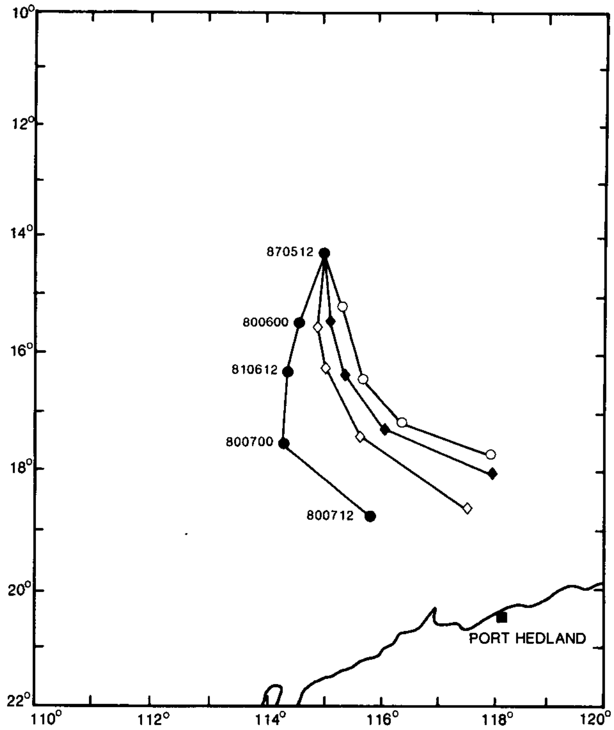

FIG. 4. 48-h track forecasts initialized at 1200 UTC 5 April, along with verifying track for Lena (● – – ●). Forecasts were initialized with the 850–500- (◇ – – ◇), 850–300- (♦ – – ♦), and 1000–100- (○ – – ○) hPa layer-mean analyses.

recorded sustained wind speed of 140 kt being one of the strongest winds ever observed from an Australian tropical cyclone. Kerry's track was a very long one, and is most notable for its erratic behavior, as evidenced in Fig. 5. By 15 February, as Kerry entered the Australian region, it was already classified as a severe tropical cyclone. The central pressure decreased to 943 hPa on 19 February. In the period of 19–26 February, Kerry moved in a large loop before heading westward towards the eastern Australian coast. In the next week or so, Kerry persisted near the coast before finally accelerating to the southeast and weakening.

Track forecasts were initialized at 1200 UTC 18 February, near the time when Kerry was most intense. As in the previous case, the forecasts from the 850–500-, 850–300-, and 1000–100-hPa initial wind analyses are compared both graphically (Fig. 6), and quantitatively (Table 6). In contrast to the weak case presented above, the best forecast in this case results when the model is initialized with a deep-layer mean (850–300 hPa). This illustrates an example of an intense system which is characterized by a well-developed (vertically) vortex which moves with a deeper flow. Note, however, that the traditionally-utilized 1000–100-hPa DLM results in an inferior forecast, indicating possible negative effects on approximating the vortex motion from the inclusion of the inflow and outflow regions, as discussed earlier. The areal-averaged upper-tropospheric flow at and above 200 hPa at this time was a weak southeasterly, while the 1000-hPa flow was from the east, resulting in the northwest shift of the 1000–100-hPa track relative to the 850–300-hPa track.

It is interesting to note from Table 3 that the optimum layer MFEs for the intense storms (<955 hPa) are significantly lower than the optimum layer MFE for the weaker storms (>975 hPa). This finding is consistent with the results of Dong and Neumann (1986) for easterly moving Atlantic hurricanes versus tropical storms. This could be physically related to the more persistent nature of deep-layer steering associated with the more intense storms, but could also be attributed to increased initial positioning errors associated with weaker systems (DeMaria et al. 1990).

The overall MFE when the optimal layer (based on the three intensity categories) is used in each individual case (dependent sample) to initialize the model is shown in Table 7. This method results in a significant reduction in MFE (up to 12% at 48 h) over that of a fixed-layer (1000–100 hPa) initialization that does not include intensity information (i.e., the current operational procedure at the Bureau of Meteorology in Australia). This is quite a remarkable improvement given that the experiment involves only a modest change in the initial analyses provided to the forecast model.

