Explosive Cyclogenesis over the West-Central North Atlantic Ocean, 1981–84. Part II: Evaluation of LFM Model Performance

FREDERICK SANDERS

9 Flint Street, Marblehead, MA 01945

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ABSTRACT

A study was made of the performance of the Limited-Area Fine-Mesh (LFM) operational forecasts for cases of explosive cyclogenesis in the west-central North Atlantic Ocean during 1981–84. For 51 instances in which the observed 12-h deepening was at least 10 mb, the LFM forecasts for 12–24 h range indicated 58% of this deepening on the average, but accounted for only 30% of the variance in individual cases. In a comparison of central pressures from manual analyses with those in LFM initializations and predictions, the latter were insufficiently deep once rapid intensification began, the discrepancy increasing from about 4 mb in the initializations to about 10 mb in the forecasts from 36 to 48 h. In a number of instances the LFM did not detect the initial appearance of the cyclone. Mean position errors increased from about 75 n mi (140 km) initially to about 185 n mi (340 km) at 48-h range. Mean vector errors were slightly southeast of the analyzed center initially and about 65 n mi (120 km) east-northeast finally, indicating a forecast track slightly too fast and slightly too far to the right. Two individual case studies showed that even when there are large quantitative discrepancies between events in the LFM and real atmospheres, the model is qualitatively correct. These results indicate the essentially baroclinic nature of the cyclogenesis, but the intensity of response to the baroclinic forcing remains intractable.

1. Introduction

Marine forecasters, like others, rely heavily on the guidance provided by the Limited-Area Fine-Mesh Model (LFM) (Gerrity, 1977; Newell and Deaven, 1981) at the National Meteorological Center (NMC). It is widely appreciated that dynamical prediction models generally fail to do justice to maritime cyclones (Leary, 1971; Druyan, 1974; Sanders and Gyakum, 1980; Silberberg and Bosart, 1982), but there has been no comprehensive attempt to verify the LFM performance with respect not only to explosive deepening of the low-pressure center but also to the important storm track.

A study of the mean behavior of a sample of "bombs" in the west-central North Atlantic during 1981–84 has been presented by Sanders (1986) in a companion paper. This study was based on 48 storms, stratified by relative intensity into 12 strong, 16 moderate and 20 weak cases. We now offer an evaluation of the LFM forecasts for these storms, which deepened rapidly in the area bounded by 32°–51°N and 53°–76°W.

The center of the 24-h period of maximum observed deepening was denoted time zero. An increment of 12 h is natural, corresponding to the period between both successive rawinsonde balloon releases and LFM initializations. Accordingly, we considered forecasts for ranges from 0–48 h, verifying at each initialization time from 24 h before to 24 h after time zero (i.e., times −2 to +2). A substantial number of potential comparisons was impossible, not only because of incompleteness of the MIT archives, which served as the sole data source, but also because the low center was not present at times −2 or −1 in either the NMC operational manual analyses (taken as the observed data) or the LFM initializations or predictions. Nevertheless, the results appear to be a reasonable representation of the performance of the model in recent years. The changes in the model over this period were few and mainly computational with little reason to expect an effect on predictions of oceanic cyclogenesis. A physical improvement of potential significance, to judge from the modeling results of Anthes et al. (1983), was the addition of evaporation from the sea surface. This change, introduced late in 1981, did not have a recognizable influence, however, within our sample of storms.

2. Prediction of deepening rate and central pressure

A simple and convenient, although not infallible, measure of storm intensity is the central pressure. Its rate of change following the cyclone center (the deepening rate) is thus a measure of the rate of intensification. Indeed, Sanders and Gyakum (1980) defined the bomb as a cyclone in which the 24 h deepening represents at least one bergeron [this value being defined as the ratio $(\Delta p/24)(\sin 60°/\sin\phi)$, where Δp is the deepening in mb]. This criterion was used by Sanders (1986).

a. Twelve-hour deepening rate

To facilitate a comparison with Sanders and Gyakum's (1980) evaluation of the performance of the relatively coarse-mesh PE model (Shuman and Hovermale, 1968) then in use, we examined LFM-predicted deepening rates for each 12-h period in which the observed deepening of a storm was at least 10 mb. At the mean latitude of the western North Atlantic region under study this value is consistent with the one-bergeron criterion.

