THE USE OF QUANTITATIVE SURFACE CYCLONE CHARACTERISTICS TO DETERMINE SYSTEMATIC DEPARTURES FROM MEAN NESTED GRID MODEL FORECAST ERRORS

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ABSTRACT

An analysis of forecast errors for surface cyclones in the Nested Grid Model (NGM) has been completed for a sample of 500 cases. In general, the NGM is more likely to forecast a cyclone too deep, too far west, and too far north. The positive correlations between 48-, 36-, and 24-h forecast errors confirm that the NGM's forecast errors depend strongly on a cyclone's characteristics. Therefore, the expected systematic exceptions to the general errors are revealed by categorizing the cyclones according to readily determinable quantitative characteristics. These characteristics include a cyclone's position relative to the 500-mb height contour longwave pattern, its geographic location, and its forecast intensity. A review of previous studies suggests possible origins for some of the forecast errors.

1. INTRODUCTION

The purpose of this paper is to identify and explain systematic central pressure (hereafter called pressure) and displacement errors for cyclonic storm (hereafter called cyclone) forecasts of the National Meteorological Center's Nested Grid Model (NGM). These results should help forecasters improve on the NGM's cyclone forecasts by using corrections which vary with the cyclone's characteristics. Grumm and Siebers (1989) performed a similar study of the NGM's cyclone forecast errors. Our study extends their results by examining the influence of a larger set of cyclone characteristics on forecast errors using a data set approximately three times larger.

The hypothesis upon which this data analysis is based is that the NGM's 48-, 36-, and 24-h cyclone forecast errors are correlated. If this hypothesis is true, then cyclone forecast errors must be related directly to some fundamental characteristics of the cyclone, or else a cyclone would not suffer similar errors in successive model runs. As discussed in Section 3a, these errors are indeed significantly correlated.

We are using 3 parameters to classify a cyclone's type: position relative to 500-mb height contour longwave pattern, longitude, and intensity. For each parameter, we divide the cyclone sample between several categories. We then show the categorical breakdown of the pressure forecast errors, zonal displacement errors, and meridional displacement errors. This format permits the forecaster to use these results to determine the typical NGM cyclone forecast errors for any cyclone in an operational model run.

2. METHODOLOGY

Our sample is based on the NGM output from 24 January to 20 October 1988, not including June through August. The three month period studied by Grumm and Siebers (1989) immediately precedes this period.

A cyclone in this study is defined as a point of relatively low sea-level pressure that has a closed isobar (analyzed at 4-mb intervals) around its center at the verification time. The cyclone's verification pressure and location were defined as those of the low pressure center plotted on the NGM surface analysis. On the occasions when multiple low pressure centers were plotted within the inner closed isobar, the strongest was selected. If, in addition, there was a tie for the deepest low pressure center within this inner closed isobar, the cyclone position was taken to be the mean of the positions of the multiple centers.

For each cyclone at each verification time (the time for which all 3 forecasts are valid), we recorded the following information for each cyclone's center.

1) 48-, 36-, and 24-h forecasts of pressure, latitude, and longitude
2) verification of pressure, latitude, and longitude (based on the NGM initial analysis panel)
3) location relative to 500-mb height contour longwave pattern (see Fig. 1)

A total of 500 cyclone cases were studied. The cyclone's forecast pressure and location were defined as those of the low pressure center plotted on the NGM surface chart which was closest to the verification position. Because of the nature of this analysis technique, no consideration is given to cyclones which are forecast but not verified or vice versa. The latitude and longitude of the cyclone center are rounded to the nearest degree (approximately one model grid space), while the pressure is rounded to the nearest millibar. A

