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MODEL PERFORMANCE DURING EXPLOSIVE CYCLOGENESIS FOR TWO COLD SEASONS

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The Florida State University, 1990
74 Pages

Analyses and forecasts from the National Meteorological Center (NMC) were examined over two cold seasons to find forecast errors during explosive and moderate cyclogenesis over the region bounded by 25 and 60 degrees north and by 90 degrees west and the eastern edge of the nested grid model (NGM) display. An explosive cyclone was defined as any cyclone which deepened at least one bergeron during any 24 hr period, while any cyclone which deepened between .5 and 1 bergeron was defined a moderate cyclone. There were 53 explosive and 43 moderate cyclones found during the study.

The mean central pressure errors for the NGM 24 and 48 hr forecasts following the maximum 24 hr deepening were 6.2 and 12.5 mb respectively, while the corresponding errors for the moderate cyclones were 2.5 and 6.0 mb. The correlations between the predicted and analyzed deepening rates were higher for the explosive cyclones. The NGM forecasts of both the explosive and moderate cyclones showed a significant southwest bias which grew with time. The bias was due to the NGM forecasting the cyclones to move too slowly.

The performance of the NGM to forecast explosive cyclogenesis events in terms of the critical success index (CSI) has not changed much over the last three years. The CSI scores for the 24, 36, and 48 hr forecasts were .62, .53, and .43 respectively. The correlation between the predicted and analyzed 12 hr deepening rates during explosive cyclogenesis improved slightly over those reported in previous studies.

THE FLORIDA STATE UNIVERSITY
COLLEGE OF ARTS AND SCIENCES

MODEL PERFORMANCE DURING EXPLOSIVE CYCLOGENESIS FOR TWO COLD SEASONS

By

DALE R. LASHER

A Thesis submitted to the
Department of Meteorology
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded:

Fall Semester, 1990

DEDICATION

This thesis is dedicated to my wife Angela and my daughter Alyssa. They provide a constant source of love and joy which brightens my life each and every day.

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Finally, I would like to thank Dr. Fred Sanders who providing the initial motivation for my work.

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Dale R. Lasher, M.S.
The Florida State University, 1990
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CHAPTER 1

INTRODUCTION

Over the past decade, the skill of NMC (National Meteorological Center) operational models in predicting explosive cyclogenesis has dramatically improved. This improvement can be attributed to models with finer horizontal and vertical resolution, more complete physics, and better initialization. Even though the operational models have demonstrated greater skill, they continue to underforecast the intensity of cyclones during explosive cyclogenesis. In this study, the skill of the NGM (Nested-Grid Model) in predicting explosive cyclogenesis over the past two cold seasons will be determined. The results will be compared with some earlier studies to see if the NGM skill has improved.

Climatological studies of explosive cyclogenesis have been carried out by Sanders and Gyakum (1980), Roebber (1984), Rogers and Bosart (1986), and Sanders (1986a). These studies have shown that explosive cyclogenesis is primarily a cold-season maritime event which usually occurs about 500 km downstream of a shortwave trough, ahead of the planetary-scale trough, and within or poleward of the maximum in the westerlies. The maximum frequency of explosive cyclogenesis occurs in western portions of the Atlantic and Pacific

Oceans near the strong sea surface temperature (SST) gradients of the Gulf Stream and Kuroshio current.

Several studies have found systematic errors in the operational models. Leary (1971) examined systematic errors in the 36 hour forecast of the 6-LPE (six-layer Primitive Equation model). She showed that the 36 hr forecasts of the 6-LPE model underestimated the cyclone's intensity over the oceans by an average of about 10 mb, while it overforecasted the cyclone's strength to the lee of the Rocky Mountains by an average of about 3 mb. Leary also found the majority of the storms verified east of the forecasted position (forecast too slow), and that in general storms deepen more rapidly and fill more slowly than the model predicts. Leary believed that the effects of friction and sensible heating needed to be strengthened in the model.

Silberberg and Bosart (1982) analyzed systematic cyclone errors in the 24 hr and 48 hr forecasts of the LFM (Limited-Area Fine-Mesh model). They also found that the LFM underforecasted the intensity of the cyclones over both oceans and along the eastern coast of North America. The average central pressure errors over the oceans were about 4 mb for the 24 hr forecasts and 8 to 10 mb for the 48 hr forecasts. The LFM overforecasted the cyclones intensity to the lee of the Rockies eastward to the Ohio Valley by an average of 1-2 mb for the 24 hr forecasts and 2-4 mb for the 48 hr forecasts. They found that the LFM forecasted the cyclones to move too slowly in October and November and too fast during March and April. Silberberg and Bosart believed that the failure of the model to simulate oceanic cyclogenesis was due to inadequate treatment of the affects of cumulus convection, boundary layer heat and moisture fluxes, and vertical resolution.

Systematic surface cyclone errors of the NGM were analyzed from November 1988 to January 1989 by Grumm and Siebers (1989). Their results were similar to those of previous studies for different models; the NGM overestimates the cyclone strength over the North American continent and underestimates the cyclone strength over the western North Atlantic. Grumm and Siebers also calculated the overall distance errors (measured from the analyzed to predicted positions of the low center) for the NGM, and found some improvement over the LFM results calculated by Silberberg and Bosart (1982). The NGM overall distance errors were 256 km and 417 km for the 24 hr and 48 hr forecast respectively, while the LFM had errors of 299 km and 432 km. The distance errors indicated that the NGM forecasts were too slow in the area bounded by 45 N, and 100 W, and to the southern and eastern boundaries of the NGM C-grid (i.e., the finest mesh grid, see figure 1a).

Grumm and Siebers (1989) believe that the inability of the NGM to predict explosive cyclogenesis was due to the lack of data over the ocean, as well as the models inability to properly simulate the physical processes. Their analysis of the thickness errors showed a cold bias over the cyclone center. They believe that the higher static stability associated with the cold bias may inhibit the model's ability to simulate ascent around the cyclone.

In addition to the studies which have analyzed systematic errors in the models, several studies have explicitly evaluated the skill of the numerical weather prediction models to predict explosive cyclogenesis. Sanders and

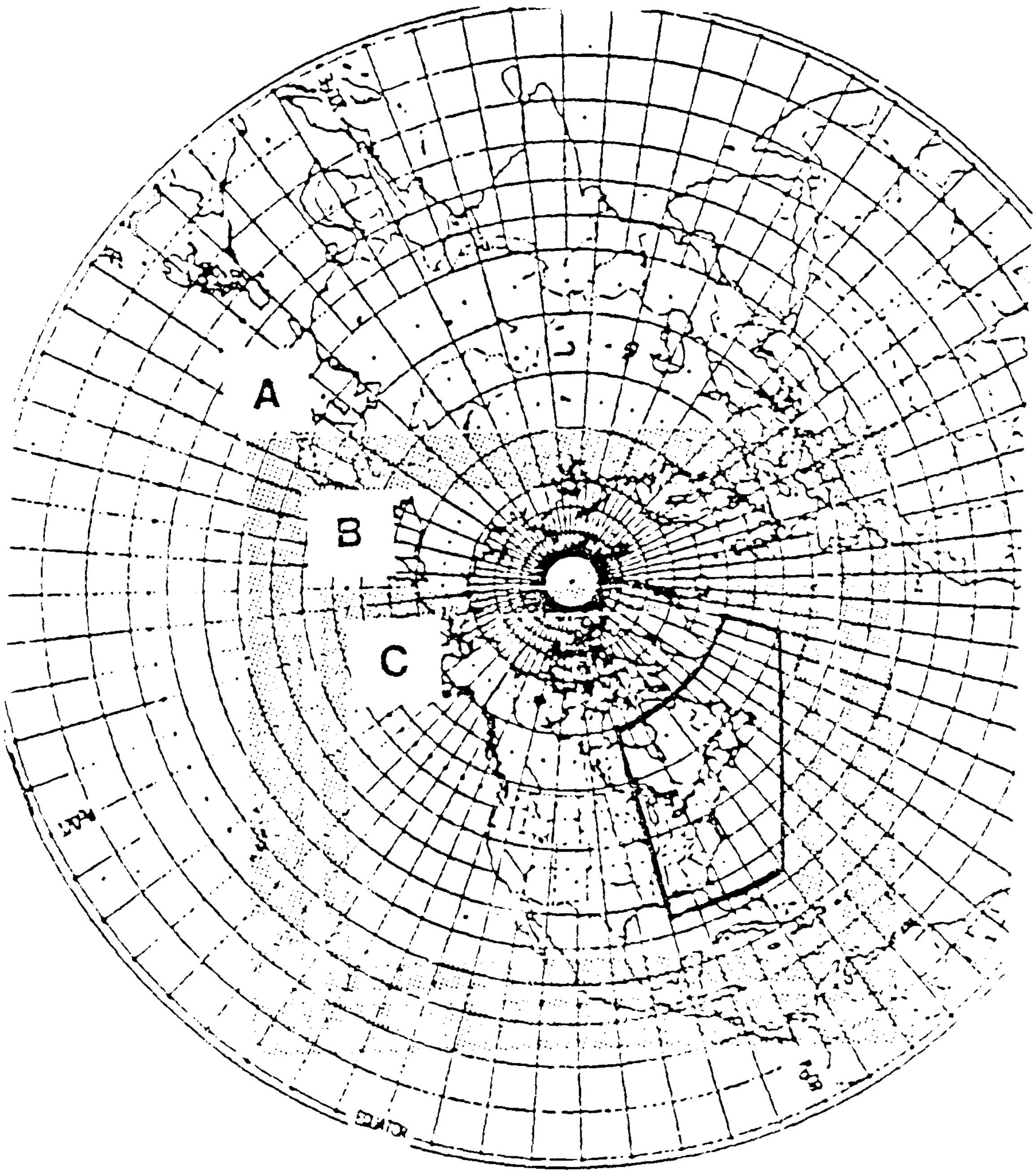


Figure 1a. The configuration of the NGM grids as of February 1987. The outer grid is hemispheric and each interior grid is twice the horizontal resolution. The solid line inside the C-grid is the outline of the study area.

Gyakum (1980) compared the performance of the 6-LPE to the 7-LPE (seven-layer Primitive Equation model) during explosive cyclogenesis. The comparison demonstrated the effect of doubling the horizontal resolution since that was essentially the only difference between the models (the extra layer was added in the stratosphere). They found that the 6-LPE model on average predicted only one fourth of the observed 12 hr deepening during explosive cyclogenesis while the 7-LPE model predicted one third of the observed deepening. Although the 7-LPE model was able to produce explosive cyclones, it did not produce them as often as the real atmosphere. The explosive cyclones which were predicted by the model generally overforecasted the observed deepening rate, and had a higher occurrence over land. Their findings were consistent with Leary's (1971) study which showed that the model overdevelops continental cyclones. They calculated the correlation coefficient (r) between the 12 to 24 hr predicted deepening and the observed deepening for that same time. The correlation coefficient for the 7-LPE model was .32 while the correlation coefficient for the 6-LPE model was only .08. Sanders and Gyakum concluded that for explosive cyclones about 10% of the model error was eliminated when the grid spacing was halved.

Sanders (1986b) evaluated the LFM's ability to predict explosive cyclogenesis in the western North Atlantic (area bounded by 32-51 N and 53-76 W) from January 1981 to November 1984. The mean central pressure error after the maximum 24 hr deepening for all 48 cases ranged from 4.9 mb for the initialization to 11.1 mb for the 48 hr forecast. The mean distance errors for all of the forecasts of explosive cyclones ranged from 142 km (0 hr) to 341 km (48 hr). The 48 hr distance errors for the explosive cyclones were actually smaller than those reported by the NWS (National Weather Service) for all lows in the eastern two-thirds of US from November 1984 through January 1985 (411 km). Sanders again computed the correlation coefficient between the LFM 12 to 24 hr predicted deepening and the observed deepening for the same time. The correlation coefficient was .55 for the LFM compared to .33 calculated earlier for the 7-LPE. The mean predicted deepening for the LFM was 9 mb versus an observed deepening of 15.5 mb; the 7-LPE had a mean predicted deepening of 6 mb versus an observed deepening of 16.5 mb. Sanders concluded that, for this time and geographical area, the LFM performance was much better than the 7-LPE.

Sanders (1987) investigated the skill of the NGM and the AVN (Aviation Run of the Global Spectral Model, GSM) in forecasting explosive cyclogenesis from September 1986 through April 1987. He verified the forecasts against NMC preliminary analyses and calculated the probability of detection (POD), false-alarm rate (FAR), and the critical success index (CSI) for both models at each forecast range. See Appendix A for definitions and interpretation. Sanders found that the highest POD and the highest FAR occurred within the NGM C-grid. In the NGM C-grid, the POD ranged from .51 (0-24 hr) to .26 (24-48 hr), and the FAR ranged from .38 (0-24 hr) to .29 (12-24 hr). The POD values for the AVN were similar to those of the NGM in the C-grid while the FAR for the AVN were slightly lower than the C-grid of the NGM. As in the earlier studies, Sanders correlated the 12 to 24 hr predicted deepening with the observed deepening for the same time. The NGM correlation coefficient was as high as .72 in the Atlantic fine mesh region, but only .03 for the Pacific. The correlations for the AVN were .65 for the Atlantic and .40 for the Pacific.

Sanders and Auciello (1989) evaluated the performance of the NGM and the AVN in predicting explosive cyclogenesis in the western North Atlantic from September 1987 through April 1988. Although both the NGM and AVN forecasts had improved over the previous year, it is difficult to compare the results of this study with those of the earlier Sanders (1987) study for several reasons. The NGM C-grid of the earlier study extended only a short distance off either coast for most of the season. The NGM C-grid results included the eastern Pacific, where the forecast skill is lower. In addition, the verification of the earlier study was more lenient; a forecast for a specific range verified if it showed explosive deepening at least once for a particular storm (i.e., neglecting timing errors). For this study each 24 hour period was considered separately. Keeping this in mind, the POD were higher and the FAR were lower than Sanders (1987) at all ranges. The POD for the NGM ranged from .72 (0-24 hr) to .37 (24-48 hr), and the FAR ranged from .21 (24-48 hr) to .10 (12-36 hr). The POD and FAR values for the AVN forecasts were very similar to those of the NGM.

Sanders and Auciello suspected that the models did not predict the initiation of explosive cyclogenesis as well as they forecast the continuation of it. They analyzed the POD for only the first 24 hour period in which explosive deepening occurred for each cyclone. They found that the POD for initial explosive deepening were lower than those for all the forecasts in the 0-24 hr and 12-36 hr ranges. The POD for the 24-48 hr forecast of the initial explosive deepening was about the same as the POD for all the forecasts of explosive deepening. They believe that there is a problem with the initial analysis, and the model may be too sensitive to the initial conditions, which depend strongly on the previous model cycle short range forecast. At longer ranges the model does not appear to be as sensitive to the initial conditions. Sanders and Auciello calculated the average predicted and analyzed deepening at 12 hr intervals during explosive cyclogenesis. They found that the NGM underforecast the deepening in the first 24 hours but caught up later.

As shown in Table 1, the skill of operational models in predicting explosive cyclogenesis has improved during the 1980s. The purpose of this study is to determine the current skill of the NGM in predicting explosive cyclogenesis and to compare these results with those of earlier studies. Forecast errors and deepening rates for a sample of cyclones which deepened moderately but not explosively will be compared with those cyclones which deepened explosively.

Table 1. Results from previous studies of explosive cyclogenesis. All statistics are for the 12 to 24 hr forecast range

Model	Studies of systematic errors	Study dates	Correlation coef. obs vs fcst deepening	% of analyzed deepening predicted
6-LPE (Shuman and Hovermale 1968)	Sanders and Gyakum (1980)	9/76 - 1/78	.08	29
7-LPE	Sanders and Gyakum (1980)	1/78 - 5/79	.32	38
LFM (Newell and Deaver, 1981)	Sanders (1986b)	1/81 - 11/84	.55	58
NGM (Phillips 1979)	Sanders (1987)	9/86 - 4/87	.72 *	90 *
	Sanders and Auciello (1989)	9/87 - 4/88	.55	82
AVN (Sela, 1980)	Sanders (1987)	9/86 - 4/87	.60	75
	Sanders and Auciello (1989)	9/87 - 4/88	.50	77

* Atlantic and North American C-grid (the C-grid extended only a short distance off the coast for most of the study)

CHAPTER 2

Methodology

A cyclones deepening rate can be expressed in bergerons (B); one bergeron is equivalent to a deepening rate of 24 mb in 24 hours geostrophically adjusted to 60 degrees, i.e.,

$$B \approx \frac{\Delta p}{\Delta t_{ref}} \frac{\sin 60°}{\sin \phi} , \qquad (1)$$

where Δp is the pressure change in mb, Δt_{ref} is the time over which Δp is evaluated (usually 24 hr), and ϕ is the observed latitude. Following Sanders and Gyakum (1980), an explosively deepening cyclone or "bomb" is one which attains a deepening rate of at least one bergeron. Since the NMC manual analyses are available at 6 hr intervals, the deepening rates were computed every six hours. If the cyclone attained at least a 1 B deepening rate during any 24 hr period (computed every six hours), it was considered an explosive cyclone. For comparison purposes, errors were also calculated for a sample of moderately deepening cyclones. For this study, a moderately deepening cyclone is one which attains a maximum deepening rate of at least .5 B during any 24 hr period but does not qualify as an explosive cyclone.

The analyzed and predicted cyclone positions for this studied were gathered manually from facsimile maps received at Florida State University.

Unfortunately the data set is not complete because some of the maps were either not transmitted or lost. The NMC preliminary analyses were used to verify the forecasts. If the NMC preliminary analysis was missing (about 2% of the time), the NMC final analysis, only available at 0000 UTC for this study, was used to verify the forecasts. Although the manual analyses are subject to uncertainties (especially over the oceans), Sanders (1990) compared the NMC manual analyses with his research analyses during ERICA (Experiment on Rapidly Intensifying Cyclones over the Atlantic, Hadlock and Kreitzberg (1988)). He found that the NMC manual analyses estimates of central pressure for the ERICA storms were on average only 0.6 mb higher than his research analyses. There was some difficulty reading central pressure off several of the facsimile maps. If the central pressure could not be read, two millibars were subtracted from the last closed contour as an estimate of the central pressure.

The verification was undertaken for twelve and a half months over two cold seasons (12 December 1988 to 30 April 1989 and 1 September 1989 to 30 April 1990) over the region bounded by 25 and 60 degrees north latitude and 90 degrees west longitude and the eastern edge of the NGM display which varies from 70 W at 25 N to around 30 W at 60 N. The data for the 88/89 cold season were not complete because the NMC preliminary analyses were not available before 12 December 1988.