In the 48-storm sample, 51 comparisons were made between observed and predicted changes at the range from 12 to 24 h and are shown in Fig. 1. In another 11 instances the actually deepening cyclone was not detected in the 12-h forecast. From a comparison of Fig. 1 with Sanders and Gyakum's (1980) Fig. 15 we see that the LFM performance for this time and geographical area is clearly better than that of the more skilled of the earlier models. For example, the mean LFM-predicted deepening was about 9 mb versus an observed 15.5 mb, while the 7-LPE values were about 6 mb versus an observed 16.5 mb. The LFM and 7-LPE results showed correlation coefficients of 0.55 and 0.32, respectively, between observed and predicted deepening.

It is difficult to partition the difference in these results between surface evaporation, the better horizontal resolution of the LFM and the more reliable analyses, especially at upper levels, in the western North Atlantic versus the larger oceanic area examined by Sanders and Gyakum (1980). Limited modeling results (Anthes et al., 1983) show improvement in intensity forecasts down to (but not below) a mesh length of 45 km, substantially smaller than the LFM's 127 to 190 km. On the other hand, the central North Pacific is generally perceived as a data-sparse region in which the upper-level forcing essential to explosive cyclogenesis may be poorly represented. None of the three considerations can be dismissed without further study.

No trend within the 1981–84 period is evident in Fig. 1. The more recent, circled data yield a regression line slightly nearer to perfection than the one for the entire sample, but also a slightly lower correlation coefficient. Overall, only 30% of the variance in the deepening data from analyses is being explained by the LFM forecasts, and a substantial shortfall persists in the predictions.

It might be argued that the small scale of the intense portion of the bomb itself, in view of the mesh length of the LFM, makes accurate numerical forecasting impossible aside from limitations imposed by the imperfect representation of physical processes. Perhaps so, but we note from Fig. 1 that the most intense 12-h deepening in the sample, by a generous margin, is a predicted value of 35 mb! We shall examine this case in some detail later, noting here only that the model can do it if so inclined—so to speak.

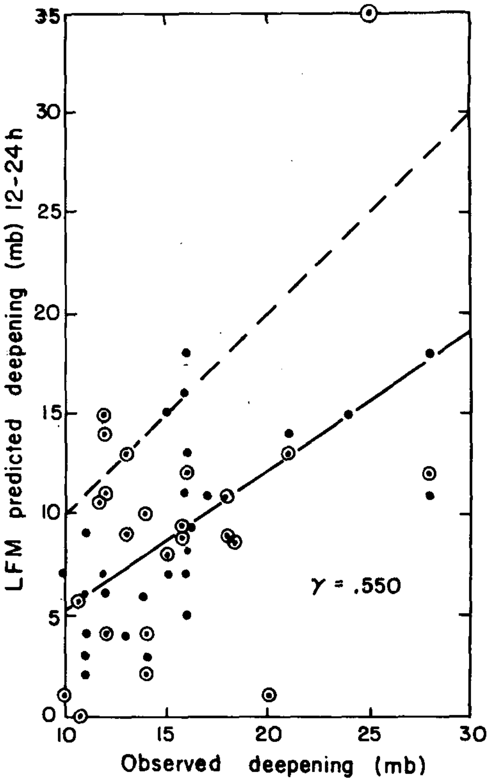

FIG. 1. Deepening (mb) in the range from 12 to 24 h, in LFM forecasts, vs observed deepening in the corresponding 12-h period, from manual analyses. The dashed line indicates a perfect forecast and the heavy solid one the regression of observed on predicted deepening. The circled points are those for the more recent half of the instances.