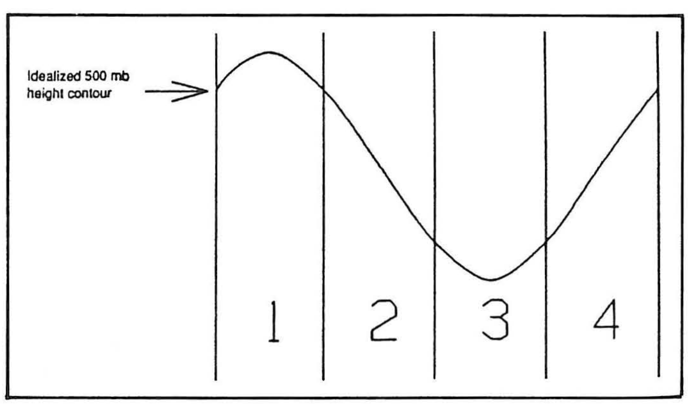

Fig. 1. Category number for a cyclone based on its position relative to the 500-mb height contour longwave pattern. Cyclones located under a closed low pattern are classified as category 5.

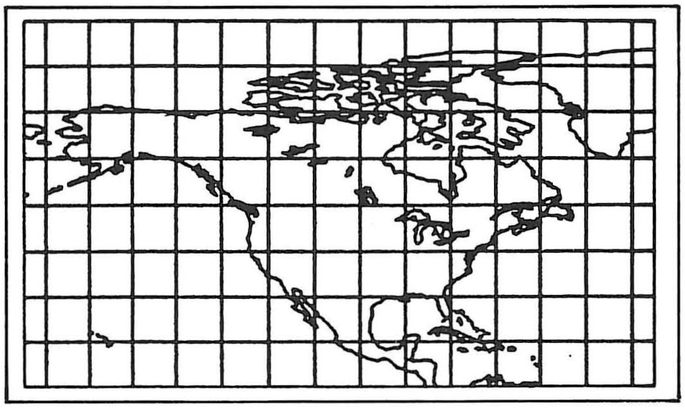

Fig. 2. The geographical area covered by this analysis encompasses 10° to 90° north latitude and 35° to 174° west longitude.

cyclone's location relative to the 500-mb height contours is subjectively determined to be in one of five categories using the verifying 500-mb analysis and verifying cyclone position. The geographical area covered by this analysis encompasses 10° to 90° north latitude and 35° to 174° west longitude (see Fig. 2).

We compute the forecast errors for each parameter by subtracting the observed value from the forecast value. Thus, a negative (positive) pressure error represents overforecasting (underforecasting) cyclone intensity, where intensity is defined as the lowness of the cyclone's pressure. A negative (positive) cyclone zonal displacement error indicates that a cyclone is forecast too far east (west). Similarly, a negative (positive) cyclone meridional displacement error indicates that a cyclone is forecast too far south (north). These displacement errors are converted to km to enhance their operational utility.

3. RESULTS

a. Errors for All Cyclones

Table 1 shows the mean and standard deviation of pressure and displacement errors for all cyclones. The mean error quantifies the systematic bias of the forecasts while the standard deviation measures the non-systematic component of the error, as pointed out by Wallace and Woessner (1981) and Harr et al. (1983). Together these statistics provide considerable insight into the degree and consistency of the errors.

At all lead times the model tends to overforecast the intensity. The mean error (bias) increases from the 48- to 24-h forecast. Because positive and negative errors will cancel each other in computation of the mean error, the standard deviation of the errors is a better indicator of the forecasts' consistency. This statistic steadily increases with increasing lead time. At all three lead times, the NGM forecasts cyclones too far north and west of the verifying position. Although we did not consider the possibility here, the NGM's biases may vary seasonally. Silberberg and Bosart (1982) found this to be the case with the LFM-II, whose slow bias almost disappears in the winter.

This study finds that 48-, 36-, and 24-h pressure errors are not statistically independent, thereby confirming the hypothesis discussed in the introduction. Instead, the errors for all forecast lead times tend to be related to the type of cyclone the model is dealing with in each case. Whichever physical or numerical effects cause the model to misforecast a cyclone at 48 h lead time will cause it to make a similar misforecast at 36 and 24 h. Table 2 shows the evidence supporting this conclusion. It lists the correlation coefficients between 24- and 36-h as well as 36- and 48-h values of pressure and displacement errors. Recall that a correlation coefficient of 0 indicates no correlation between the two variables, while a value of 1 indicates a perfect positive correlation. Here, the correlation coefficients range between 0.61 and 0.79.