While relative comparisons are the main focus of this paper, the forecast results using the optimal layer are also compared, in an absolute sense, to persistence and the official track forecasts from these 300 cases to assess the competitiveness of this numerical guidance (Table 7). It is shown that the MFE are much lower than persistence, and quite competitive with the official forecasts (derived from operational storm positions). This is despite the fact that the model is governed solely by environmental steering, and does not include the contributions to motion from linear and nonlinear effects of vortex propagation.

5. Discussion

The results show that the initialization of a barotropic tropical cyclone track forecast model with a variable-depth wind analysis that best approximates the

TABLE 5. Track forecast position errors (km) for weak tropical cyclone Lena (987 hPa) from 1200 UTC 5 April 1983. A comparison is made between model forecasts initialized with the 850–500-, 850–300-, and 1000–100-hPa layer-means.

	Forecast interval (h)			
	12	24	36	48
Layer-mean (hPa)				
850–500	47	106	134	202
850–300	63	129	171	249
1000–100	71	147	189	268

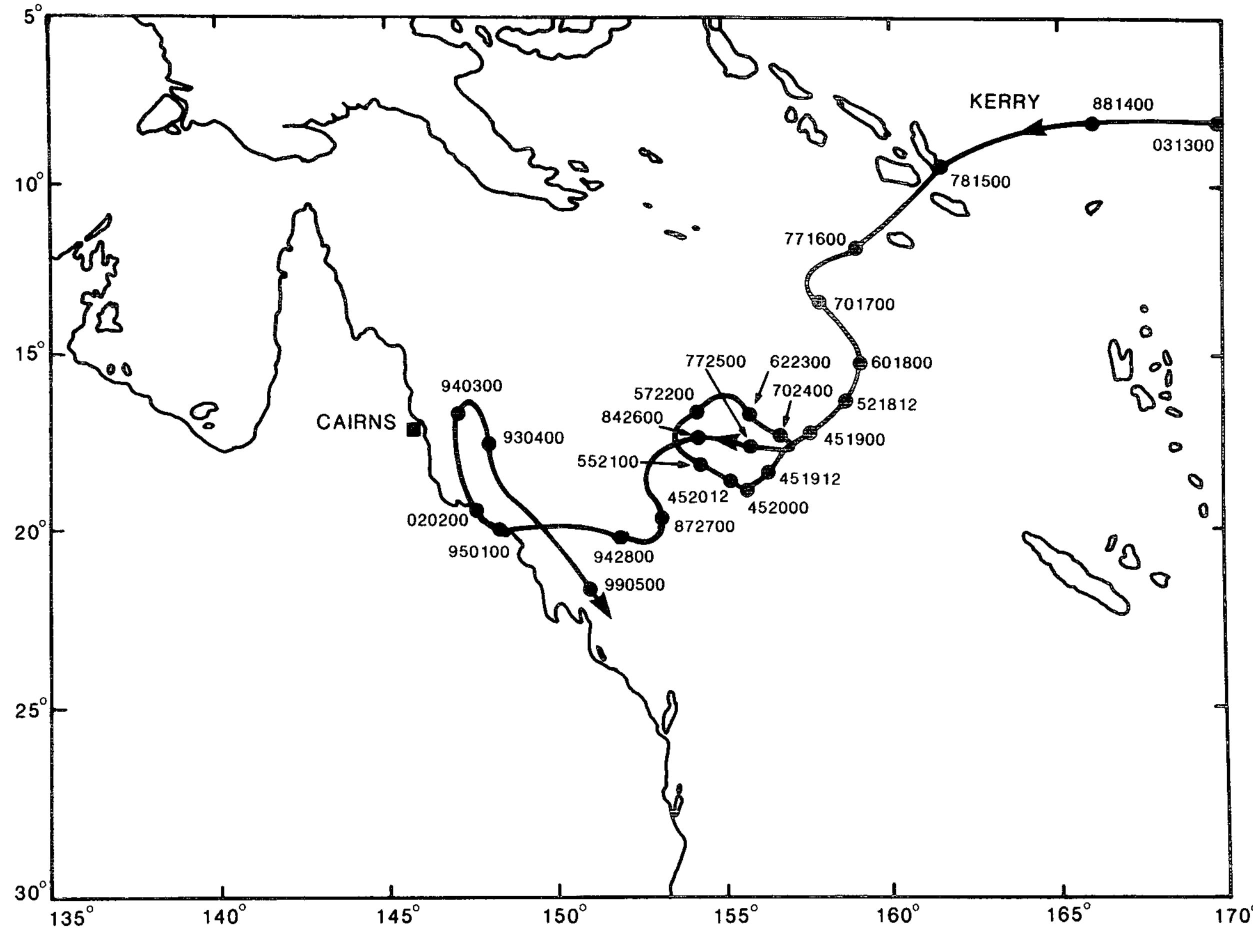

FIG. 5. Track of tropical cyclone Kerry during February and March of 1979. The numbers are as explained in Fig. 3.

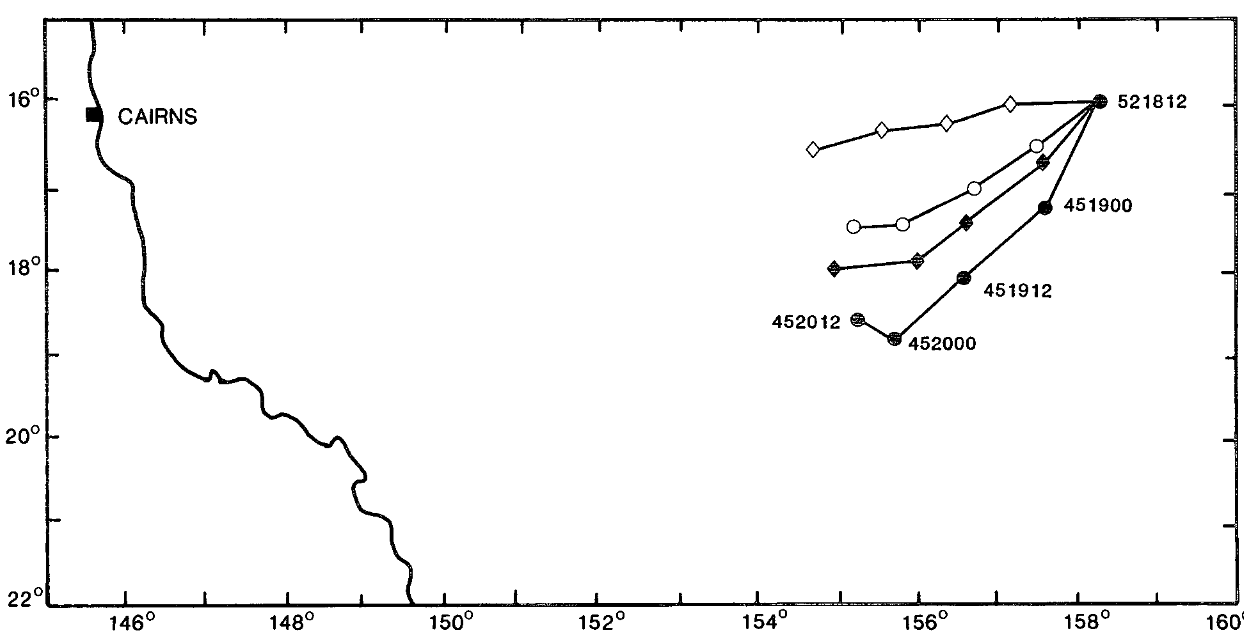

FIG. 6. 48-h track forecasts initialized at 1200 UTC 18 February, along with verifying track for Kerry (● – – ●). Forecasts were initialized with the 850–500- (◇ – – ◇), 850–300- (♦ – – ♦), and 1000–100- (○ – – ○) hPa layer-mean analyses.