The NMC preliminary analyses were examined to find occurrences of cyclogenesis greater than .5 bergeron. For every cyclone that deepened at least .5 B in the NMC preliminary analyses, central pressure and position errors were calculated for the NGM 0 hr through 48 hr forecasts and the AVN 60 hr forecast. The forecast errors were calculated at twelve hour intervals throughout the cyclones deepening. On two occasions some filling was allowed during the last 12 hours because the 24 hour deepening rate was still greater than 1 B. The errors were determined by subtracting the analyzed central pressure from the forecast central pressure (i.e., positive errors means underforecasting). There were times when the analyzed low was not forecasted. In some instances, the forecast position and central pressure of the cyclone were estimated by placing the low along a trough using continuity. If the forecast position could not be estimated with any degree of certainty, the forecast was not used.

All the NGM forecasts were examined to find the ability of the model to forecast at least 1 B of deepening. The POD, FAR, and CSI were calculated for three overlapping 24 hour forecast periods of the NGM. The periods are named for the ending forecast time (i.e., the 36-hr forecast represents the time series of forecasts from the 12 hr to the 36 hr forecast). If a forecast was missing for a particular 24 hour period when the analyses were indicating explosive deepening, the event was not counted for that 24 hour forecast period.

During the study, there were 53 explosively deepening cyclones and 43 moderately deepening cyclones. Table 12 of appendix B is a chronological list of all the explosive cyclones in the study. The moderate cyclones are listed in Table 13 of appendix B. The number of explosive and moderate cyclones which occurred each month during the study are shown in figure 1b. The explosive cyclones occurred most frequently during the months December and January, and least frequently in April which is consistent with the findings of Sanders and Gyakum (1980). The moderate cyclones occurred with the highest frequencies in March and April (except March 1989) with a secondary peak in January.

Figures 2 through 7 shows the storm tracks for all the cyclones in the study. The storm tracks for the abbreviated 1988/89 cold season are shown in figures 2 and 3. The storm tracks for the first half of the 1989/90 season are included in figures 4 and 5, while those from the second half of the season are shown in figures 6 and 7. In general, the cyclone tracks of both the explosive and moderate cyclones move toward the northeast with some cyclonic turn near the end of the deepening stage. The storm tracks for the explosive cyclones tend to cluster over two regions. The first region extends from just off the coast of the Carolinas to about 50 N and 45 W, and the second region runs from the Gulf of St. Lawrence to about 55 N and 50 W. These two regions coincide very closely with a 28 year climatology of the preferred January cyclone tracks found by Zishka and Smith (1980) shown in figure 8. The northern cyclone track was a little farther south and east for both explosive and moderate cyclones during the early part of the 1989/90 cold season which was during an outbreak of record cold temperatures over the eastern US.

While several bombs had long tracks over the land, most of the explosive deepening occurred over the water. In November 1989, two bombs

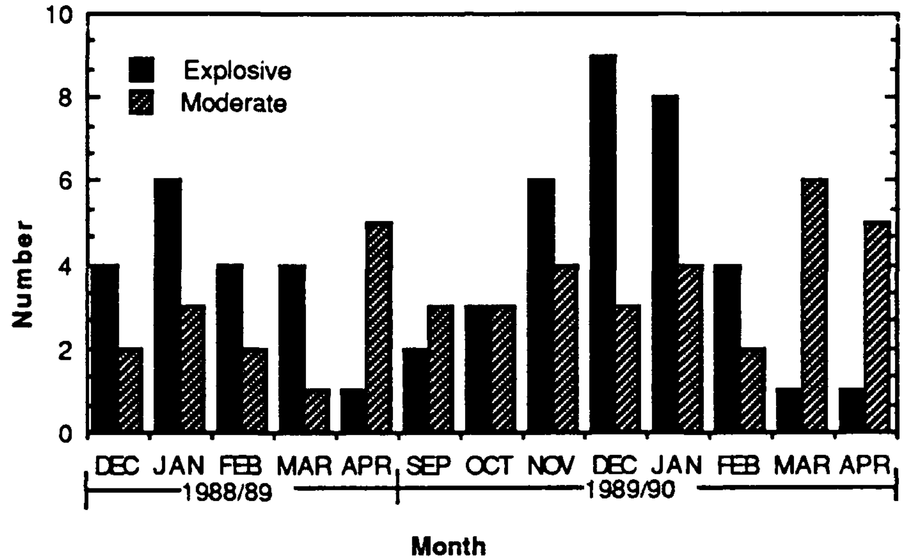


Figure 1b. The monthly occurrences of the explosive and moderate cyclones.

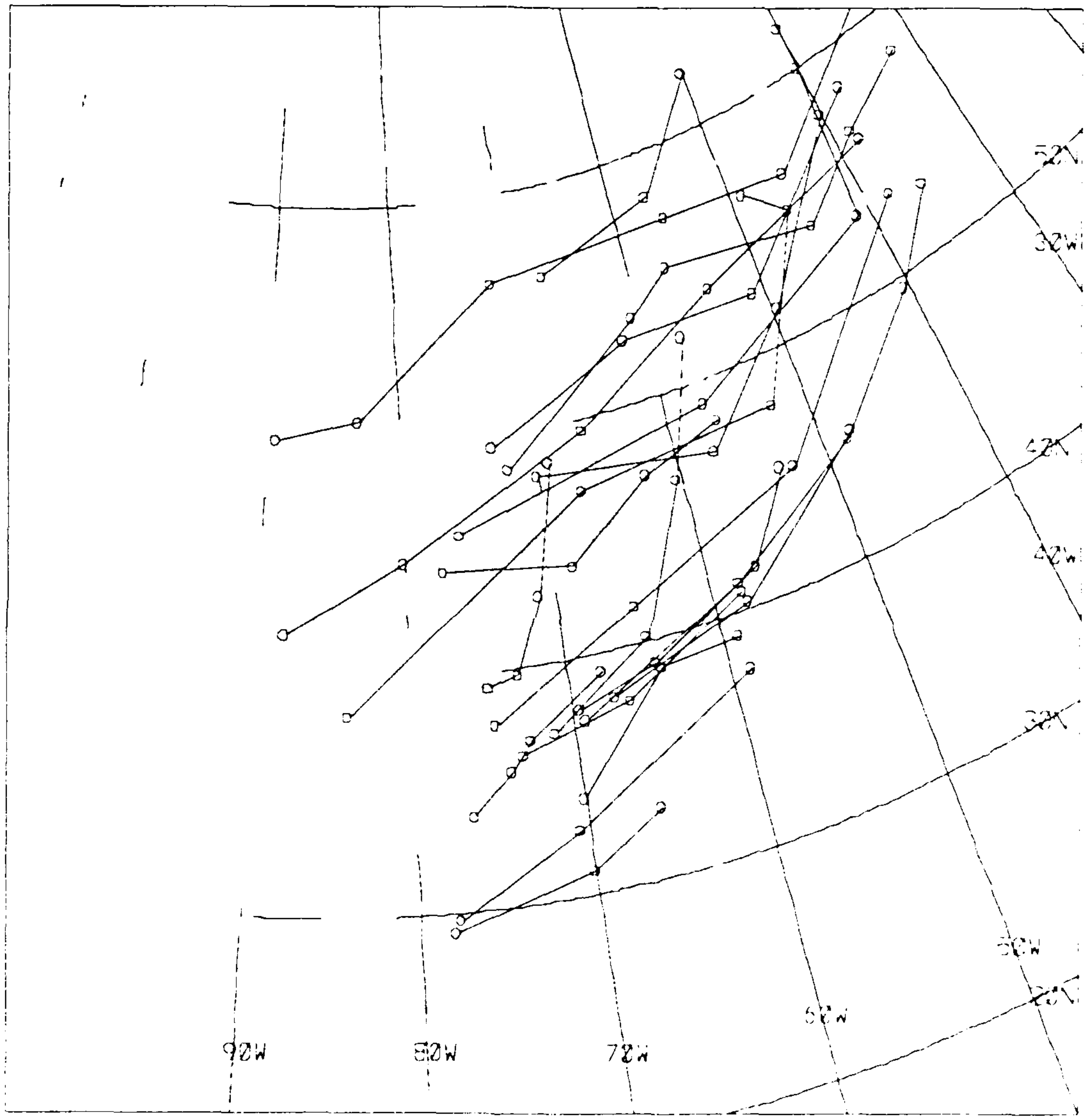


Figure 2. The cyclone tracks of the explosive cyclones from 12 December 1988 to 30 April 1989. The circles represent 12 hour positions.

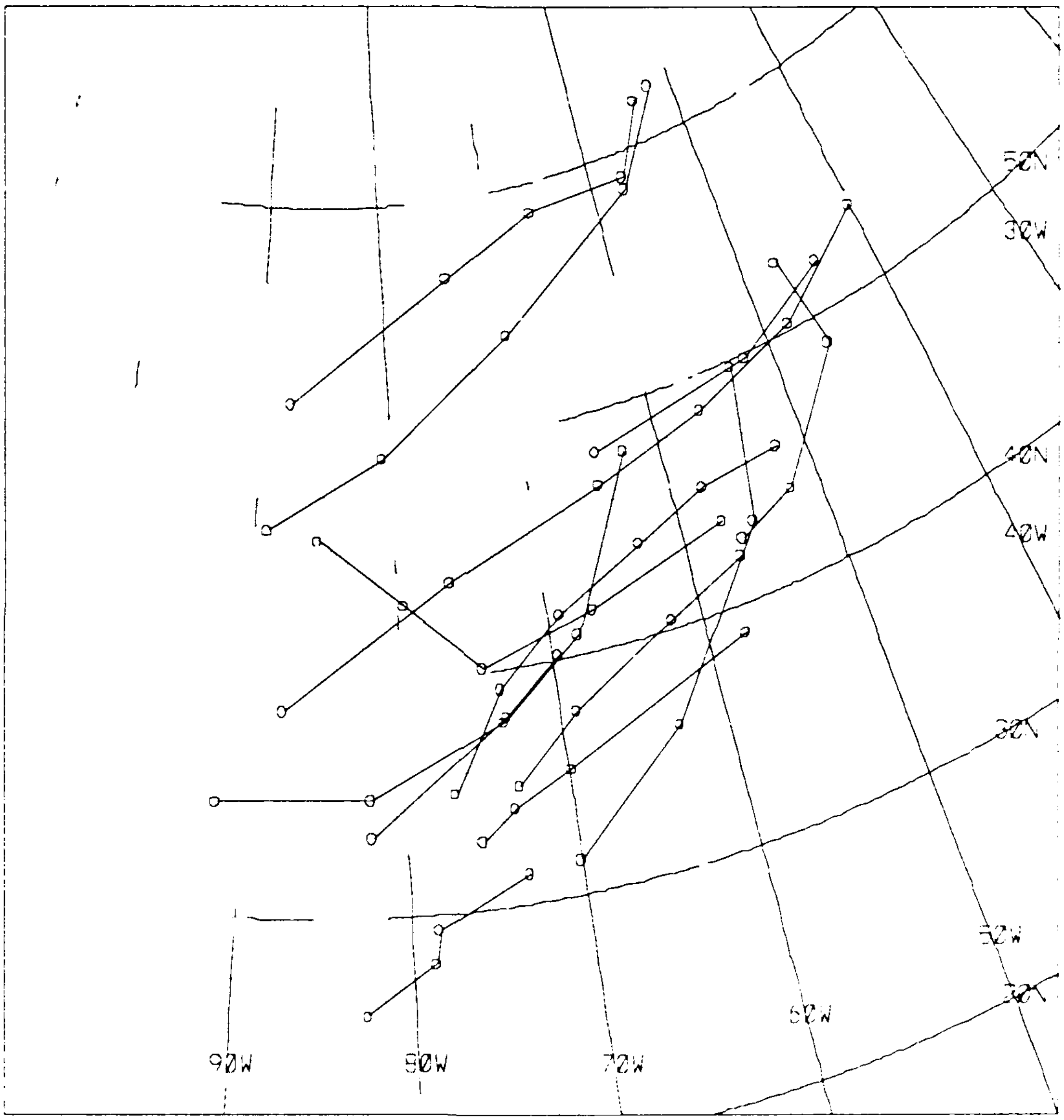


Figure 3. The cyclone tracks of the moderate cyclones from 12 December 1988 to 30 April 1989. The circles represent 12 hour positions.

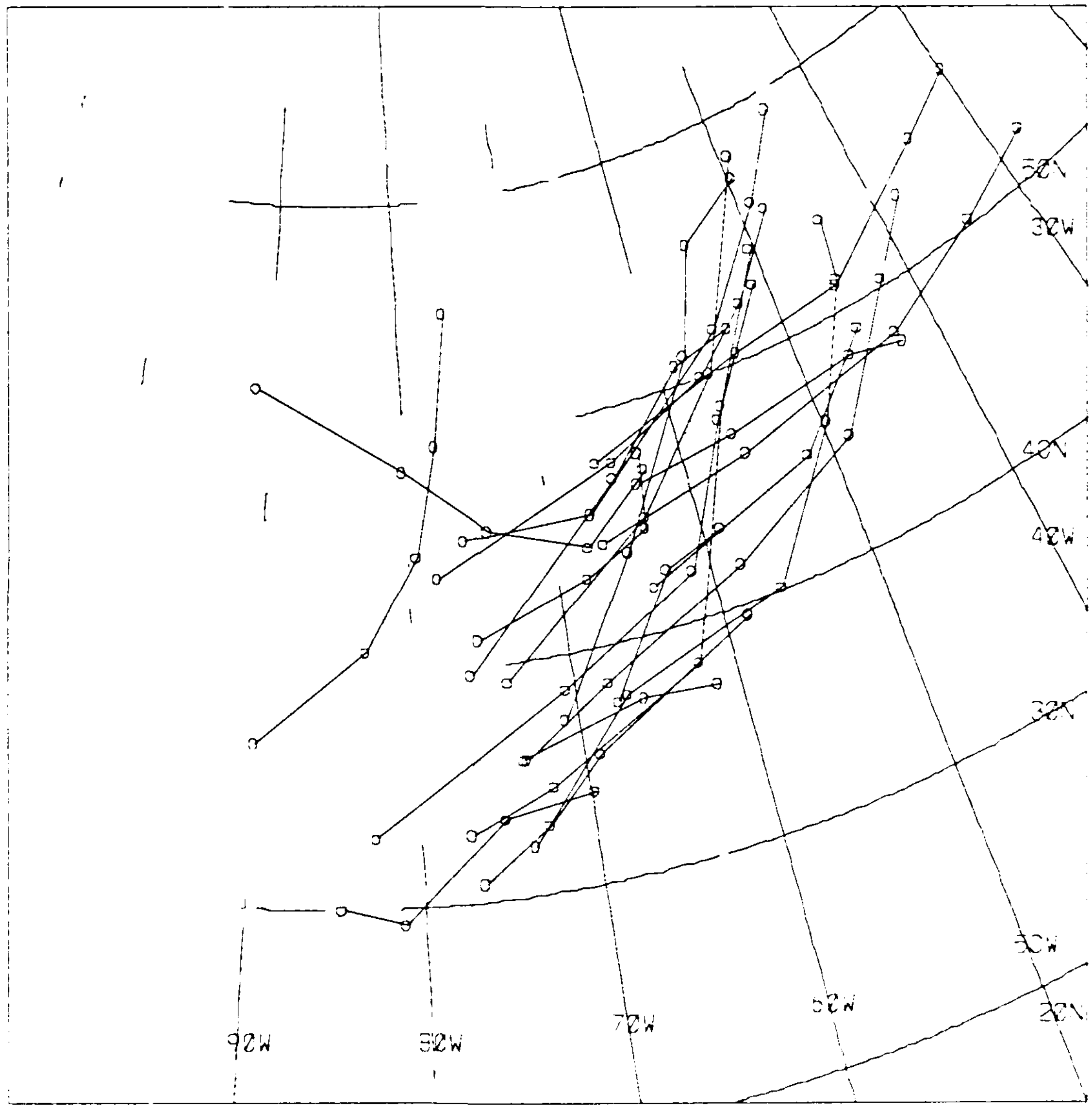


Figure 4. The cyclone tracks of the explosive cyclones from 1 September 1989 to 30 December 1989. The circles represent 12 hour positions.

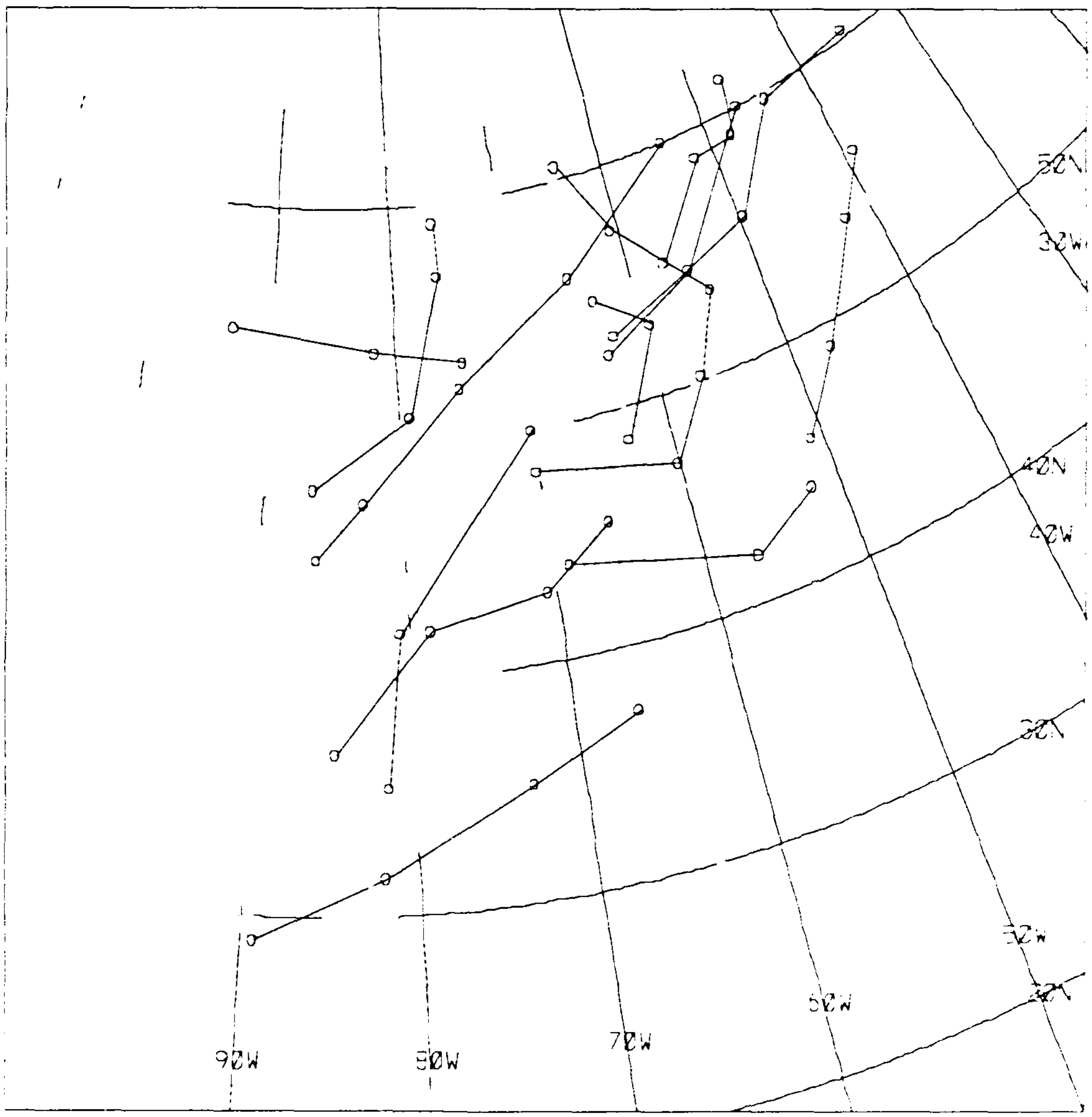


Figure 5. The cyclone tracks of the moderate cyclones from 1 September 1989 to 30 December 1989. The circles represent 12 hour positions.