Table 2. Correlation coefficients for mean pressure and displacement errors.

	Pressure	Zonal displacement	Meridional displacement
24- vs. 36-h error	0.73	0.61	0.63
36- vs. 48-h error	0.79	0.69	0.72

b. Errors Categorized by Cyclone Characteristics

1) *Position relative to 500-mb height contour longwave pattern*

Cyclone dynamics are known to depend strongly on the cyclone's position relative to waves and closed lows aloft. Therefore, we studied the relationship of cyclone forecast errors to this cyclone characteristic. Table 3 (4) shows the mean and standard deviation of the 48-h (24-h) pressure and displacement errors for cyclones in each 500-mb flow category (Refer to Fig. 1 for category explanation).

The magnitude and sign of the errors differ depending on the flow category. For example, the mean 48-h pressure error for all cyclones is −0.41 mb. However, it varies from −3.27 to +1.10 mb depending on the category. A similar degree of variation also occurs for the displacement errors. It will later be shown that similar variations in systematic errors occur for other methods of cyclone categorization.

Cyclones located beneath a 500-mb ridge show the largest mean pressure errors. In general, as a cyclone's position moves eastward from under a ridge to downstream of a trough, the mean forecast errors steadily decrease. Only cyclones under a closed low aloft show no significant tendency to be overforecast. Cyclones under a ridge, which exhibit the largest mean pressure errors, also have the smallest standard deviations of pressure errors, indicating that these errors are more consistent. Conversely, the NGM fore-

Table 1. Mean and standard deviation (in parentheses) of pressure and displacement errors for all cyclones. Errors are computed by subtracting the observed value from the forecast value.

	48-h		36-h		24-h	
Pressure (mb)	−0.41	(7.24)	−0.43	(5.81)	−0.66	(4.38)
Zonal displacement (km)	+54	(333)	+43	(280)	+41	(229)
Meridional displacement (km)	+77	(364)	+58	(302)	+30	(219)

Table 3. Mean and standard deviation (in parentheses) of 48-h pressure and displacement errors according to cyclone position relative to 500-mb height contour longwave pattern. See Fig. 1 for category explanation.

Category	Number of cases	Pressure error (mb)	Zonal displacement error (km)	Meridional displacement error (km)
1	11	−3.27 (4.84)	+118 (299)	+ 91 (494)
2	36	−1.89 (7.99)	+146 (382)	+145 (400)
3	91	−0.36 (6.49)	+ 75 (306)	+131 (376)
4	186	−1.40 (6.98)	+ 82 (335)	+ 81 (378)
5	176	+1.10 (7.55)	− 8 (325)	+ 30 (315)

Table 4. Mean and standard deviation (in parentheses) of 24-h pressure and displacement errors according to cyclone position relative to 500-mb height contour longwave pattern. See Fig. 1 for category explanation.

Category	Number of cases	Pressure error (mb)	Zonal displacement error (km)	Meridional displacement error (km)
1	11	−1.82 (2.98)	+127 (204)	−101 (138)
2	36	−1.53 (4.38)	+ 69 (356)	+114 (259)
3	91	−0.99 (4.23)	+ 6 (218)	+ 57 (212)
4	186	−0.79 (3.89)	+ 70 (216)	+ 26 (236)
5	176	−0.10 (4.90)	+ 18 (209)	+ 9 (191)

casts cyclone pressure less consistently for cyclones under a closed low aloft.

The NGM tends to forecast all categories too far west and north, with the exception of cyclones under a cutoff low, which tend to be forecast too far east at 48 h, and those under a ridge, which tend to be forecast too far south at 24 h. Cyclones located east of a ridge and west of a trough show the largest meridional displacement errors. Displacement errors are relatively small for cyclones under a closed low aloft.