Further, if the model suffers from too wide a spacing of grid points, so does the analysis from an even wider typical spacing between observations. The effect of spacing of the data points operates differently in the two cases, but the result is qualitatively the same. Often an analysis performed after the fact based on a larger data sample and on two-way continuity, shows deeper central values than the operational analysis relied on in this study. Thus, we believe that the LFM underprediction is not a procedural artifact but reflects a physical shortcoming. Modeling studies by Chen et al. (1983) and by Anthes et al. (1983) have demonstrated the importance of detailed treatment of the air–sea interaction process.

b. Central pressure

In an evaluation of prediction of central pressure, we compiled all forecasts from initialization (0-h range) to 48-h range, verifying at times from −2 to +2, as stated earlier. These were compared with the corresponding operationally analyzed central values. The number of comparisons (and the number of times the LFM failed to predict an analyzed center) is given in

TABLE 1. Number of comparisons for central-pressure verification; all bombs. Number of cases with low analyzed but not predicted in parentheses.

Time of verification	Time of initialization −6	−5	−4	−3	−2	−1	0	+1	+2
−2	16 (10)	18 (10)	12 (12)	14 (11)	19 (7)				
−1		29 (11)	26 (12)	28 (11)	31 (6)	32 (7)			
0			29 (9)	33 (6)	35 (4)	36 (3)	37 (1)		
+1				32 (1)	34 (1)	37 (0)	35 (0)	35 (0)	
+2					24 (0)	23 (0)	24 (0)	26 (0)	26 (0)
Range of forecast (h)					48	36	24	12	0

TABLE 2. Mean difference in millibars (forecast-analyzed) for central-pressure verification; all bombs. Standard deviations in parentheses.

Time of verification	Time of initialization −6	−5	−4	−3	−2	−1	0	+1	+2
−2	−1.6 (4.9)	−0.8 (4.4)	+0.4 (3.3)	−0.2 (3.0)	+1.2 (2.2)				
−1		−2.0 (6.2)	+0.1 (4.9)	+0.7 (3.1)	+0.8 (2.9)	+1.3 (1.3)			
0			+5.4 (6.5)	+4.5 (5.3)	+4.1 (5.7)	+3.8 (5.6)	+1.8 (2.6)		
+1				+11.1 (7.6)	+10.2 (7.4)	+9.7 (7.7)	+7.7 (5.5)	+4.9 (5.2)	
+2					+9.9 (9.2)	+10.9 (10.1)	+8.2 (7.3)	+5.4 (8.2)	+4.1 (3.9)
Range of forecast (h)					48	36	24	12	0

TABLE 3. Mean difference in millibars (forecast-analyzed) for central-pressure verification; strong bombs, max bergerons ⩾ 1.9.

Time of verification	Time of initialization −6	−5	−4	−3	−2	−1	0	+1	+2
−2	−5.5	−2.2	−4.0	0.0	−0.3				
−1		−5.3	−1.2	+0.2	+0.5	+0.8			
0			+3.0	+3.3	+1.9	+0.9	+1.0		
+1				+13.1	+12.6	+9.6	+9.3	+7.1	
+2					+12.0	+9.5	+9.1	+6.4	+5.1
Range of forecast (h)					48	36	24	12	0

TABLE 4. Mean difference in millibars (forecast-analyzed) for central-pressure verification; moderate bombs, 1.3 ⩽ max bergerons < 1.9.

Time of verification	Time of initialization −6	−5	−4	−3	−2	−1	0	+1	+2
−2	−1.7	+0.8	+1.2	−1.8	+1.6				
−1		0.0	+1.3	+1.2	+1.6	+1.7			
0			+8.3	+6.8	+6.8	+6.9	+1.9		
+1				+14.1	+12.8	+13.1	+9.2	+6.4	
+2					+11.5	+15.4	+9.4	+5.2	+4.0
Range of forecast (h)					48	36	24	12	0

TABLE 5. Mean difference in millibars (forecast-analyzed) for central-pressure verification; weak bombs, max bergerons ≤ 1.2.