environmental steering can significantly reduce the MFE relative to a "fixed-depth" analysis. The current operational schemes at the Australian Bureau of Meteorology utilize a 1000–100-hPa DLM in all forecast situations regardless of intensity, as does the operational SANBAR barotropic model (Sanders et al. 1975) in the Atlantic and eastern North Pacific basins. This study shows that the selection of the optimum wind analysis is dependent on storm intensity, with tropospheric layer-means outperforming single-level analyses. The model MFE for weaker systems (>975 hPa) are minimized using the 850–500-hPa layer-mean, while the optimal wind analysis for very intense storms (<955 hPa) is the 850–300-hPa layer-mean.

These findings for the Australian region support the intuitive concept that the depth of the environmental steering increases with tropical cyclone intensity. The fact that a strong relationship was found in this tropical cyclone basin, which is characterized by relatively weak environmental flow regimes and erratic tracks, suggests that the basic concept would apply in other basins. In fact, Dong and Neumann (1986) found similar results in the Atlantic, although their stratifications and optimal layer-means differed somewhat.

There are physical and environmental factors which can affect the basic relationships and optimum steering layer-means. Some of these (storm latitude, intensity tendency, season, specific area of development, and environmental easterlies versus westerlies regimes) will be a subject of future work, and can be incorporated into the operational schemes. There are other situations that could lead to deviations from the above results in individual storm events. Initial analysis and intensity estimate uncertainties (Holland 1981), land effects (Holland 1984), and strongly sheared environments (Chan and Gray 1982); or subtropical "hybrid" developments might require special considerations.

The tropical cyclone vortex was eliminated from the flow field in our study to isolate the effects on forecast motion exclusively by the environmental flow. Thus, we have not considered the potential effects of the variable-depth analyses on the component of tropical cyclone motion associated with vortex propogation (Chan and Williams 1987; Fiorino and Elsberry 1989). However, these findings may be important to studies of the interaction of the vortex with the environment by more accurately defining the basic flow.

TABLE 6. Track forecast position errors (km) for strong tropical cyclone Kerry (945 hPa) from 1200 UTC 18 February 1979. A comparison is made between model forecasts initialized with the 850–500-, 850–300-, and 1000–100-hPa layer-means.

	Forecast interval (h)			
	12	24	36	48
Layer-mean (hPa)				
850–500	127	210	246	238
850–300	59	76	105	82
1000–100	86	112	137	121

TABLE 7. A comparison of mean track forecast errors (km) by different methods for the homogeneous sample of 300 cases. From the barotropic model forecasts, the operational layer-mean is the 1000–100-hPa DLM (fixed for all cases), and the optimum layer-mean (variable in each case) is based on the intensity stratification of Table 3. The official forecasts were made from operational initial positions and all others from best track position.

	Forecast interval (h)			
	12	24	36	48
Method				
Persistence	87	203	358	505
Official	96	201	280	382
Operational layer-mean	93	193	267	359
Optimum layer-mean	81	172	230	319

From an operational standpoint, the performance of the barotropic track forecast model with the inclusion of the intensity information should boost the confidence Australian forecasters have in the ability of these simple models to predict tropical cyclone tracks. There has been a tendency to overlook these models with the recent influx of sophisticated schemes and dynamic models. Certainly, the sheer simplicity of the model dynamics will explain much of the forecast position error in barotropic track forecasting. However, it is suggested from these results that a significant part of the forecast error can be attributed simply to the improper specification of the depth of the wind analysis used to initialize these models.

These results also suggest that intensity prediction could be very important to barotropic track forecasting. The plausibility exists of incorporating prognostic intensity information into the barotropic track forecast model (to determine if the optimum layer changes during the integration). Any additional reduction in track MFE will of course be dependent upon the ability to accurately forecast intensity. Current operational methods show limited skill, however, preliminary results of experimental schemes being tested at the Australian Bureau of Meteorology are showing promise (Leslie et al. 1990). The possibility of incorporating this prognostic intensity information into the track forecast model described here is being investigated.

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