2) *Cyclone intensity*

Because cyclone intensity is closely related to cyclone structure and dynamics the intensity may be related to cyclone forecast errors. Therefore, we examined the relationship between cyclone forecast errors and cyclone intensity. Rather than using the verification intensity, we categorized the cyclones using the 24-h forecast value of intensity. This procedure should increase the utility of the results to a forecaster, because prior to the verification time only the forecast intensity is known. Table 5 (6) shows the mean and standard deviation of the 48-h (24-h) pressure and displacement errors for each intensity category.

The model severely underforecasts cyclones deeper than 970 mb at 48 h, but this error disappears at 24-h lead time. The model forecasts cyclones with pressures deeper than 980 mb most erratically.

Cyclone displacement errors also depend on intensity. The NGM tends to forecast cyclones weaker than 1009 mb too

Table 5. Mean and standard deviation (in parentheses) of 48-h pressure and displacement errors according to cyclone intensity.

Intensity (mb)	Number of cases	Pressure error (mb)	Zonal displacement error (km)	Meridional displacement error (km)
< 970	13	+4.54 (9.39)	−126 (450)	+ 60 (178)
970– 979	30	+1.57 (12.5)	+ 79 (324)	+ 85 (275)
980– 989	98	−1.27 (6.61)	+ 82 (292)	+ 69 (311)
990– 999	178	−0.43 (6.51)	+ 79 (322)	+107 (394)
1000–1009	140	−0.31 (6.87)	+ 71 (345)	+ 66 (372)
>1009	41	−1.59 (5.87)	−135 (319)	+ 3 (400)

Table 6. Mean and standard deviation (in parentheses) of 24-h pressure and displacement errors according to cyclone intensity.

Intensity (mb)	Number of cases	Pressure error (mb)	Zonal displacement error (km)	Meridional displacement error (km)
< 970	13	−1.23 (5.51)	+21 (134)	0 (157)
970– 979	30	−2.70 (7.27)	− 6 (239)	+19 (138)
980– 989	98	−2.02 (3.71)	+65 (224)	+19 (208)
990– 999	178	−0.65 (4.31)	+60 (241)	+59 (218)
1000–1009	140	+0.45 (3.80)	+43 (231)	+21 (236)
>1009	41	+0.41 (3.11)	−67 (218)	−27 (236)

far east, while it forecasts most other cyclones too far west. Generally, the NGM forecasts cyclones too far north, with cyclones in the 990–999 mb range showing the largest mean errors. Differences in meridional displacement errors between intensity categories are small, although the strongest and weakest cyclones show less tendency to be forecast too far north. The more intense the cyclone, the more consistent the meridional displacement error is, as shown by the generally decreasing standard deviations of mean errors with increasing intensity.

3) *Longitude*

We categorized the cyclones according to longitude because cyclones in similar longitude ranges tend to be dynamically similar and occur in similar positions relative to the North American terrain. Table 7 (8) shows the mean and standard deviation of the 48-h (24-h) pressure and displacement errors for each longitude category.

Cyclones west of 94° W, especially West Coast and Rockies cyclones, are more likely to be overforecast than cyclones east of there. Cyclones over the Atlantic (east of 80° W) and Pacific (west of 149° W) Oceans are most likely to be underforecast. This pattern is similar to that reported by Grumm and Siebers (1989). Pacific cyclones show the largest standard deviation of pressure errors, while Rockies cyclones show comparatively small values. Only Plains and Rockies cyclones have eastward displacement errors, and even those only show at 48 h. Cyclones west of 94° W have much larger northward displacement errors than those east of there, which are more likely to be forecast too far south.

4. SUMMARY

We have completed an analysis of errors in the NGM's forecasts for cyclone pressure and position. The following generalizations could be tempered with the word "typically" because there are exceptions to all of them. The principal findings are as follows.