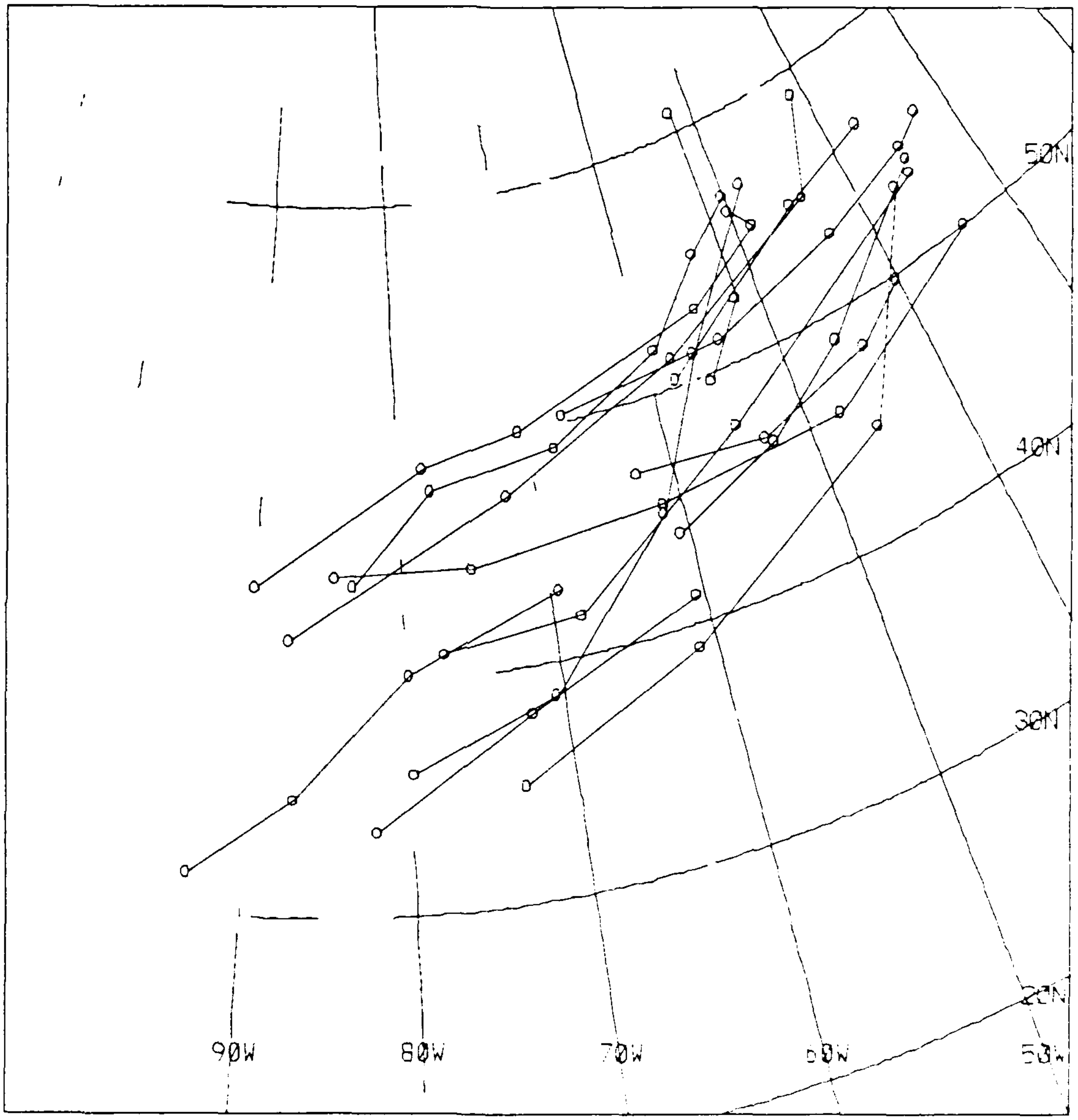


Figure 6. The cyclone tracks of the explosive cyclones from 1 January 1990 to 30 April 1990. The circles represent 12 hour positions.

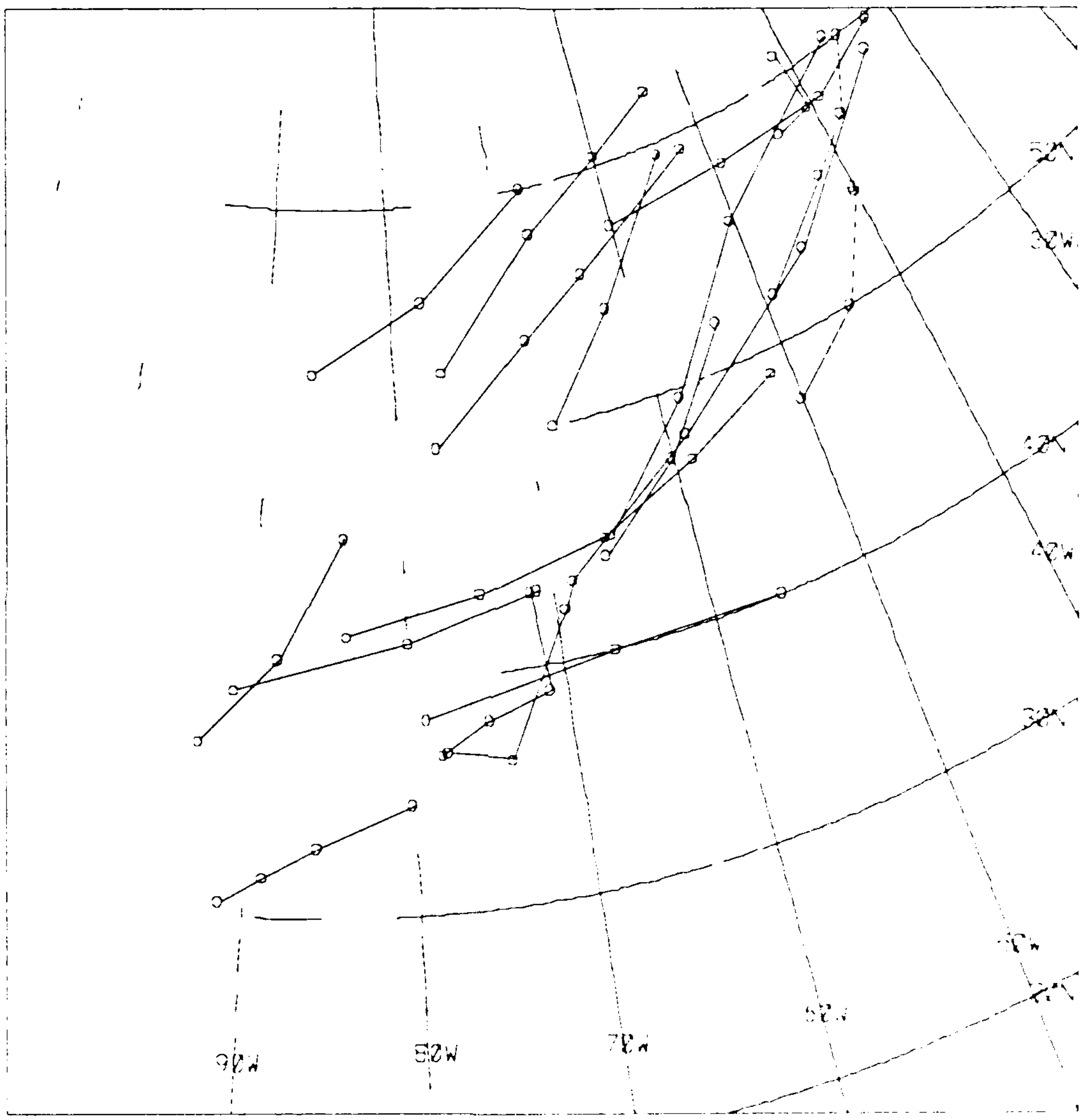


Figure 7. The cyclone tracks of the moderate cyclones from 1 January 1990 to 30 April 1990. The circles represent 12 hour positions.

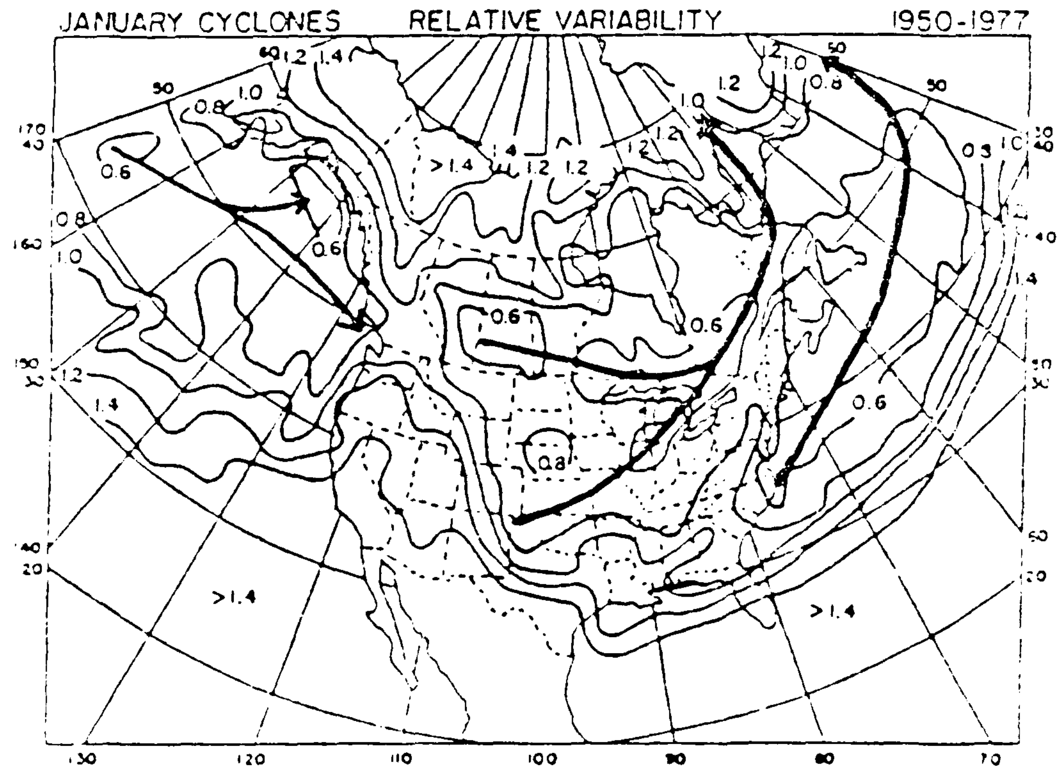
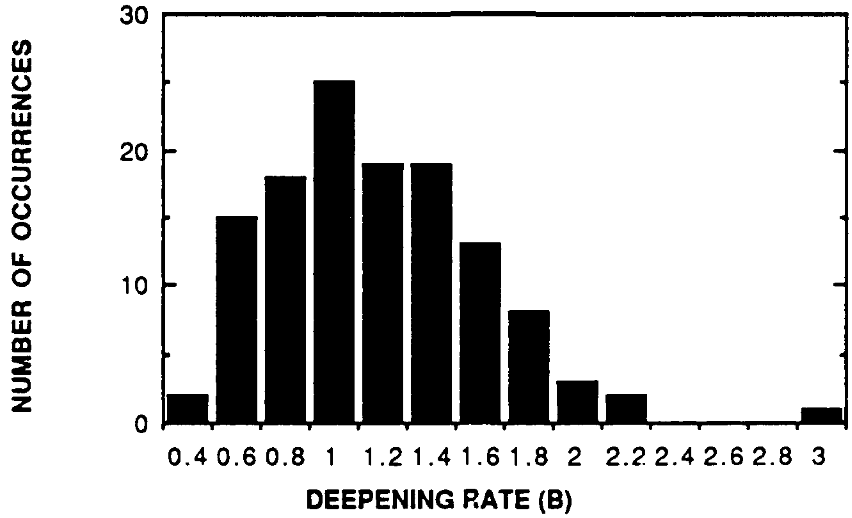


Figure 8. The 28 year (1950-1977) preferred January cyclone tracks with relative variability (from Zishka and Smith 1980).

deepened explosively over land. The storm tracks for the moderate cyclones are spread more evenly throughout the study area with a higher frequency over land.

The distribution of the 24 hr deepening rates for all the explosive and moderate cyclones are shown in figure 9. Although the highest frequency for the bombs occurs at 1 B, the frequencies are fairly high and evenly distributed from .8 B to 1.4 B. There was one extremely large deepening rate of 3 B which occurred during ERICA. Most of the deepening rates for the moderate cyclones were between .6 B and .9 B. Figure 10 shows the maximum 24 hr deepening rate for each explosive and moderate cyclone in the study. Most of the explosive cyclones had maximum deepening rates ranging from 1 B to 1.4 B while most of the moderate cyclones ranged from .7 B to .9 B.

a)



b)

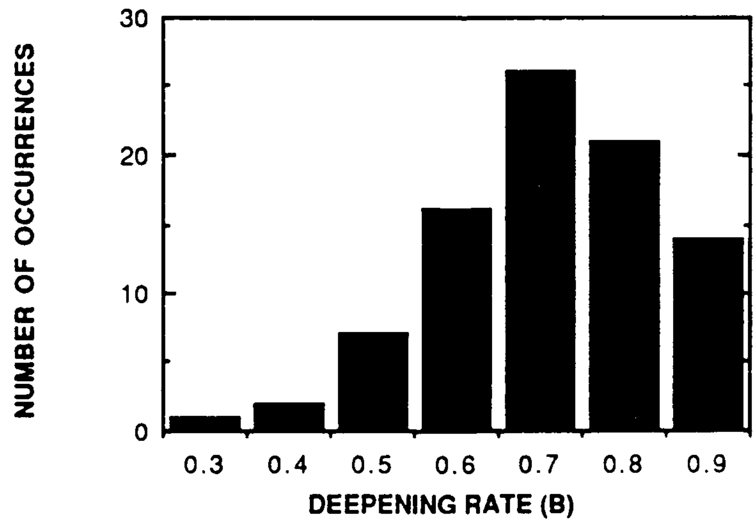
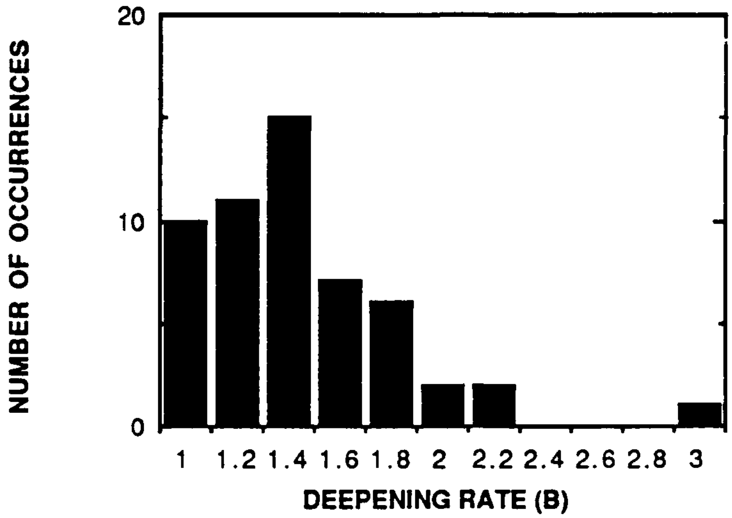


Figure 9. The distribution of all 24 hr deepening rates for: a) explosive cyclones b) moderate cyclones.

a)



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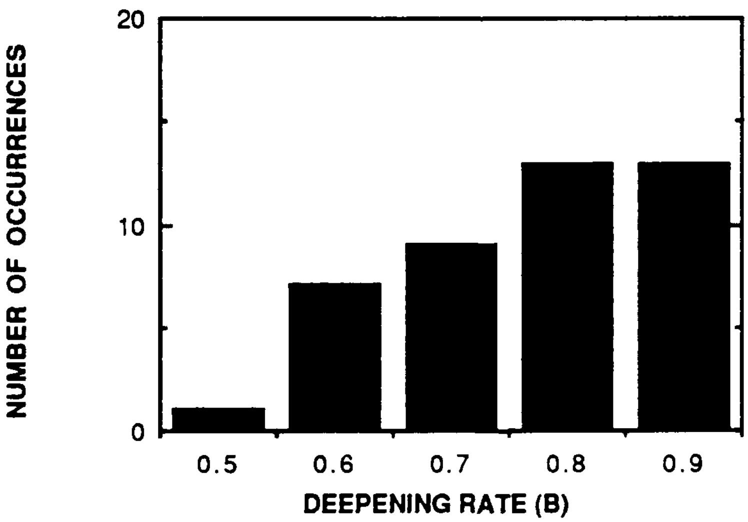


Figure 10. The distribution of the maximum 24 hr deepening for each cyclone: a) explosive b) moderate.

CHAPTER 3

RESULTS

3.1 Central Pressure Errors

The central pressure is a good (but not always perfect) indication of the intensity of a cyclone. Thus the central pressure error will give a good indication of how well a model is forecasting the intensity of a cyclone. The mean forecast error of the central pressure along with the standard deviation for all the forecasts of the explosive and moderate cyclones are shown in Table 2a. The mean error and the standard deviation increased almost linearly with forecast range for both samples and were larger at all forecast ranges for the explosive cyclones. The NGM forecasts of the explosive cyclones had mean central pressure errors ranging from 1.9 mb (0 hr) to 6.0 mb (48 hr); the NGM forecasts of the moderate cyclones had mean errors ranging 1.3 mb (0 hr) to 3.5 mb (48 hr). The NGM central pressure errors were on average about 37% less for the moderate cyclones, and the average deepening rate for the moderate cyclones was also about 37% less. The NGM central pressure errors appear to be proportional to the deepening rate. Sanders (1986b) also found that the mean central pressure errors of the LFM

TABLE 2a. Mean forecast errors and standard deviations of the central pressure (mb) for the explosive and moderate cyclones. N is the number of comparisons. NGM0 represents the NGM initialization, while NGM12, NGM24, NGM36, and NGM48 represents the NGM 12, 24, 36 and 48 hr forecasts respectively. AVN60 represents the 60 hr forecast of the AVN.

	Explosive			Moderate		
	Mean	SDev	N	Mean	SDev	N
NGM0	1.9	3.1	223	1.3	2.3	166
NGM12	2.2	4.0	220	1.5	3.2	167
NGM24	3.0	5.2	222	2.0	3.7	165
NGM36	4.4	6.4	218	2.6	4.8	168
NGM48	6.0	8.0	211	3.5	6.2	158
AVN60	7.0	7.7	178	6.2	5.9	147

were proportional to the deepening rate when he compared the errors of strong bombs with those of weak bombs. On average the standard deviations of the moderate cyclones were about 24% less.

The AVN 60 hr forecasts had nearly the same central pressure errors for both the explosive (6.7 mb) and moderate (6.2 mb) cyclones. Since the mean error is only 7.5% less for the moderate cyclones, the mean error for the AVN 60 hr forecast does not appear to be as dependent on the deepening rate. The standard deviation of the AVN 60 hr forecasts of the moderate cyclones was 23% less than those of the explosive cyclones. While the AVN 60 hr forecasts of the moderate cyclones had a mean error that was nearly double that of the NGM 48 hr, the AVN 60 hr forecast errors for the explosive cyclones were only slightly higher than the NGM 48 hr.

In order to see how the forecast errors change during the deepening phase of the cyclone, the mean central pressure errors were stratified similar to Sanders (1986), where time zero is the midpoint of the cyclones maximum 24 hr deepening. Each unit of time is one hour, so time T+12 is 12 hours after the midpoint of the maximum 24 hr deepening and T-12 is 12 hours before. The results are shown in Table 2b. Both models underforecast the central pressure at all times except the 12 hr forecasts of the explosive cyclones at time T+24. In general, the mean errors for both samples were small for times T-24 and T-12. With the exception of the AVN 60 hr, the mean forecast errors were less than 2 mb at time T-24, and less than 3 mb at time T-12. The standard deviations increased with increasing forecast range for all the times,

TABLE 2b. Mean forecast errors and standard deviations of the central pressure (mb) for times T-24 to T+24. N is the number of comparisons. In parentheses are LFM errors calculated by Sanders (1986b).

	Explosive						Moderate		
	Mean		SDev		N		Mean	SDev	N
Time = -24									
NGM0	1.5	(1.2)	2.1	(2.2)	28	(19)	1.3	1.3	14
NGM12	1.5	(-0.2)	2.5	(3.0)	27	(14)	1.3	2.0	15
NGM24	0.7	(0.4)	4.0	(3.3)	28	(12)	0.4	2.9	16
NGM36	0.9	(-0.8)	5.5	(4.4)	27	(18)	0.0	5.2	15
NGM48	1.2	(-1.6)	6.7	(4.9)	26	(16)	0.4	4.7	15
AVN60	1.9		5.7		24		3.8	4.7	16
Time=-12									
NGM0	1.1	(1.3)	1.9	(1.3)	52	(32)	1.0	2.0	42
NGM12	1.9	(0.8)	2.5	(2.9)	50	(31)	1.1	3.0	42
NGM24	1.3	(0.7)	3.4	(3.1)	50	(28)	1.2	4.0	39
NGM36	2.0	(0.1)	5.5	(4.9)	51	(26)	1.2	5.0	42
NGM48	2.5	(-2.0)	6.8	(6.2)	49	(29)	0.5	6.8	37
AVN60	2.7		5.6		43		4.9	4.8	37
Time=0									
NGM0	2.2	(1.8)	3.1	(2.6)	51	(37)	1.9	2.4	43
NGM12	2.4	(3.8)	3.9	(5.6)	49	(36)	2.1	2.7	42
NGM24	4.8	(4.1)	4.8	(5.7)	52	(35)	2.8	3.1	41
NGM36	5.4	(4.5)	5.4	(5.3)	50	(33)	3.7	3.9	40
NGM48	7.7	(5.4)	6.6	(6.5)	49	(29)	4.1	6.4	40
AVN60	8.0		6.1		41		6.5	4.8	35
Time=+12									
NGM0	2.5	(4.9)	3.5	(5.2)	52	(35)	1.4	2.6	40
NGM12	4.5	(7.7)	4.5	(5.5)	52	(35)	2.0	3.6	42
NGM24	6.2	(9.7)	5.7	(7.7)	51	(37)	2.5	3.8	43
NGM36	9.7	(10.2)	6.2	(7.4)	50	(34)	3.3	4.6	43
NGM48	12.5	(11.1)	7.8	(7.6)	47	(32)	6.0	4.8	38
AVN60	12.2		8.9		38		8.0	7.4	33
Time=+24									
NGM0	1.9	(4.1)	5.1	(3.9)	27	(26)	.7	2.6	19
NGM12	-1.0	(5.4)	4.9	(8.2)	28	(26)	1.2	3.8	17
NGM24	0.3	(8.2)	4.6	(7.3)	27	(24)	2.2	4.5	18
NGM36	2.1	(10.9)	5.3	(10.1)	26	(23)	3.3	5.7	19
NGM48	4.7	(9.9)	7.2	(9.2)	26	(24)	4.4	5.6	19
AVN60	9.0		6.9		21		6.5	7.7	19

and tended to be slightly lower at time T-24 and T-12.

During the early stages of the cyclones development (T-24 and T-12), some of the longer range forecasts had lower mean errors than the shorter range forecast. As pointed out by Grumm and Siebers (1989), the NGM tends to overforecast the cyclone's intensity over land and underforecast the intensity over water. Since the cyclones were located over land more frequently during the early stages of development, there were a few cases of the model overforecasting the cyclones intensity at this time; this tended to lower the mean errors but increase the standard deviations for the longer range forecasts.

As one might expect, the central pressure errors peaked after the maximum 24 hr deepening (T+12). At time T+12, the mean forecast errors for the explosive cyclones ranged from 2.5 mb (0 hr) to 12.5 mb (48 hr), while the forecasts of the moderate cyclones had mean errors ranging from 1.4 mb (0 hr) to 8.0 mb (60 hr). At time T+24, the NGM forecasts for the explosive cyclones were actually slightly better than the forecasts of the moderate cyclones. Thus the central pressure errors tend to increase from the beginning of cyclogenesis until the end of the maximum 24 hr deepening and then decrease 12 hours later which is similar to the findings of Sanders and Auciello (1989). They found that during the first 24 hours of deepening the NGM failed to match the analyzed deepening, but caught up later.

In order to get a better idea of how the central pressure errors change during each forecast cycle, the mean central pressure errors are again shown in Table 3. The mean errors for each forecast cycle run down the table

Table 3. The mean central pressure errors (mb) for the NGM 0 hr through 48 hr forecasts of explosive and moderate cyclones for times T-24 through T+24. Each forecast cycle is enclosed by a circle.

Explosive Cyclones

	T-24	T-12	T 0	T+12	T+24
NGM0	1.5	1.1	2.2	2.5	1.9
NGM12	1.5	1.9	2.4	4.5	-1.0
NGM24	0.7	1.3	4.8	6.2	0.3
NGM36	0.9	2.0	5.4	9.7	2.1
NGM48	1.2	2.5	7.7	12.5	4.7

Moderate Cyclones

	T-24	T-12	T 0	T+12	T+24
NGM0	1.3	1.0	1.9	1.4	0.7
NGM12	1.3	1.1	2.1	2.0	1.2
NGM24	0.4	1.2	2.8	2.5	2.2
NGM36	0.0	1.2	3.7	3.3	3.3
NGM48	0.4	0.5	4.1	6.0	4.4

diagonally and are enclosed by an ellipse. A caveat to keep in mind, when looking at the individual forecast cycles, is that the size of the samples are smaller for times T-24 and T+24. The mean central pressure errors for the 24 hr forecast from T-12 to T+12 for the explosive cyclones increased from 5.1 mb for the 0 to 24 hr forecast to 11.2 mb for the 24 to 48 hr forecast. For the same forecast periods, the moderate cyclones mean errors increased from 1.5 mb for the 0 to 24 hr forecast to 4.8 mb for the 24 to 48 hr forecast. The mean errors for the 12 hr forecast from T+12 to T+24 of the explosive cyclones fell by an average of 4.2 mb, while the errors for moderate cyclones for the same time increased by an average of .5 mb.

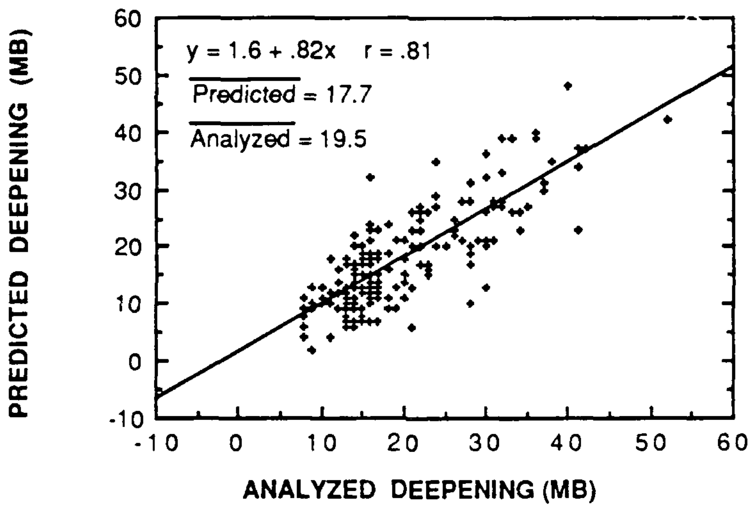
Although there have not been studies which have calculated the central pressure errors of the NGM during explosive cyclogenesis, Sanders (1986b) calculated the LFM forecast errors during explosive cyclogenesis. His results are shown in parentheses in Table 2b. Although the LFM had slightly lower mean errors for times T-24 and T-12, Sanders had a different sampling procedure for this study. He only considered the cases in which the low appeared in both the analysis and the forecast, so he had fewer comparisons at these times. In the present study, the forecasted central pressure was estimated if the low was not forecasted. Since the model is probably handing the situation better if the low is forecasted, it is not fair to compare the two samples at times T-24 and T-12. With the exception of the 12 hr forecast, the LFM mean errors were slightly lower than the NGM errors at time T 0. At time T+12, the NGM's 0 through 24 hr forecasts had mean errors about 3 mb lower than the LFM's, while the 36 and 48 hr forecasts were within 1 mb. At time T+24, the NGM mean errors were considerably lower (4 to 8 mb) than the LFM mean errors at all the forecast ranges, indicating that perhaps NGM does a better job at "catching up" near the the end of the explosive deepening.

3.2 Deepening Rates

If the central pressure is a good indication of the intensity of a cyclone, then the deepening rate is the measure of the intensification of a cyclone. The analyzed 12 and 24 hr deepening rates were compared with the predicted deepening rates for each available period during the development of all the cyclones in the study. The comparisons of the analyzed versus predicted deepening rates were divided into three samples. The first sample (ALL) includes all the forecast periods in the study. The forecasts for the explosive cyclones are included in the sample EXP, while the forecasts of the moderate cyclones are included in the MOD sample.

Figures 11 through 13 show the scatter diagrams of the analyzed versus the predicted 24 hr deepening rates for NGM 24 and 48 hr forecasts of the three samples. Also included in the figures are the mean analyzed and predicted deepening rates. The mean analyzed 24 hr deepening rate for all the forecasts was 19.5 mb; the mean analyzed deepening rate for the explosive cyclones was 23.2 mb, while the moderate cyclones deepened 14.1 mb. On average, the 24 hr predicted deepening for all the cyclones was 1.8 mb less than the analyzed, while the 48 hr predicted deepening was 5.5 mb

a)



b)

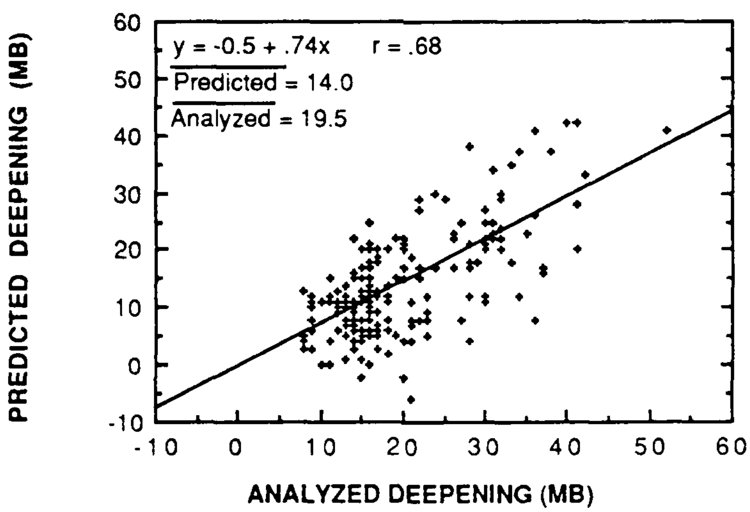
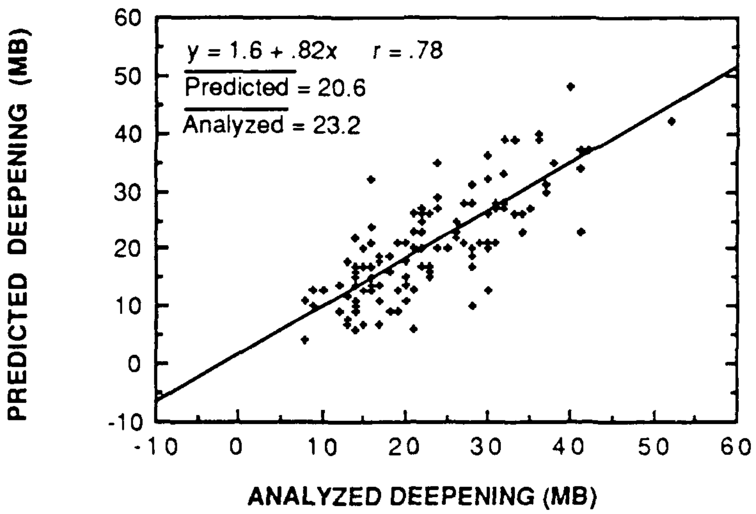


Figure 11. Scatter diagram of the predicted versus analyzed 24 hr deepening rate for all the 24 hr periods in the study. The solid line is the regression line. The mean values of the analyzed and predicted deepening are given along with the correlation coefficient. (a) NGM 24 hr forecast; (b) NGM 48 hr forecast

a)



b)

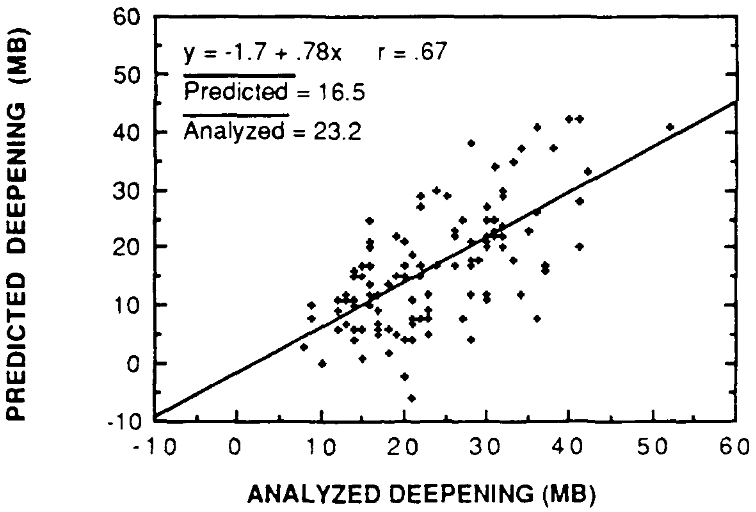
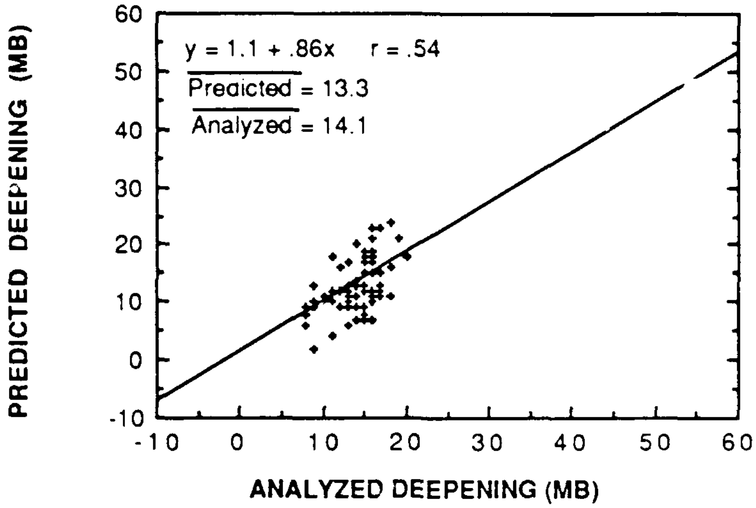


Figure 12. Scatter diagram of the predicted versus analyzed 24 hr deepening rate for all the 24 hr periods during the cyclogenesis of the explosive cyclones. The solid line is the regression line. The mean values of the analyzed and predicted deepening are given along with the correlation coefficient. (a) NGM 24 hr forecast; (b) NGM 48 hr forecast

a)



b)

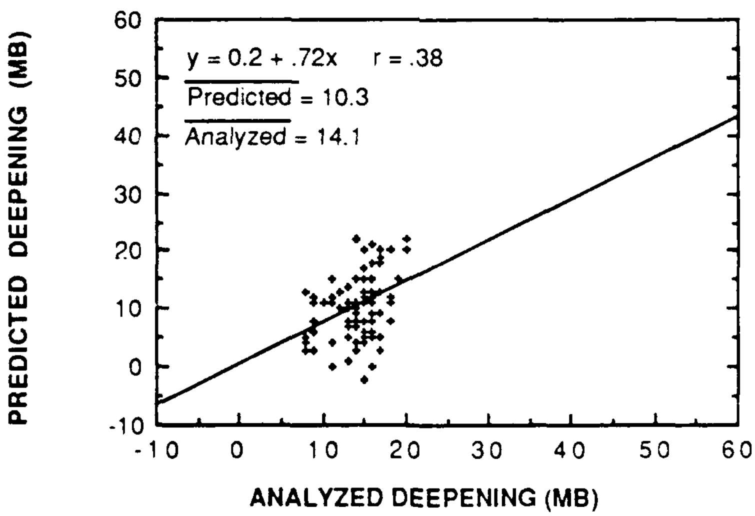
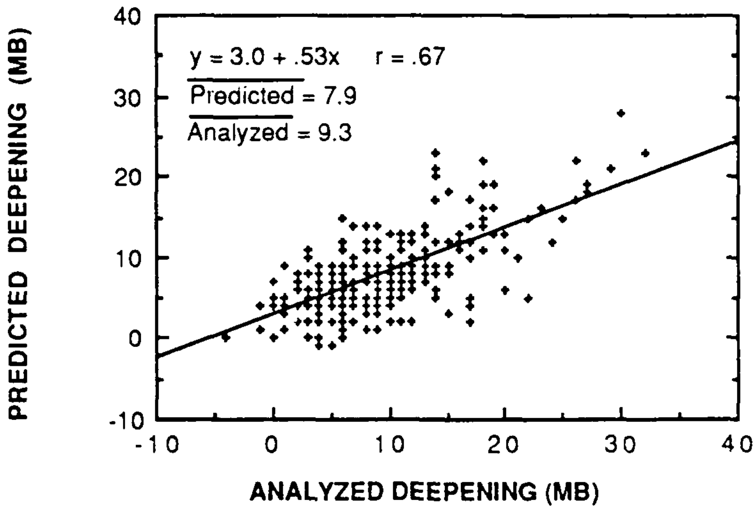


Figure 13. Scatter diagram of the predicted versus analyzed 24 hr deepening rate for all the 24 hr periods during the cyclogenesis of the moderate cyclones. The solid line is the regression line. The mean values of the analyzed and predicted deepening are given along with the correlation coefficient. (a) NGM 24 hr forecast; (b) NGM 48 hr forecast

less. Thus for all the forecasts in the study, the 24 hr forecast captured about 91% of the analyzed deepening, and the 48 hr forecast deepening captured 72% of the analyzed deepening. The mean predicted deepening for 24 and 48 hr forecasts of explosive cyclones captured 89% and 71% of the analyzed deepening, respectively, while the moderate cyclones captured 94% and 73% of the analyzed deepening respectively. Thus on average, the model predicted only 2-5% more of the analyzed deepening for the moderate cyclones.