1) In general, the NGM
   a) overforecasts cyclones at all lead times
   b) forecasts cyclones too far north and west at all lead times
   c) shows a positive correlation between its 24- vs. 36-h and 36- vs. 48-h forecast errors
2) When considering a cyclone's 500-mb relative position, the NGM
   a) overforecasts cyclones under a ridge more than those in other positions
   b) is least likely to overforecast cyclones under a closed low aloft
   c) has the largest northern displacement errors for cyclones east of a ridge and west of a trough
3) When considering the cyclone's intensity, the NGM
   a) shows large underforecast errors at 48 h for cyclones deeper than 970 mb
   b) is most likely to forecast cyclones weaker than 1009 mb too far east and too far south
   c) has more consistent meridional displacement errors for stronger cyclones
4) When considering a cyclone's longitude, the NGM
   a) is more likely to overforecast western cyclones, especially those near the West Coast
   b) is more likely to underforecast Atlantic (east of 80° W) and Pacific (west of 149° W) cyclones at 48 h lead time
   c) forecasts cyclones west of 79° W too far north and those east of 65° W too far south

These generalizations and the information in Tables 1 through 8 can be compared with forecast cyclone characteris-

Table 7. Mean and standard deviation (in parentheses) of 48-h pressure and displacement errors according to cyclone longitude.

(°W)	Location	Number of cases	Pressure error (mb)		Zonal displacement error (km)		Meridional displacement error (km)	
< 65	Atlantic	78	+0.31	(6.55)	+ 96	(253)	− 83	(257)
65– 79	East Coast	39	+1.18	(5.10)	+106	(270)	+ 48	(335)
80– 94	Midwest	122	−0.64	(6.72)	+ 65	(264)	+ 29	(355)
95–104	Plains	53	−1.21	(6.54)	− 87	(241)	+220	(373)
105–119	Rockies	43	−1.79	(5.42)	− 29	(333)	+ 83	(435)
120–134	West Coast	33	−3.97	(5.80)	+211	(471)	+182	(376)
135–149	E. Pacific	55	−1.62	(8.64)	+117	(431)	+113	(347)
>149	Pacific	77	+2.16	(9.09)	+ 1	(377)	+156	(364)

Table 8. Mean and standard deviation (in parentheses) of 24-h pressure and displacement errors according to cyclone longitude.

(°W)	Location	Number of cases	Pressure error (mb)		Zonal displacement error (km)		Meridional displacement error (km)	
< 65	Atlantic	78	−0.23	(3.99)	+15	(198)	−10	(189)
65– 79	East Coast	39	−0.38	(4.05)	+68	(170)	−11	(165)
80– 94	Midwest	122	+0.46	(4.28)	+48	(210)	+ 2	(218)
95–104	Plains	53	−1.53	(4.32)	+49	(206)	+52	(251)
105–119	Rockies	43	−2.14	(3.28)	+39	(213)	+75	(260)
120–134	West Coast	33	−2.48	(2.99)	+ 6	(304)	+84	(252)
135–149	E. Pacific	55	−0.71	(4.66)	+21	(271)	+42	(202)
>149	Pacific	77	−0.77	(5.23)	+67	(259)	+61	(205)

tics to estimate the NGM forecast error. Because of the statistical nature of this analysis a cautionary note is in order. Forecasters should never make systematic error corrections without surveying the complete weather situation. Also, while we used the NGM analysis to determine the accuracy of the NGM's forecasts, the actual pressure of a cyclone may differ from what the NGM analysis indicates.

5. DISCUSSION

We use the term systematic error to describe the NGM's tendency to show a bias in treating certain types of synoptic situations. As Harr et al. (1983) stated, shortcomings in the model (i.e., incomplete physics, grid resolution, numerical effects) are responsible for systematic errors in numerical weather prediction models. We have quantified the NGM's systematic errors, but it is difficult to qualitatively assess the origins of these errors.