The scatter diagrams for the analyzed versus the predicted 12 hr deepening rates for the three samples are shown in figures 14 through 16. The scatter diagram of the explosive cyclones (figure 15) is similar to the diagram given by Sanders and Auciello (1989 figures 3 and 4), even though there was a slight difference in the sampling. They only included the periods of explosive deepening while the present study includes all the periods during development of the explosive cyclones. The mean analyzed 12 hr deepening rate for the explosive cyclones was 11.0 mb, while the 24 and 48 hr mean predicted deepening rates were 9.2 and 6.8 mb, respectively. Both the 24 and 48 hr forecasts captured only 2% more of the analyzed deepening than found by Sanders and Auciello. The correlation coefficient between the predicted and analyzed deepening rates for this study were higher than those found by for the 1987/88 season (Sanders and Auciello, 1989). For the present study the correlation coefficients for the 24 hr and 48 hr forecasts were .67 and .50 compared to .55 and .24 found for the 1987/88 season.

a)



b)

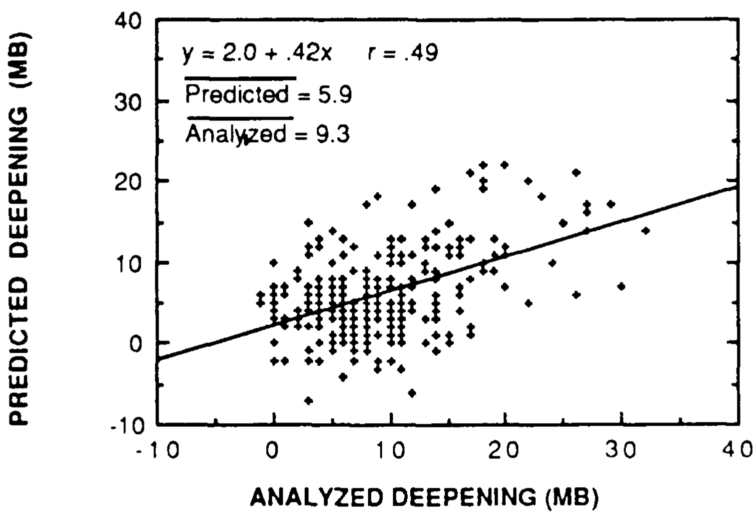
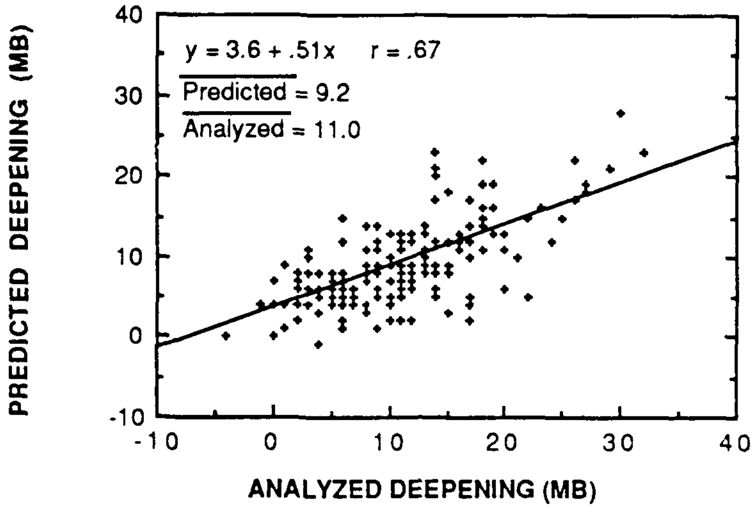


Figure 14. Scatter diagram of the predicted versus analyzed 12 hr deepening rate for all the 12 hr periods in the study. The solid line is the regression line. The mean values of the analyzed and predicted deepening are given along with the correlation coefficient. (a) NGM 24 hr forecast; (b) NGM 48 hr forecast

a)



b)

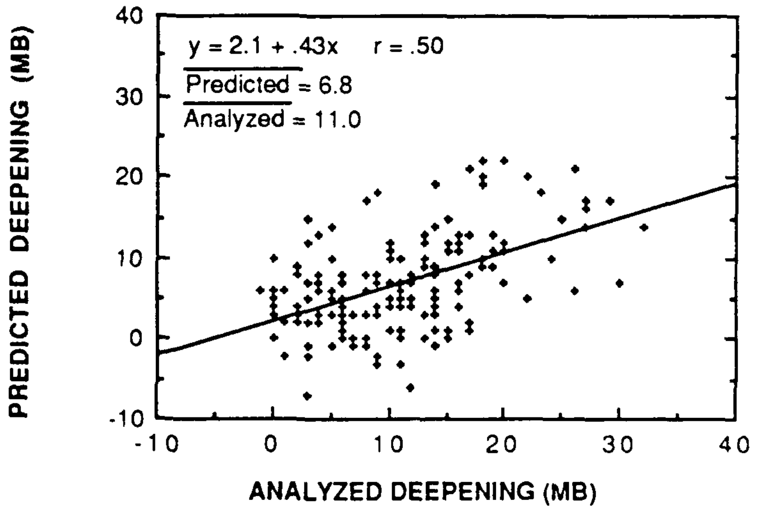
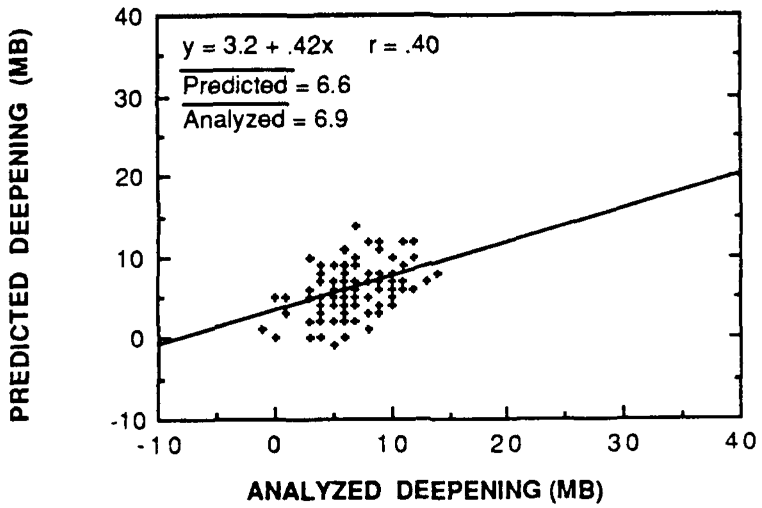


Figure 15. Scatter diagram of the predicted versus analyzed 12 hr deepening rate for all the 12 hr periods during the cyclogenesis of the explosive cyclones. The solid line is the regression line. The mean values of the analyzed and predicted deepening are given along with the correlation coefficient. (a) NGM 24 hr forecast; (b) NGM 48 hr forecast

a)



b)

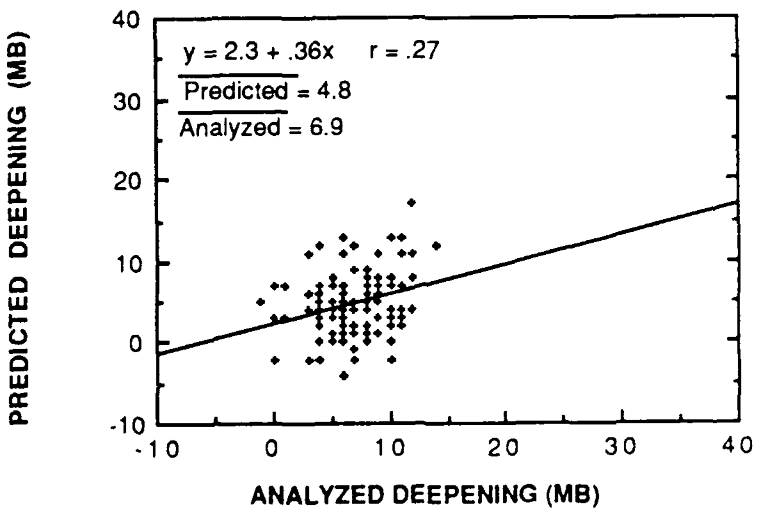


Figure 16. Scatter diagram of the predicted versus analyzed 12 hr deepening rate for all the 12 hr periods during the cyclogenesis of the moderate cyclones. The solid line is the regression line. The mean values of the analyzed and predicted deepening are given along with the correlation coefficient. (a) NGM 24 hr forecast; (b) NGM 48 hr forecast

Table 4 compares the correlation coefficients for the analyzed versus the predicted 12 and 24 hr deepening rates for the three samples. The correlation coefficients decreased with increasing forecast range for all the samples. The correlation coefficients for the 24 hr deepening rates were significantly higher than those for the 12 hr deepening rates. The correlations for the 24 hr deepening rates for all the forecasts ranged from .81 (24 hr) to .68 (48 hr), while the 12 hr deepening rates had values ranging from .72 (12 hr) to .42 (48 hr). The correlations for the explosive cyclones were nearly the same as those for all the forecasts in the study for both the 12 and 24 hr comparisons. However, the correlations for the moderate cyclones were considerably lower; the 24 hr deepening rates had correlations ranging from .54 to .38, and the 12 hr deepening rates had correlations ranging from .40 to .27.

The reason for the correlation coefficients being higher for the explosive cyclones is unclear. Perhaps the models can initialize strong baroclinic systems better than weaker ones, leading to better forecasts. During cases of explosive cyclogenesis, there is usually a very strong vorticity center upstream of a low-level baroclinic zone. It is probably easier for the model to initialize the stronger vorticity center associated with the explosive cyclones than the weaker one associated with moderate cyclones. Despite the fact that the model will underforecast the cyclones deepening rate during explosive cyclogenesis, the atmospheric forcing is strong enough to ensure that some deepening does take place.

TABLE 4. A comparison of the correlation coefficients (R) for the analyzed verses predicted 12 and 24 hr deepening rates (mb) for: all the 12 and 24 hr periods in the study (ALL), all the forecasts for the explosive cyclones (EXP), and all the forecasts for the moderate cyclones (MOD).

	All		EXP		MOD	
	12	24	12	24	12	24
NGM12	.72		.74		.38	
NGM24	.67	.81	.67	.78	.40	.54
NGM36	.61	.79	.63	.77	.29	.54
NGM48	.49	.68	.50	.67	.27	.38

TABLE 5. A comparison of the regression lines for the analyzed verses predicted 24 hr deepening rates (mb). The slopes (SLP) and the Y intercepts (YIN) are shown for: all 24 hr periods in the study (ALL), all the forecasts for the explosive cyclones (EXP), and all the forecasts for the moderate cyclones (MOD).

	All		EXP		MOD	
	SLP	YIN	SLP	YIN	SLP	YIN
NGM24	.82	1.6	.82	1.6	.86	1.1
NGM36	.79	0.7	.81	0.0	.84	0.2
NGM48	.74	-0.5	.78	-1.7	.72	0.2

TABLE 6 Same as table 5, except for the 12 hr deepening rates.

	All		EXP		MOD	
	SLP	YIN	SLP	YIN	SLP	YIN
NGM12	.65	2.7	.65	3.3	.44	3.6
NGM24	.53	3.0	.51	3.6	.42	3.2
NGM36	.51	2.3	.51	2.6	.36	3.0
NGM48	.42	2.0	.43	2.1	.36	2.3

The higher correlations for the 24 hr deepening rates over 12 hr deepening rates are probably due in part to timing errors in the 12 hr forecast. There were a couple of instances in which all of the explosive deepening occurred within a 12 hr period. For these cases, the timing of the forecast is crucial. Therefore smoothing these rapid fluctuations over a 24 hour period probably helps these model forecasts because they are then less sensitive to these types of timing errors.

Tables 5 and 6 compare the regression lines for the analyzed versus predicted 24 and 12 hr deepening rates respectively. All of the slopes of the regression lines were less than one, which points out the obvious fact that the model is underforecasting the deepening rates. The regression lines for the 24 hr deepening rates were steeper (about .2) than those for the 12 deepening rates. The slopes of the regression lines for the 24 hr deepening rates were nearly the same (within .06) for the all the samples. The regression lines for the 12 deepening rates had larger intercepts and smaller slopes indicating some overforecasting when the analyzed deepening rate was less than 5 mb. There was a significant difference in the slopes of the regression lines for the 12 hr deepening. The slopes for the explosive cyclones were on average about .13 steeper than those for the moderate cyclones.

3.3 POD, FAR and CSI

All the of the overlapping 24 hr forecast of the NGM were examined to find occurrences of 1 B of deepening in order to calculate the POD, FAR and the CSI. Table 7 shows the POD, FAR and CSI for the 1989/90 season, the partial 88/89 cold seasons, and the combined results. Table 7 also shows the results from Sanders and Auciello (1989) and Sanders (1987). The NGM performed well during the 1988/89 season; the POD were .79, .70 and .50 for the 24, 36 and 48 hr forecasts respectively, and the FAR were a modest .12 (24 hr), .14 (36 hr) and .13 (48 hr). These POD and FAR combined for very respectable CSI values of .71 (24 hr), .63 (36 hr) and .46 (48 hr). Although the results for the 1988/89 seasons indicated a significant improvement over 1987/88 results found by Sanders and Auciello (1989), the abbreviated season may have contributed to the improvement. Since the model has an underforecasting bias, it is more difficult for the model to predict 1 B of deepening for weaker bombs (near 1 B) than it is to predict 1 B of deepening for strong bombs. There was an unusually high number of strong bombs during the abbreviated 1988/89 season, making it easier for the model to forecast at least 1 B. It's quite possible that there would have been a number of weaker bombs earlier in the season which might have brought the numbers down for the whole season.

Keeping the previous caveat in mind, the 1989/90 model performance declined from 1988/89 season. The decline was most prevalent in the POD for the 36 hr forecast which dropped from .70 to .52. The POD for the 1989/90 season were .71, .52 and .45 for the 24, 36, and 48 hr forecasts respectively. Comparing these POD with those found by Sanders and Auciello for the 1987/88 season (the last complete season of data), they were slightly lower

Table 7. The POD, FAR and the CSI for 1 B of deepening during the 1988/89 and 1989/90 seasons as well as the combined results for the the two seasons (88-90). Also included are the results for 1987/88 from Sanders and Auciello (1989) and 1986/87 from Sanders (1987).

		24hr			36hr			48hr	
	POD	FAR	CSI	POD	FAR	CSI	POD	FAR	CSI
88-90	.74	.20	.62	.58	.13	.53	.47	.18	.43
89/90	.71	.24	.58	.52	.13	.48	.45	.20	.40
88/89	.79	.12	.71	.70	.14	.63	.50	.13	.46
87/88	.72	.17	.63	.62	.10	.58	.37	.21	.33
86/87	.51	.38	.39	.49	.29	.40	.26	.36	.22

for the 24 and 36 hr forecasts and slightly higher for the 48 hr forecast. The FAR for the 1989/90 season were .24 (24 hr), .13 (36 hr) and .20 (48 hr) which resulted in CSI scores of .58 (24 hr), .48 (36 hr) and .40 (48 hr). Comparing the 1989/90 with the 1987/88 season there was a slight drop in skill for 24 and 36 hr forecasts and increase in skill for the 48 hr forecast.

If the results of the 1988/89 and the 1989/90 seasons are combined, the POD, FAR and CSI are very similar to those found by Sanders and Auciello for the 1987/88 season. While most of the values are within a few percent, there was a 10% jump in the POD for the 48 hr forecast. With the exception of the improvement in the 48 hr POD (which was also reflected in the CSI), there has been little change in the skill of the model to predict at least 1 B of deepening.