Atlantic Ocean cyclones tend to be underforecast at 48-h lead time. These systematic underforecasts are less frequent in the Pacific, and in fact, cyclones in the East Pacific and West Coast areas tend to be overforecast. Grumm and Siebers (1989) found a similar pattern in their study of NGM cyclone forecast errors. Although the NGM predicts explosive coastal cyclogenesis more readily than the Limited-area Fine-mesh Model (LFM), it still routinely misses explosive cyclogenesis (Sanders 1987). To further illustrate the universal nature of this type of error in numerical models, we should add that Chen and Yang (1987) found that both the U.S. Navy's Operational Global Atmospheric Prediction System (NOGAPS) and the Japan Meteorological Agency's Finemesh Limited Area Model (JFLM) systematically underforecast the existence and genesis of oceanic cyclones, while Hodur (1987) found that the Navy Operational Regional Atmospheric Prediction System consistently underforecast oceanic cyclone intensity.

Davis and Emanuel (1988) suggested that the systematic underprediction of the rate of oceanic cyclogenesis is related to the amount of atmospheric warming that can occur through sensible heating from the ocean and condensation of evaporated sea water aloft. Orlanski and Katzfey (1987) used a nested limited-area model to predict the 1979 President's Day cyclone, and found that when running the model without latent heating, the cyclone was much weaker and failed to develop vertically. Sanders (1986) concluded that the tendency of explosive cyclogenesis to occur over western ocean regions is tied to diabatic processes because the maximum sea surface temperatures at a given latitude are located here. He also pointed out that these areas are downstream of climatological planetary trough axes and are regions of strong baroclinicity, both factors favorable for cyclogenesis. Mullen and Baumhefner (1988) found that total diabatic heating accounts for about one-half of an oceanic cyclone's deepening rate, with baroclinic dynamics accounting for the remaining part. Furthermore, the deepening rate resulting from diabatic heating is split evenly between the effect of the surface flux of sensible heat and the effect of latent heating caused by grid-scale resolvable precipitation associated with surface latent heat flux. Kuo and Reed (1988) found comparable results using the Penn State/National Center for Atmospheric Research mesoscale model to determine the relative effects of various physical processes in eastern Pacific cyclone development.

Inadequate model resolution can also contribute to the underforecasting of the rate of oceanic cyclogenesis (Chen and Yang 1987). Hoke (1987) found that expansion of the fine resolution inner grid in February 1987 dramatically improved the NGM's forecasts of explosive coastal cyclogenesis. The pressure forecast error decreased by several millibars in many cases while the forecast movement also improved. He cautioned, however, that the use of higher resolution in oceanic regions could actually be a disadvantage because it makes the model more sensitive to often poorly analyzed small-scale features here. All cyclones in our study were located in the new inner C-grid, but the underforecasting errors persisted.

Another grid related effect is that forecast cyclone development can be suppressed when the developing cyclone is on the inner grid, but is so close to its boundaries that the outer edges of the cyclone are affected by the coarser resolution of the surrounding grid (Hoke 1987). Chan (1986) found such results in the NOGAPS model's forecast of typhoon Abby. Here, Abby was such a large cyclone that its circulation extended well beyond the fine grid of the model, causing a poor forecast.

It is difficult to pinpoint what combination of effects causes the NGM's forecasting problems in oceanic regions. Without the NGM improvements in parameterizations of radiative and mixing processes and surface fluxes of heat, moisture, and momentum, these errors may have been worse. It isn't clear that further increasing spatial resolution would improve the forecasts, especially in light of Kuo and Reed (1988) finding that reducing the PSU/NCAR model's grid spacing from 80 to 40 km had a limited effect of forecast improvement. On the other hand, NOGAPS, which has a coarser horizontal grid than the JFLM, has mean cyclone position errors 11 % greater (Chen and Yang 1987).