3.4 Distance Errors

The mean forecast distance errors (measured from analyzed to predicted positions of the low center) for all the explosive and moderate cyclones are shown in Table 8. Although the distance errors for the explosive cyclones were larger than those of the moderate cyclones at all the forecast ranges, the differences in the mean errors were generally less than 10 km. The mean distance error for the forecasts of the explosive cyclones ranged from 114 km (0 hr) to 408 km (60 hr) while the moderate cyclones had errors ranging from 110 km (0 hr) to 385 (48 hr). Grumm and Siebers (1989) found

TABLE 8. Forecasted mean distance error (km) and standard deviation for the explosive and moderate cyclones. N is the number of comparisons. In parentheses are the forecasted mean distance error found for the LFM by Sanders (1986b).

	Explosive				Moderate		
	Mean		SDev	N	Mean	SDev	N
NGM0	114	(142)	77	223	110	74	166
NGM12	154	(202)	100	220	144	87	167
NGM24	209	(271)	136	222	209	129	165
NGM36	274	(295)	163	218	262	150	168
NGM48	335	(341)	202	211	328	198	158
AVN60	408		230	178	385	226	147

that the overall mean distance errors for the 24 hr and 48 hr NGM forecast were 256 and 417 km. Comparing their overall distance errors with those for explosive cyclones in the present study, we find that the mean distance errors for the explosive cyclones were 46 km less at 24 hr and 81 km less at 48 hr. It should be pointed out that Grumm and Siebers study was for only a three month period and they used the NGM initialization to verify the forecast errors. Sanders (1986b) had also found that the LFM distances errors during explosive cyclogenesis were smaller than the overall distance errors found by Silberberg and Bosart (1982).

The LFM distance errors during explosive cyclogenesis found by Sanders (1986b) are given in parentheses of Table 8. The NGM distance errors were smaller at all the ;orecast ranges. The differences in the mean distance errors were most prevalent for the 12 and 24 hr forecast which were 49 and 61 km less for the NGM. The differences in the errors for the 36 and 48 forecast were a modest 20 and 5 km respectively.

The distance errors were stratified from T-24 to T+24 in order to see how the errors change during the deepening of the cyclones. The results are shown in Table 9. In general, the mean distance errors and standard deviations were largest during the early stages of the cyclones development and continue to decrease throughout the cyclones deepening. This does not mean the distance errors decrease during each forecast cycle. In order to see how the distance errors change during each forecast cycle, the mean distance errors are shown in Table 10. The errors for each forecast cycle run

TABLE 9. Forecasted mean distance error (km) and standard deviation for the explosive and moderate cyclones from times T-24 to T+24. N is the number of comparisons.

	Explosive			Moderate		
	Mean	SDev	N	Mean	SDev	N
Time = -24						
NGM0	112	60	28	119	89	14
NGM12	192	100	27	146	102	15
NGM24	260	158	28	242	112	16
NGM36	338	195	27	302	150	15
NGM48	355	210	26	336	229	15
AVN60	459	262	24	392	208	16
Time=-12						
NGM0	142	84	52	131	83	42
NGM12	180	135	50	159	97	42
NGM24	235	152	50	200	141	39
NGM36	277	187	51	270	148	42
NGM48	401	225	49	373	195	37
AVN60	438	237	43	404	219	37
Time=0						
NGM0	111	77	51	107	74	43
NGM12	142	86	49	146	83	42
NGM24	188	129	52	230	142	41
NGM36	284	137	50	284	171	40
NGM48	324	192	49	358	196	40
AVN60	397	220	41	404	218	35
Time=+12						
NGM0	98	54	52	96	60	40
NGM12	128	67	52	138	83	42
NGM24	196	124	51	194	124	43
NGM36	245	142	50	239	144	43
NGM48	316	184	47	290	206	38
AVN60	370	204	38	389	250	33
Time=+24						
NGM0	91	96	27	106	70	19
NGM12	131	78	28	119	89	17
NGM24	159	80	27	180	95	18
NGM36	207	127	26	245	112	19
NGM48	256	153	26	289	178	19
AVN60	324	186	21	315	231	19

Table 10. The mean distance errors (km) for the NGM 0hr through 48 hr forecasts of explosive and moderate cyclones for times T-24 through T+24. Each forecast cycle is enclosed by a circle.

Explosive Cyclones

	T-24	T-12	T 0	T+12	T+24
NGM0	112	142	111	98	91
NGM12	192	180	142	128	131
NGM24	260	235	188	196	159
NGM36	338	277	284	245	207
NGM48	355	401	324	316	256

Moderate Cyclones

	T-24	T-12	T 0	T+12	T+24
NGM0	119	131	107	96	106
NGM12	146	159	146	138	119
NGM24	242	200	230	194	180
NGM36	302	270	284	239	245
NGM48	336	373	358	290	289

diagonally down the table and are enclosed by an ellipse. With the exception of the 12 hr forecast at T 0, the distance errors increased during each forecast cycle. The distance errors appear to decrease for the forecasts which initialized at T-12 or later. Thus the model appears to do better after it has initialized the incipient cyclone.

3.5 Position Errors

Figure 17 shows the cyclone position errors for all the forecasts in the study. The center of the plots represents the analyzed position and each "plus" represents the forecast position. In addition, Table 11 shows the frequency in which the predicted cyclone position verified in each quadrant relative to the NMC analyzed position. The cyclone position errors of the NGM initialization were evenly distributed around the analyzed position. The NGM initialization verified most frequently to the nortneast (27%) and least frequently to the northwest (21%). Although NGM initialization did not show any significant bias, the NGM forecasts showed a significant southwest bias. The 12 hr forecasts verified southwest of the analyzed position 38% of the time and verified west 65% of the time. The bias was most pronounced for the 24 hr forecast with nearly 74% of the forecasts verifying to the west of the analyzed position and 48% to the southwest. The 36 and 48 hr forecasts verified with nearly the same frequency in each quadrant as the 24 hr forecasts. The AVN 60 hr forecasts verified less frequently to the southwest

Figure 17. The cyclone position errors for all the forecasts. The center of the plot represents the analyzed position and the "plus" represents the forecast positions. The radial distances are in degrees of latitude (1 degree of latitude equals 111.11 km). (a) NGM0, (b) NGM12, (c) NGM24, (d) NGM36, (e) NGM48, (f) AVN60

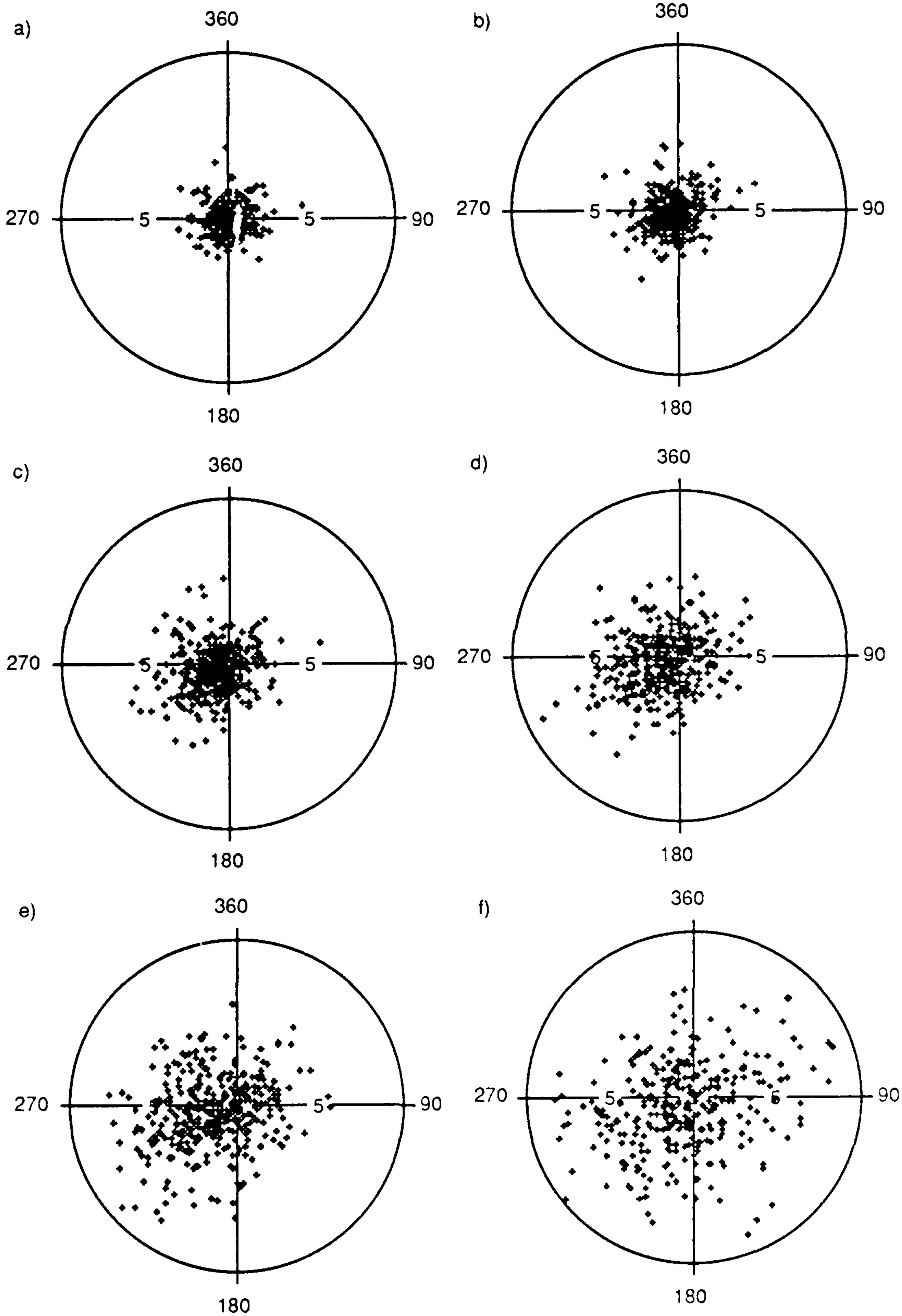

a)
360
270
5
5
90
180
b)
360
270
5
5
90
180
c)
360
270
5
5
90
180
d)
360
270
5
5
90
180
e)
360
270
5
90
180
f)
360
270
5
5
90
180

Table 11. The frequency in which the forecasted position of the cyclone verified in each quadrant relative to the analyzed position for: all the forecasts (ALL), explosive cyclones (EXP), and the moderate cyclones (MOD). Also included are the vector mean errors.

ALL

	NE	SE	SW	NW	Vector Mean Error
NGM0	27.3	26.8	24.7	21.2	132 / 6 km
NGM12	20.0	14.6	38.2	27.2	249 / 46 km
NGM24	13.6	12.6	48.2	25.6	243 / 101 km
NGM36	16.5	11.6	47.0	24.9	249 / 130 km
NGM48	16.1	12.6	44.1	27.2	254 / 163 km
AVN60	18.3	19.5	40.5	21.6	227 / 100 km

EXP

	NE	SE	SW	NW	Vector Mean Error
NGM0	28.3	27.0	23.0	21.7	69 / 10 km
NGM12	19.3	14.3	41.3	25.1	243 / 55 km
NGM24	13.3	15.1	47.1	24.4	236 / 102 km
NGM36	16.7	13.6	48.0	21.7	241 / 122 km
NGM48	20.1	12.1	43.9	23.8	250 / 147 km
AVN60	19.9	18.9	39.8	21.5	232 / 90 km

MOD

	NE	SE	SW	NW	Vector Mean Error
NGM0	25.9	26.5	27.1	20.5	199 / 14 km
NGM12	21.0	15.0	34.1	30.0	261 / 36 km
NGM24	13.9	9.1	49.7	27.3	251 / 102 km
NGM36	16.1	8.9	45.8	29.2	257 / 145 km
NGM48	10.8	13.3	44.3	31.6	258 / 182 km
AVN60	16.3	20.4	41.5	21.8	223 / 109 km

than any of the NGM forecasts. However the bias was still evident with nearly 40% of the AVN 60 hr forecasts verifying to the southwest of the analyzed position, while the other three quadrants each had about 20% Since most of the storms in the study moved toward the northeast, it is evident that the NGM predicted the cyclones to move too slowly.

The vector mean errors, shown in Table 11, indicate a virtually unbiased NGM initialization and a southwest bias which grows with time for all the NGM forecasts. The initialization for the explosive cyclones tended to be slightly to the northeast (69 / 10 km) while the moderate cyclones tended to initialize slightly to the southwest (199 / 14 km). The mean vector errors for the explosive cyclones were a little south of those for the moderate cyclones. The direction of the mean displacement errors for the explosive cyclones ranged from 243 to 254 degrees, while the directional errors for the moderate cyclones ranged from 251 to 261 degrees. The vector mean distance errors for the 36 and 48 hr forecasts were actually larger for the moderate cyclones. The AVN 60 hr forecast had southwest bias equal in magnitude to the NGM 24 hr forecast.

In order to test whether the initial position error of the cyclone had any effect on the forecast error, the forecast position errors were found for all the forecasts which initialized in each quadrant relative to the analyzed position. Figure 18 shows the forecast position errors for all the forecasts which originally initialized northeast of the analyzed position. Figures 19, 20 and 21 show the forecast position errors for all the forecasts which originally

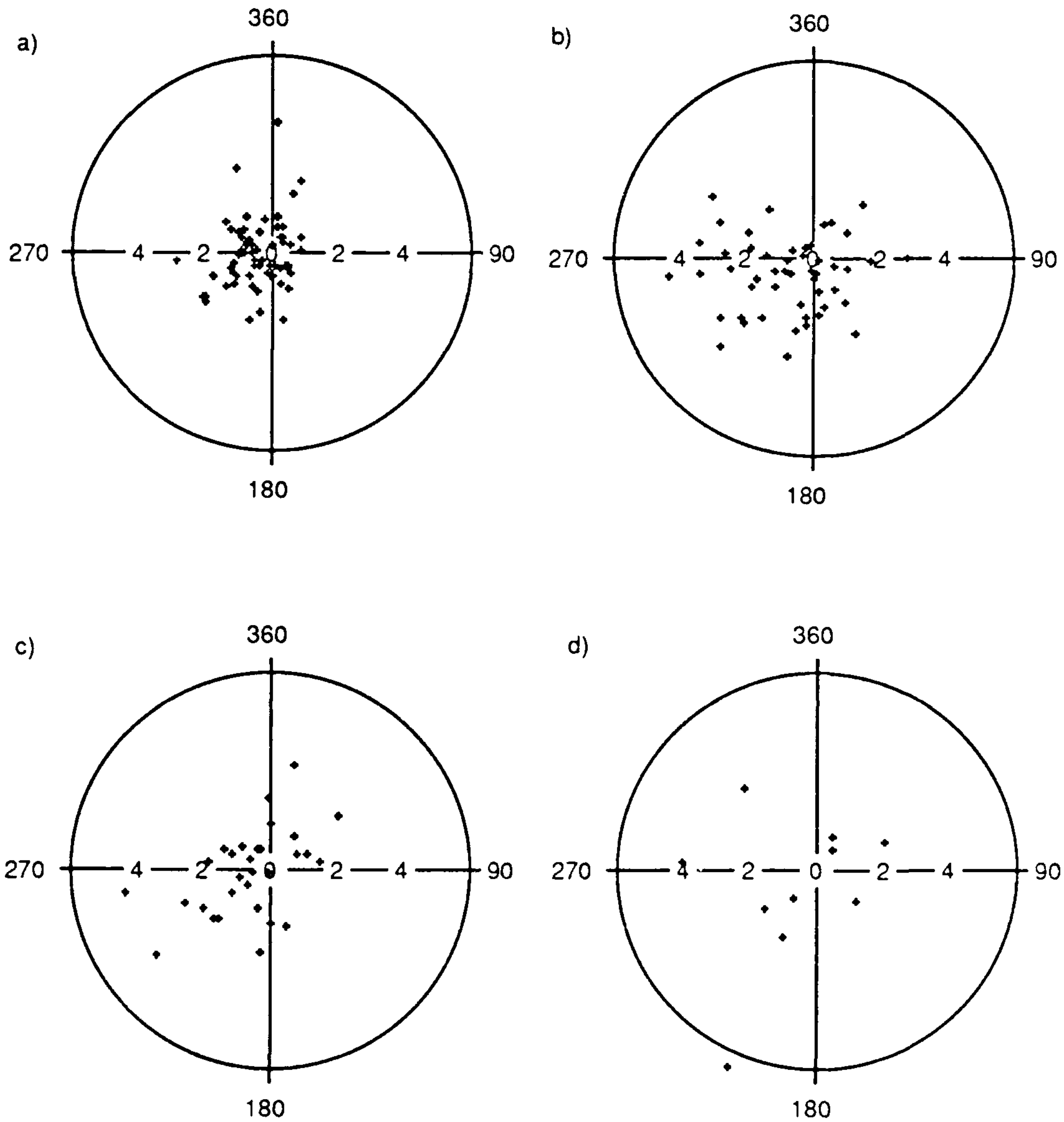


Figure 18. The forecast position errors for all the forecasts which originally initialized to the northeast of the analyzed position. The center of the plot represents the analyzed position and the "plus" represents the forecast positions. The radial distances are in degrees of latitude (1 degree of latitude equals 111.11 km). (a) NGM12, (b) NGM24, (c) NGM36, (d) NGM48

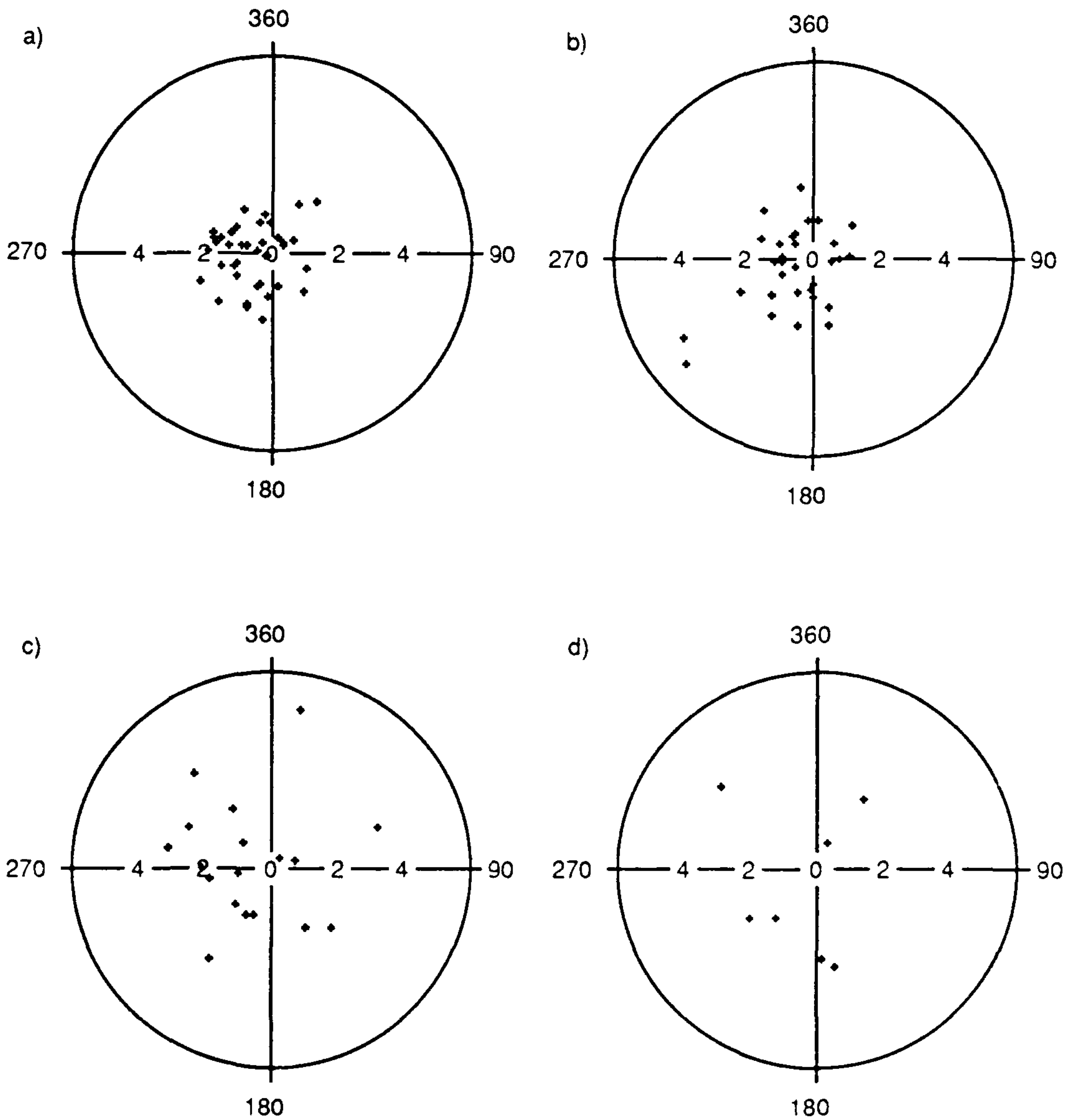


Figure 19. The forecast position errors for all the forecasts which originally initialized to the northwest of the analyzed position. The center of the plot represents the analyzed position and the "plus" represents the forecast positions. The radial distances are in degrees of latitude (1 degree of latitude equals 111.11 km). (a) NGM12, (b) NGM24, (c) NGM36, (d) NGM48

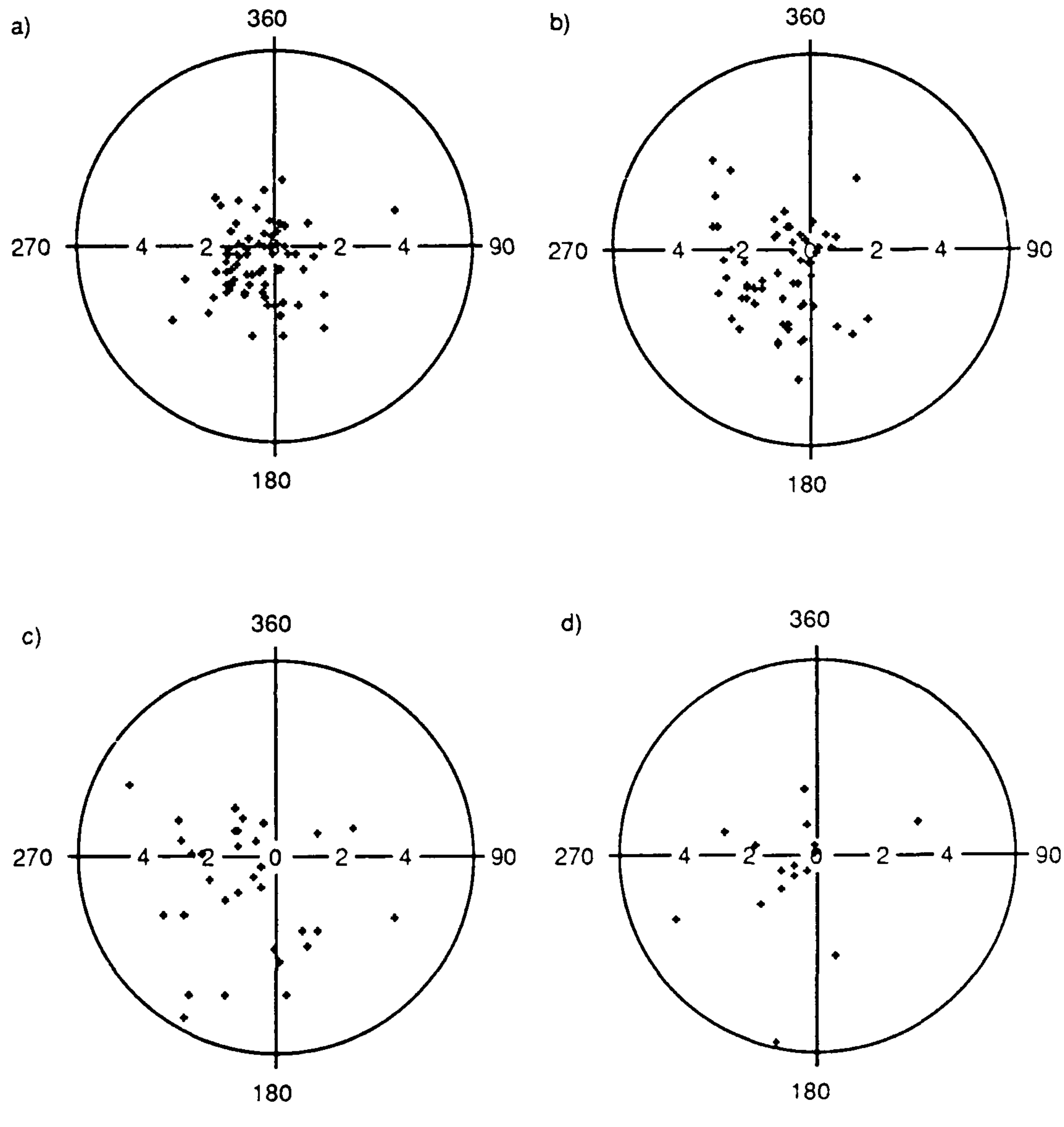


Figure 20. The forecast position errors for all the forecasts which originally initialized to the southwest of the analyzed position. The center of the plot represents the analyzed position and the "plus" represents the forecast positions. The radial distances are in degrees of latitude (1 degree of latitude equals 111.11 km). (a) NGM12, (b) NGM24, (c) NGM36, (d) NGM48

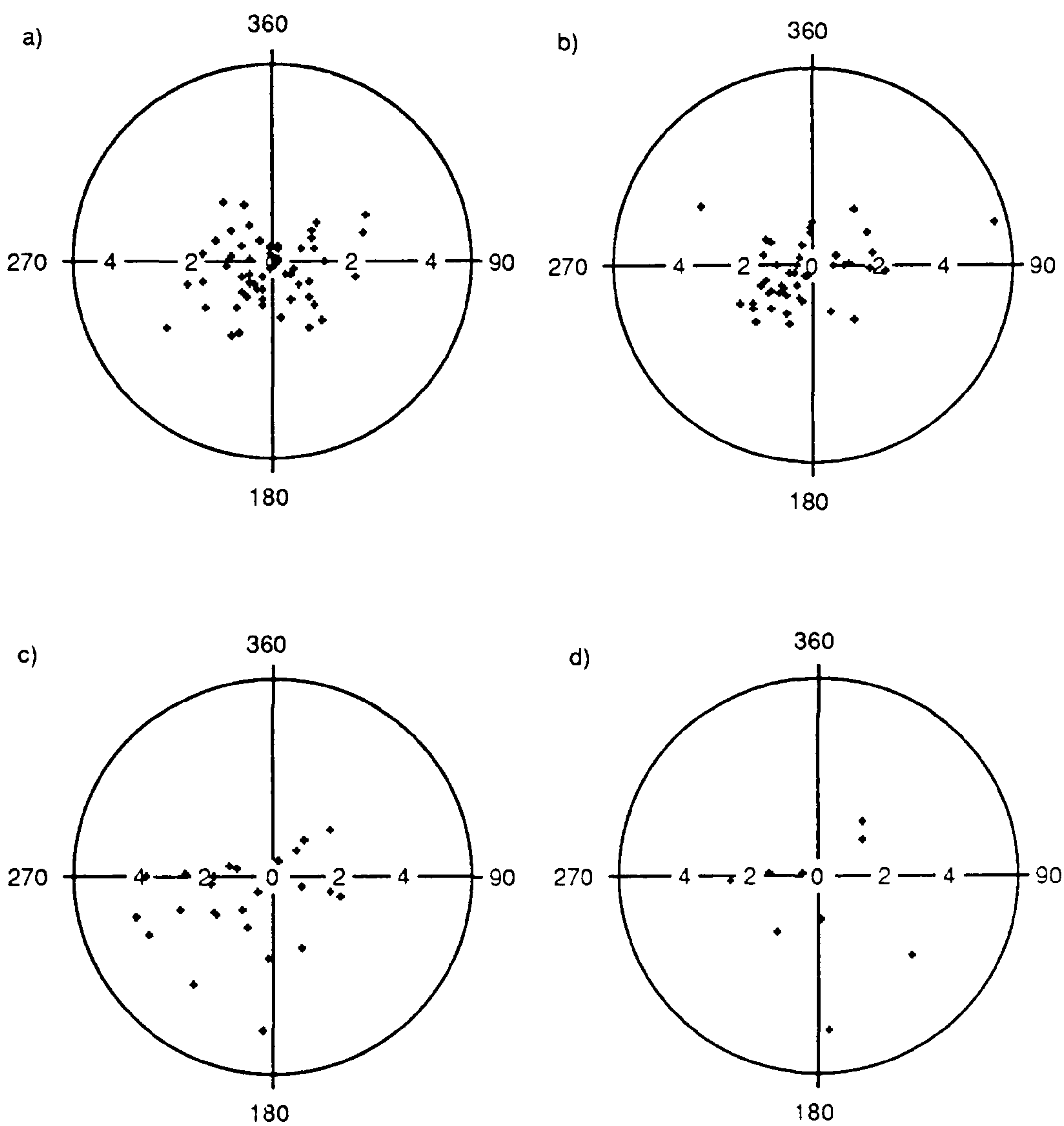


Figure 21. The forecast position errors for all the forecasts which originally initialized to the southeast of the analyzed position. The center of the plot represents the analyzed position and the "plus" represents the forecast positions. The radial distances are in degrees of latitude (1 degree of latitude equals 111.11 km). (a) NGM12, (b) NGM24, (c) NGM36, (d) NGM48

The members of the committee approve the thesis of Dale R. Lasher defended on 18 September, 1990.

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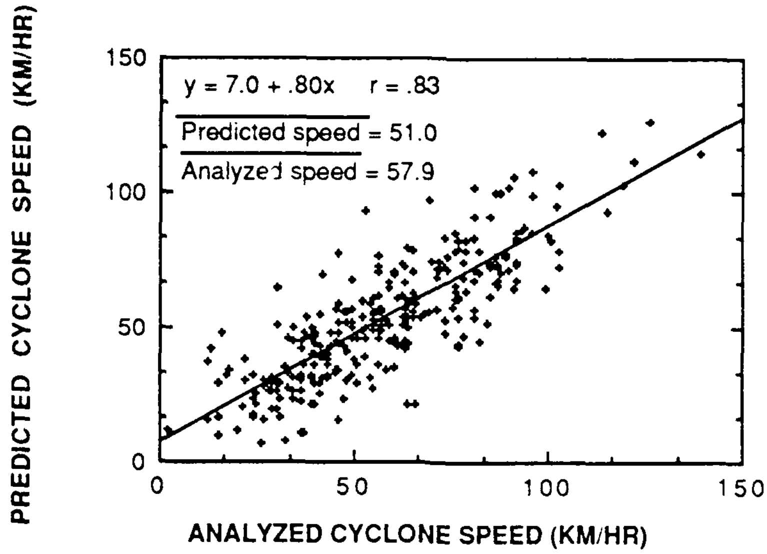
Committee Member

initialized to the northwest, southwest and southeast respectively. The west to southwest bias of the forecasts was evident regardless of which quadrant the forecast had initialized. Although forecasts which originally initialized east of the analyzed position may have a few more forecasts which stayed to the east, the vast majority of the forecast verified to the west and southwest.

3.6 Forecast Speed

Since the predicted cyclone position had a strong southwest bias, a more detailed analysis of the forecast cyclone speed was carried out. The analyzed and predicted cyclone speeds were calculated at 12 hr intervals using the straight line distance between 12 hr positions. Using a straight line distance would tend to underestimate the cyclone speed, but would probably have the same effect for both the analyzed and predicted storms. The scatter diagrams of the analyzed versus predicted cyclone speed for 24 and 48 hr forecasts are shown in figures 22 through 24. The mean analyzed speed for all the cyclones in the study was 57.9 km/hr. The mean speed of the explosive cyclones was faster than the mean speed for the moderate cyclones 62.5 km/hr compared to 51.5 km/hr. The correlations between the predicted and analyzed cyclone speeds were higher for the explosive cyclones. The mean predicted speeds for both the explosive and moderate cyclones were on average about 85% of the mean analyzed speed. Thus for this area and time, the NGM forecasts the cyclones to move too slowly. Grumm and Siebers

a)



b)

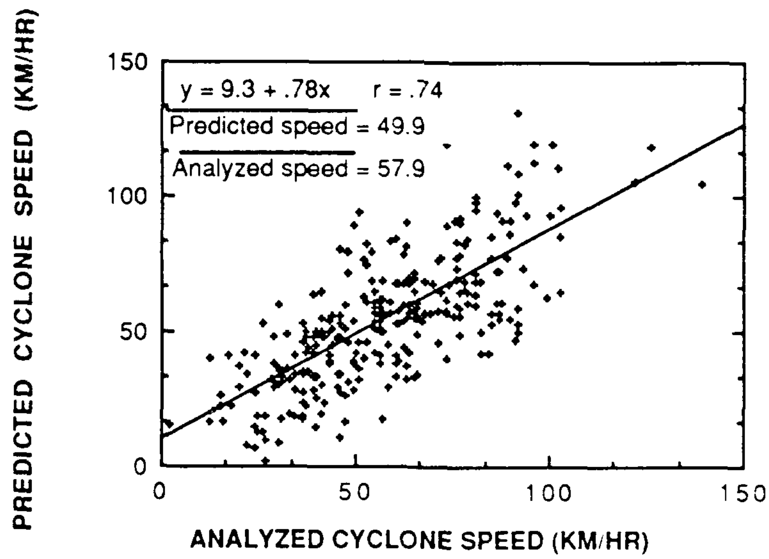
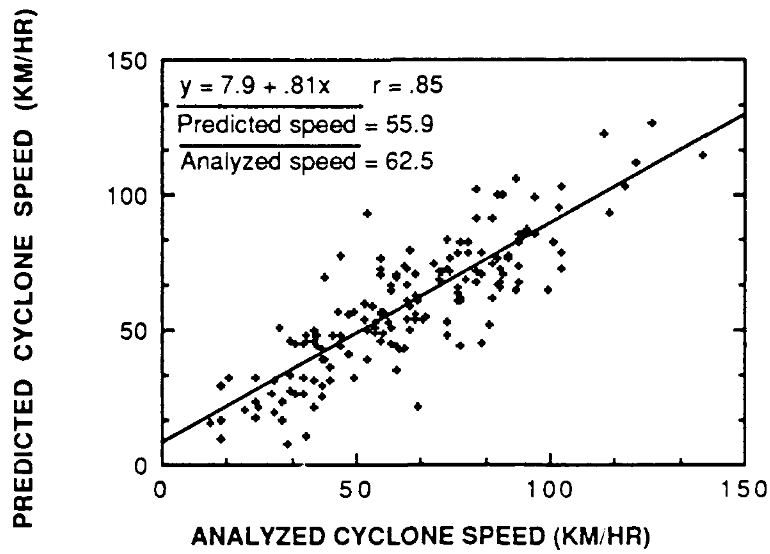


Figure 22. Scatter diagram of the analyzed versus predicted cyclone speed for all the forecasts in the study. The solid line is the regression line. The mean analyzed and predicted speeds are shown along with the correlation coefficient. (a) NGM 24 hr forecast (b) NGM 48 hr forecast

a)



b)

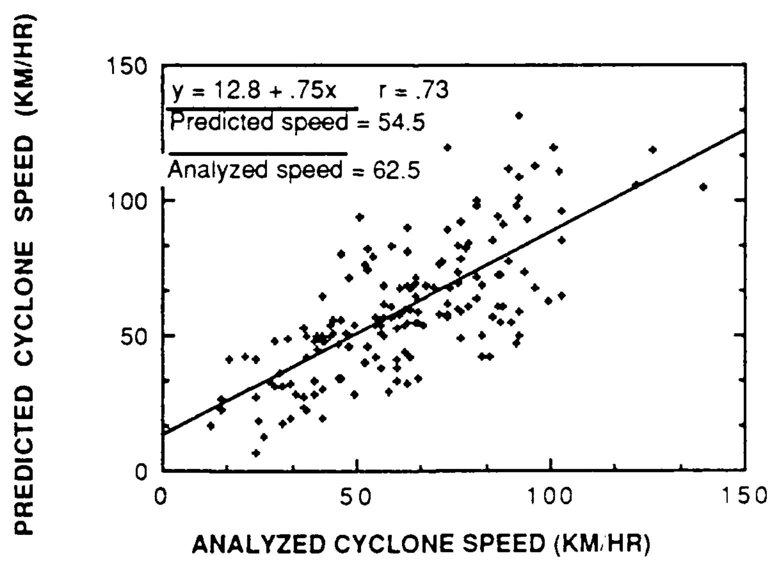
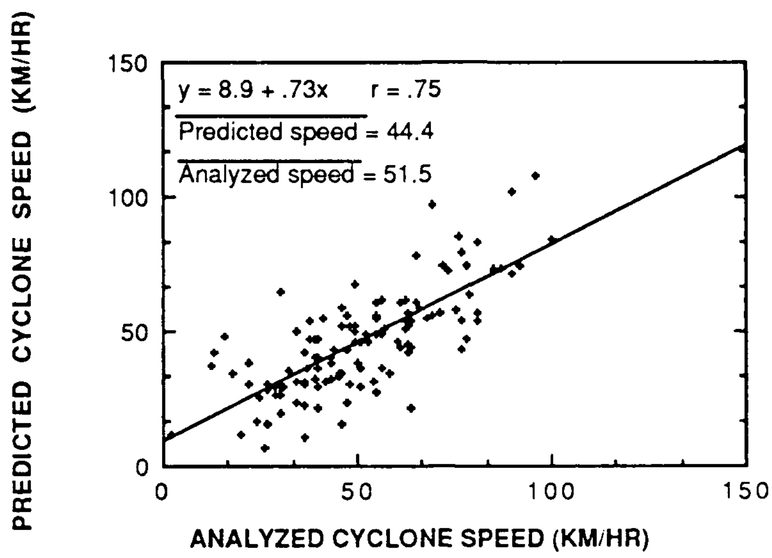


Figure 23. Scatter diagram of the analyzed versus predicted cyclone speed for all the forecasts during the cyclogenesis of the explosive cyclones. The solid line is the regression line. The mean analyzed and predicted speeds are shown along with the correlation coefficient. (a) NGM 24 hr forecast (b) NGM 48 hr forecast

a)



b)

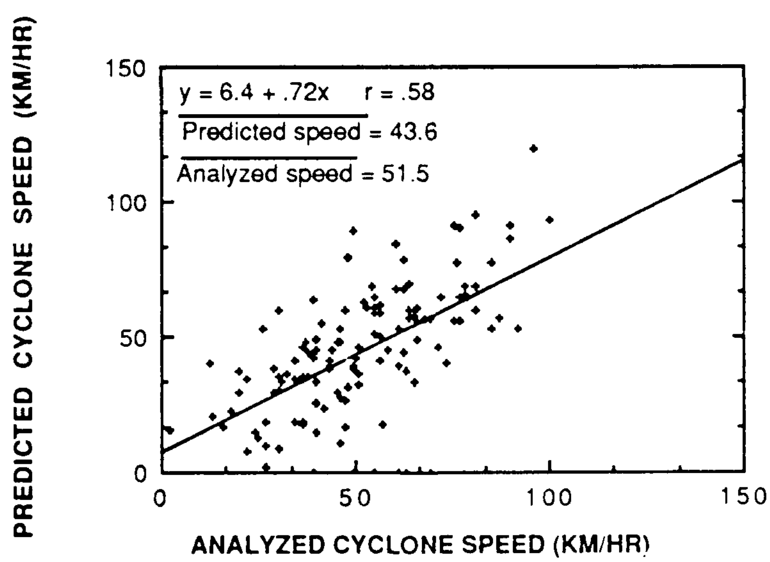


Figure 24. Scatter diagram of the analyzed versus predicted cyclone speed for all the forecasts during the cyclogenesis of the moderate cyclones. The solid line is the regression line. The mean analyzed and predicted speeds are shown along with the correlation coefficient. (a) NGM 24 hr forecast (b) NGM 48 hr forecast

(1989), which was a three month study of all the cyclones in the same area, had also found that NGM forecasts were too slow.