The NGM shows sufficient skill to indicate that it is probably simulating all critical oceanic cyclogenesis processes, so a possible root of much of the forecast error is in faulty initial analyses. While the oceanic database is generally sufficient to verify surface characteristics of a cyclone, it is lacking in observations of the dynamically important midlevels. The fact that Pacific errors are larger than Atlantic errors supports this idea, as initial analyses in the Pacific are more suspect as a result of sparser ship and aircraft observations. Moreover, the Pacific is downwind of much sparser western Pacific data coverage. Using satellite imagery is an effective way of recognizing where there is a model initialization problem. The operational forecaster must take it upon himself to use dynamic concepts to modify model output to account for model initialization errors (Hales 1979). From these results it is concluded that the NGM is not incapable of predicting explosive oceanic cyclogenesis, but the problem is serious enough to warrant consideration.

In areas of the Pacific close to North America such as the Gulf of Alaska, the NGM tends to overforecast cyclones. Businger (1986) found that strong positive vorticity and low static stability were typical of days with mature polar cyclones in the Gulf of Alaska. He found that the rapid deepening of polar cyclones occurs with the outbreak of deep convection, concluding that polar cyclone outbreaks are triggered by the destabilization associated with a migratory shortwave aloft. Walter (1986) traced the beginnings of a rapidly developing Gulf of Alaska cyclone to an area of enhanced convective activity located beneath a cold core low. The surface heat flux was sufficient to cause deep convection to occur, and as this area approached a preexisting polar front to the south, a wave cyclone developed rapidly on the front. With these studies in mind, it is conjectured that the NGM's tendency to overforecast eastern Pacific cyclones may stem from an overestimation of the effect of surface heat fluxes in that region. The failure of the NGM to resolve the full effects of the steep coastal mountain ranges is another possible explanation.

Another major result of our analysis is the NGM's tendency to overforecast cyclones in the lee of the Rockies. Grumm and Siebers (1989) also found that the NGM overdevelops cyclones in this region. Chen and Yang (1987) found that both the NOGAPS and JFLM models tended to overforecast cyclones over the Tibetan plateau. They attributed this to unrealistic treatment of mountain effects. Leary (1971) and Silberberg and Bosart (1982) found similar results in an NMC 6-layer primitive equation model and the LFM-II, respectively. Leary (1971) attributed this effect to at least two factors. First, differences in methods used by the primitive equation model and observing stations to obtain sea level pressure may have accounted for the systematic errors. Second, the smooth topography of the model likely resulted in an underestimate of terrain drag, and therefore the overintensification of the cyclones.

McGinley and Goerss (1986) noted sharp differences of predicted lee cyclone pressure and position depending on the resolution of the terrain that was used in a numerical model. Given the failure of coarser mesh models to forecast the cases properly, high-grid resolution would seem to be a requirement for accurately predicting lee cyclogenesis. They also found that adjusting the initial wind fields to enhance the details of the mountain flow significantly improved the forecast pressure and position at both low and high levels.

The NGM's overdeepening of lee cyclones could also be blamed on its overestimate of the role of baroclinic instability, which may or may not always play an important part in developing a lee cyclone. Mattocks and Bleck (1986) studied lee cyclogenesis and found that lee pressure falls are highly correlated with the intensity of the jet streak over the mountain barrier. They found that the strongest lee pressure fall is not accompanied by a conversion of available potential energy to kinetic energy. Therefore geostrophic adjustment processes, rather than baroclinic instability, cause the rapid deepening of some lee cyclones. Because the NGM has problems with overdeepening lee cyclones, it may be overestimating some cyclone-inducing processes or underestimating some cyclone-dissipating processes. The most likely candidates are friction and baroclinic instability.

Prevention of systematic errors will involve improving the NGM's representation of dynamical and physical processes, a complex task requiring more than the qualitative analysis we have provided. It is difficult to prove which physical process parameterizations are the origin of each of the NGM's systematic errors. However, our results should prove useful for correction of these errors by the operational forecaster. Moreover, the statistical approach of our study or similar studies provides a strong basis for developing statistical schemes for correcting the NGM's cyclone forecasts.

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