CHAPTER 4

SUMMARY

The NMC manual analyses were examined for twelve and a half months over two cold seasons in order to find cases of explosive and moderate cyclogenesis over the region bounded by 25 and 60 degrees north and by 90 degrees west and the eastern edge of the NGM display. An explosive cyclone was defined as any cyclone which deepened at least one bergeron during any 24 hr period, calculated every six hours. Any cyclone which attained a maximum deepening rate between .5 and 1 bergeron was defined as a moderate cyclone. There were 53 explosive and 43 moderate cyclones found during the study. The NGM and the AVN 60 hr forecasts of the central pressure and position were verified against the NMC manual analyses during the cyclogenesis of these storms.

The mean forecast errors of the central pressure were larger for the explosive cyclones. The deepening rates of the explosive cyclones were also proportionally larger. The mean central pressure error for all the 24 and 48 hr forecasts during the development of the explosive cyclones were 3.0 and 6.0 mb respectively, while the corresponding mean errors for the moderate cyclones were 2.0 and 3.5 mb respectively. The mean central pressure errors following the maximum deepening were considerably larger; the errors for the

24 and 48 hr forecast of the explosive cyclones were 6.2 and 12.5 mb respectively, while 24 and 48 hr forecast errors for the moderate cyclones were 2.5 and 6.0 mb. Twelve hours later the mean errors for the explosive cyclones decreased sharply, while the errors for the moderate cyclones continued to grow slightly.

The position errors were nearly the same for both the explosive and moderate cyclones. The NGM forecasts showed a significant southwest bias which grew with time. The vector mean displacement errors for all the 24 and 48 hr forecasts were 101 km at 243 degrees and 163 km at 254 degrees respectively. The AVN 60 hr forecast also had a southwest bias which was equal in magnitude to the NGM 24 hr forecast. Since most of the cyclones moved toward the northeast, the southwest bias indicated that the forecasts were too slow. A comparison of the analyzed and predicted cyclone speeds showed that the NGM mean predicted speed for all the cyclones was about 85% of the mean analyzed speed. The mean distance errors for the explosive cyclones were on average about 10 km larger than those for the moderate cyclones, but were still lower than the overall NGM distance errors found by Grumm and Siebers (1989). The distance errors found by Grumm and Siebers were for all the cyclones in the NGM display during a three month period. The mean distance errors for the 24 and 48 hr forecasts of the explosive cyclones for the present study were 47 and 82 km less than those found by Grumm and Siebers.

The predicted deepening rates of the explosive and moderate cyclones were compared with the analyzed deepening rates. The correlation coefficients for the analyzed versus predicted deepening rates of the explosive cyclones were significantly higher than those for the moderate cyclones. The correlations of the 24 and 48 hr forecasts of the 12 hr deepening for the explosive cyclones were .67 and .50 respectively compared with .40 and .27 for the moderate cyclones.

The ability of the NGM to forecast explosive cyclogenesis events in terms of the CSI score has not changed much over the last three years. The CSI scores for the 24 36 and 48 hr forecast over the last two cold seasons were .62, .53 and .43 respectively. The CSI scores for the 1987/88 season found by Sanders and Auciello (1989) were .63 (24 hr), .58 (36 hr) and .33 (48 hr). Thus the CSI scores for the 1988/90 seasons were slightly lower for the 24 and 36 hr forecasts, but were .10 higher for the 48 hr forecast.

Over the last two cold seasons, there were some improvements in the correlations between the predicted and analyzed deepening rates during explosive cyclogenesis. Sanders and Auciello (1989) found the correlations for the 12-24 hr and the 36-48 hr forecast ranges were .55 and .24 respectively, while the corresponding correlations over the last two years were .67 and .50. Again the most notable improvements were in the NGM 48 hr forecasts.

This study has compared the forecast errors between moderately and explosively deepening cyclones. It was found that the forecast errors for the explosive cyclones were larger than those for moderate cyclones, but the correlations between the predicted and analyzed deepening rates were higher for the explosive cyclones. This study has also found that the forecasts for both samples of cyclones were too slow, which led to a southwest bias that increased with time. The AVN forecasts did not appear to be as slow as the NGM. The AVN 60 hr forecast had a vector mean error which was equal in magnitude with the NGM 24 hr forecast. Finally this study has extended the earlier work of Sanders on the NGM wintertime predictions of explosive cyclogenesis in the western north Atlantic. It has shown that the NGM skill in predicting 1 bergeron events (in terms of CSI) has not changed much during the last three years, but there have been some slight improvements in the correlations between the predicted and analyzed deepening rates.

APPENDIX A

STATISTICS

This appendix defines the probability of detection, false alarm rate, and the critical success index, which were the three measures against which forecast skill was evaluated.

Probability of detection (POD): the number of correct forecasts (or hits) divided by the number of events. It is an indication of how likely an event would be correctly forecasted. A POD of .70 means that the event was correctly forecast 70% of the time. For this study, the event being investigated is explosive cyclogenesis (one bergeron of deepening). Therefore, any 24 hr period (calculated at 00 and 12 UTC) in which a cyclone deepens one bergeron in the NMC preliminary analyses constitutes an event. If during that same 24 hr period the cyclone is forecast to deepen at least one bergeron, the forecast is considered correct. What constitutes a correct forecast is an important point to keep in mind when evaluating these statistics. During one 24 hr period of the study, the NMC analyses had a cyclone deepening 2.2 B (41 mb) while the NGM 36 hr forecast had the cyclone deepening 1.0 B (18 mb). Although the 36 hr forecast would be considered correct using the above criterion, most meteorologists would not consider a forecast which underestimated the 24 hr deepening by 23 mb to be a good forecast. Also, some cases with fairly good forecasts were not considered correct when using the one bergeron criterion. In one instance a cyclone deepened 1 B (19 mb) in the analyses while the 36 hr forecast deepened the cyclone .9 B (17 mb). Hopefully, these instances, which are extreme examples, balance out over the whole study.

False alarm rate (FAR): the number of false alarms divided by the sum of the correct forecasts and the false alarms, where a false alarm (FA) is an unsuccessful forecast of an event. For this study, a false alarm is any 24 hr period in which a cyclone was forecast to deepen at least 1 B but, the analyses indicated less than 1 B of deepening. The FAR gives an indication of how often a forecast event would be unsuccessful. A FAR of .10 would mean that 10% of the time a forecasted event would not occur. Since the NGM usually underestimates the intensity of the cyclones over the study region, there were not many false alarms. The false alarms which did occur were usually a result of either slight overforecasting (i.e., forecast 1 B when analyses indicated .9 B) or timing errors.

Critical success index (CSI) (Donaldson et al., 1975): combines the POD and FAR into one index ($CSI = [(POD)^{-1} + (1 - FAR)^{-1} - 1]^{-1}$). Higher POD and lower FAR would contribute to higher CSI. Thus high CSI values combines the desired effects of high POD and low FAR.

APPENDIX B

LIST OF CYCLONES

Table 12. The initial and final central pressures (CP) and positions (POS) along with the maximum deepening rate (B) for each explosive cyclone.

No.	Date	Max B	Initial CP	Initial POS	Final CP	Final POS
1	13-14 Dec 88	1.1	1010	29 N 78 W	994	33 N 66 W
2	14-15 Dec 88	1.4	993	34 N 70 W	970	39 N 59 W
3	17-19 Dec 88	1.5	1006	37 N 71 W	975	52 N 57 W
4	28-30 Dec 88	2.0	1007	39 N 84 W	946	57 N 49 W
5	02-04 Jan 89	1.8	1008	38 N 70 W	964	45 N 53 W
6	04-05 Jan 89	3.0	994	36 N 73 W	942	41 N 58 W
7	12-14 Jan 89	1.0	1010	50 N 89 W	958	62 N 30 W
8	19-20 Jan 89	2.2	1006	38 N 67 W	965	45 N 48 W
9	20-22 Jan 89	1.7	1003	45 N 77 W	966	48 N 56 W
10	26-28 Jan 89	1.3	1014	42 N 88 W	978	56 N 38 W
11	31-01 Feb 89	1.4	996	48 N 70 W	960	58 N 40 W
12	03-05 Feb 89	1.2	1015	38 N 75 W	982	53 N 38 W
13	09-10 Feb 89	1.5	1002	50 N 73 W	958	58 N 38 W
14	24-25 Feb 89	1.1	1008	34 N 77 W	986	39 N 68 W
15	01-03 Mar 89	1.3	1006	37 N 69 W	970	53 N 35 W
16	05-08 Mar 89	1.7	1015	49 N 72 W	944	58 N 32 W
17	28-29 Mar 89	1.2	1000	56 N 67 W	972	62 N 50 W
18	29-31 Mar 89	1.3	994	46 N 76 W	952	62 N 40 W
19	06-07 Mar 89	1.6	1012	39 N 75 W	976	49 N 69 W
20	15-17 Sep 89	1.5	1008	44 N 67 W	963	52 N 28 W
21	26-28 Sep 89	1.0	1009	39 N 74 W	934	58 N 49 W
22	08-10 Oct 89	1.1	1006	33 N 77 W	984	54 N 50 W
23	11-12 Oct 89	1.0	1016	38 N 67 W	998	44 N 59 W
24	17-19 Oct 89	1.4	1005	48 N 66 W	970	56 N 30 W
25	03-05 Nov 89	1.5	1008	37 N 71 W	972	57 N 50 W
26	15-17 Nov 89	1.2	1004	37 N 90 W	965	55 N 76 W
27	20-22 Nov 89	1.1	993	52 N 91 W	966	47 N 63 W

Table 12 continued.

No.	Date	Max B	Initial CP	Initial POS	Final CP	Final POS
28	23-25 Nov 89	1.0	1007	33 N 83 W	977	53 N 51 W
29	27-28 Nov 89	1.4	1000	42 N 64 W	973	49 N 45 W
30	28-30 Nov 89	1.2	995	44 N 78 W	960	56 N 48 W
31	03-04 Dec 89	1.7	1004	41 N 76 W	962	48 N 63 W
32	07-08 Dec 89	1.5	1004	40 N 76 W	974	52 N 54 W
33	09-10 Dec 89	1.2	1006	30 N 85 W	988	34 N 70 W
34	13-14 Dec 89	1.0	1006	36 N 74 W	990	37 N 61 W
35	17-19 Dec 89	1.1	986	47 N 63 W	960	48 N 43 W
36	20-22 Dec 89	1.8	1010	32 N 74 W	952	54 N 44 W
37	24-25 Dec 89	1.5	1008	31 N 77 W	980	40 N 58 W
38	26-28 Dec 89	1.5	994	46 N 76 W	958	59 N 45 W
39	28-30 Dec 89	2.0	1016	36 N 73 W	939	53 N 38 W
40	01-03 Jan 90	1.7	1006	44 N 83 W	940	57 N 50 W
41	04-06 Jan 90	1.2	1002	42 N 88 W	966	59 N 41 W
42	06-08 Jan 90	2.1	1015	35 N 73 W	956	53 N 37 W
43	08-09 Jan 90	1.1	1009	34 N 82 W	990	41 N 61 W
44	16-18 Jan 90	1.3	1018	44 N 61 W	986	54 N 35 W
45	17-20 Jan 90	1.0	1006	44 N 90 W	969	56 N 50 W
46	27 28 Jan 90	1.8	982	50 N 58 W	941	56 N 37 W
47	29-30 Jan 90	1.3	1015	32 N 93 W	985	43 N 69 W
48	02-04 Feb 90	1.5	999	50 N 67 W	945	55 N 33 W
49	16-18 Feb 90	1.5	1005	45 N 85 W	965	50 N 34 W
50	20-21 Feb 90	1.7	999	47 N 63 W	961	50 N 40 W
51	24-25 Feb 90	1.0	998	41 N 77 W	969	53 N 35 W
52	01-02 Mar 90	1.4	1002	50 N 56 W	970	61 N 52 W
53	07-09 Apr 90	1.0	1007	36 N 80 W	985	57 N 48 W

Table 13. The initial and final central pressures (CP) and positions (POS) along with the maximum deepening rate (B) of each moderate cyclone.

			Initial		Final	
No.	Date	Max B	CP	POS	CP	POS
1	22-23 Dec 88	.66	1007	48 N 65 W	993	52 N 44 W
2	24-27 Dec 88	.85	1005	39 N 88 W	969	53 N 40 W
3	08-10 Jan 89	.89	994	47 N 89 W	960	62 N 52 W
4	15-17 Jan 89	.61	996	52 N 88 W	971	62 N 54 W
5	22-23 Jan 89	.85	1014	26 N 83 W	999	31 N 73 W
6	18-20 Feb 89	.55	1020	33 N 76 W	1004	39 N 58 W
7	26-28 Feb 89	.75	1008	46 N 85 W	988	44 N 57 W
8	24-27 Mar 89	.78	1014	35 N 77 W	982	46 N 52 W
9	07-09 Apr 89	.94	1009	35 N 91 W	982	48 N 63 W
10	13-15 Apr 89	.90	1019	35 N 73 W	997	42 N 57 W
11	15-16 Apr 89	.84	1010	33 N 82 W	996	40 N 70 W
12	22-23 Apr 89	.89	1003	32 N 70 W	985	50 N 53 W
13	26-28 Apr 89	.81	996	43 N 56 W	975	53 N 47 W
14	22-23 Sep 89	.62	1010	55 N 93 W	996	53 N 75 W
15	22-23 Sep 89	.85	994	35 N 82 W	978	50 N 70 W
16	24-25 Sep 89	.70	994	52 N 63 W	978	60 N 47 W
17	04-05 Oct 89	.60	992	49 N 63 W	979	55 N 63 W
18	13-14 Oct 89	.85	998	46 N 51 W	974	56 N 39 W
19	22-24 Oct 89	.85	995	53 N 62 W	970	60 N 35 W
20	31-02 Nov 89	.82	1006	45 N 86 W	975	60 N 54 W
21	09-11 Nov 89	.77	991	48 N 86 W	968	59 N 76 W
22	13-14 Nov 89	.67	987	55 N 57 W	967	61 N 47 W
23	19-21 Nov 89	.89	1011	48 N 70 W	970	61 N 64 W
24	01-02 Dec 89	.78	1000	44 N 69 W	985	44 N 52 W
25	12-14 Dec 89	.64	1008	29 N 89 W	994	37 N 66 W
26	15-17 Dec 89	.79	1009	37 N 85 W	990	45 N 66 W
27	04-05 Jan 90	.56	999	53 N 86 W	986	60 N 67 W
28	10-12 Jan 90	.69	998	42 N 84 W	976	49 N 51 W
29	12-13 Jan 90	.83	990	44 N 66 W	973	52 N 54 W
30	25-26 Jan 90	.87	1000	37 N 93 W	984	46 N 84 W
31	04-05 Feb 90	.86	1006	38 N 79 W	991	40 N 56 W
32	15-16 Feb 90	.67	978	58 N 44 W	962	61 N 41 W
33	02-03 Mar 90	.55	1018	31 N 91 W	1006	35 N 80 W
34	05-06 Mar 90	.51	1006	52 N 49 W	986	60 N 35 W
35	12-14 Mar 90	.84	998	47 N 50 W	974	54 N 40 W
36	19-20 Mar 90	.77	980	58 N 60 W	953	60 N 32 W
37	20-23 Mar 90	.85	1015	37 N 78 W	975	59 N 34 W
38	23-24 Mar 90	.67	996	53 N 76 W	974	62 N 54 W
39	03-04 Apr 90	.72	1004	37 N 78 W	987	43 N 72 W

Table 13 Continued.

No.	Date	Max B	Initial CP	Initial POS	Final CP	Final POS
40	10-11 Apr 90	.76	1008	40 N 91 W	994	43 N 71 W
41	12-13 Apr 90	.75	998	45 N 65 W	973	60 N 36 W
42	16-17 Apr 90	.74	1002	50 N 77 W	985	59 N 52 W
43	18-19 Apr 90	.71	998	50 N 68 W	982	60 N 54 W

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