Time of verification	Time of initialization								
	−6	−5	−4	−3	−2	−1	0	+1	+2
−2	−0.5	−1.4	+0.5	+0.6	+1.4				
−1		−2.0	−0.6	+0.5	+0.3	+1.1			
0			+3.5	+3.2	+2.1	+2.6	+2.3		
+1				+7.5	+6.2	+6.4	+5.2	+2.2	
+2					+6.1	+7.3	+6.0	+4.6	+3.2
Range of forecast (h)					48	36	24	12	0

Table 1. Since the total number of possible comparisons was 48, it is seen that maps were missing in 11 or more instances, depending on initialization and verification times. The reduced number of comparisons at times −2 and −1 was due both to failure of the low to appear in the real atmosphere and (more frequently) in the LFM atmosphere. The loss of cases at the later times was attributable to the motion of the observed or predicted low north or east of the limits of the area under study or the area contained within the LFM prognostic charts. (The northeast corner of the study area was about 52°N, 48°W.)

Results, irrespective of bomb intensity, appear in Table 2. Systematic errors were small prior to the onset of explosive deepening. At the longer ranges the model, if it identified the nascent low at all, made it slightly too deep, possibly as part of a large-scale error. At ranges less than 36 h this bias had been replaced by one of opposite sign but slight magnitude, showing up even in the initialization (0-h forecast).

The model evidently failed to catch the onset of strong deepening, since substantial errors appeared at time zero, growing to about 10 mb at ranges from 36 to 48 h for times +1 and +2. About half this error persisted in the 12-h forecasts and even in the initializations for these times.

Stratification according to bomb intensity yielded the results shown in Tables 3–5. Each sample replicates qualitatively the features of the data in Table 2, although the standard deviations show large variability about the mean values. The excessive depth at longer ranges for the earlier times was particularly large for the strong bombs, but may be a chance result because the values are based on very small samples. For moderate bombs the time-zero mean errors were particularly large, an effect attributable to the slightly earlier start of explosive intensification pointed out by Sanders (1986). Cyclogenesis refuses to follow the precise 12-h schedule of LFM initializations. At time zero and beyond, the mean errors for weak bombs were only about half those for the moderate and strong specimens, but the deepening in the weak cases was only about half, so that the errors were roughly proportional. This result is consistent with the correlation illustrated in Fig. 1. Surprisingly, the errors were slightly smaller after maximum intensification for the strong bombs than for the moderate cases. This result is statistically fragile, however, since removal of the single case of substantially greater predicted than analyzed depth raises the mean errors for strong bombs to levels slightly higher.

The question arises how these results differ from those for all cyclones predicted by the LFM. A study for the 1978–79 cool season, reported by Silberberg and Bosart (1982), found nearly zero error in the forecast central pressure, averaged for all lows over North America and the adjacent oceanic regions. Forecasts of excessive depth for cyclones in the lee of the Rockies were balanced by as much as 10 mb depth in 48-h forecasts of cyclones over part of our area. Thus, it appears that errors in our bomb cases are not extraordinary. It is possible that some hint of moderate or strong instances, as opposed to weak ones, may be inferred from the LFM predictions.

TABLE 6. Position error for all forecasts.

Mean magnitude

Forecast range (h)	Distance		
	n mi	km	N*
0	77	142	149
12	110	202	142
24	147	271	136
36	160	295	134
48	185	341	130

* N is the number of comparisons that could be made.

Vector mean

Forecast range (h)	Bearing (analyzed to predicted) (deg)	Distance	
		n mi	km
0	125	35	64
12	117	28	53
24	077	48	89
36	067	69	127
48	063	63	116

3. Storm track prediction

For all forecasts taken together irrespective of bomb intensity, data on position errors (measured from analyzed to predicted positions of the low center) are given for each time range in Table 6. The mean magnitude of the error in the initialization seems high (relative to, say, that for tropical cyclones in regions of comparably dense data coverage), but the error growth was slow, particularly over ranges from 24 to 48 h. The 341-km (185-n mi) error at 48 h is comparable to or smaller than the 48-h errors cited by the National Weather Service (1985) for lows in the eastern two-thirds of the United States November 1984 through January 1985: 411 km for the LFM and 322 km for the new Regional Analysis and Forecast System (RAFS).

Vector-mean position errors, shown in Table 6, show an eastward bias at all ranges, growing with time. An

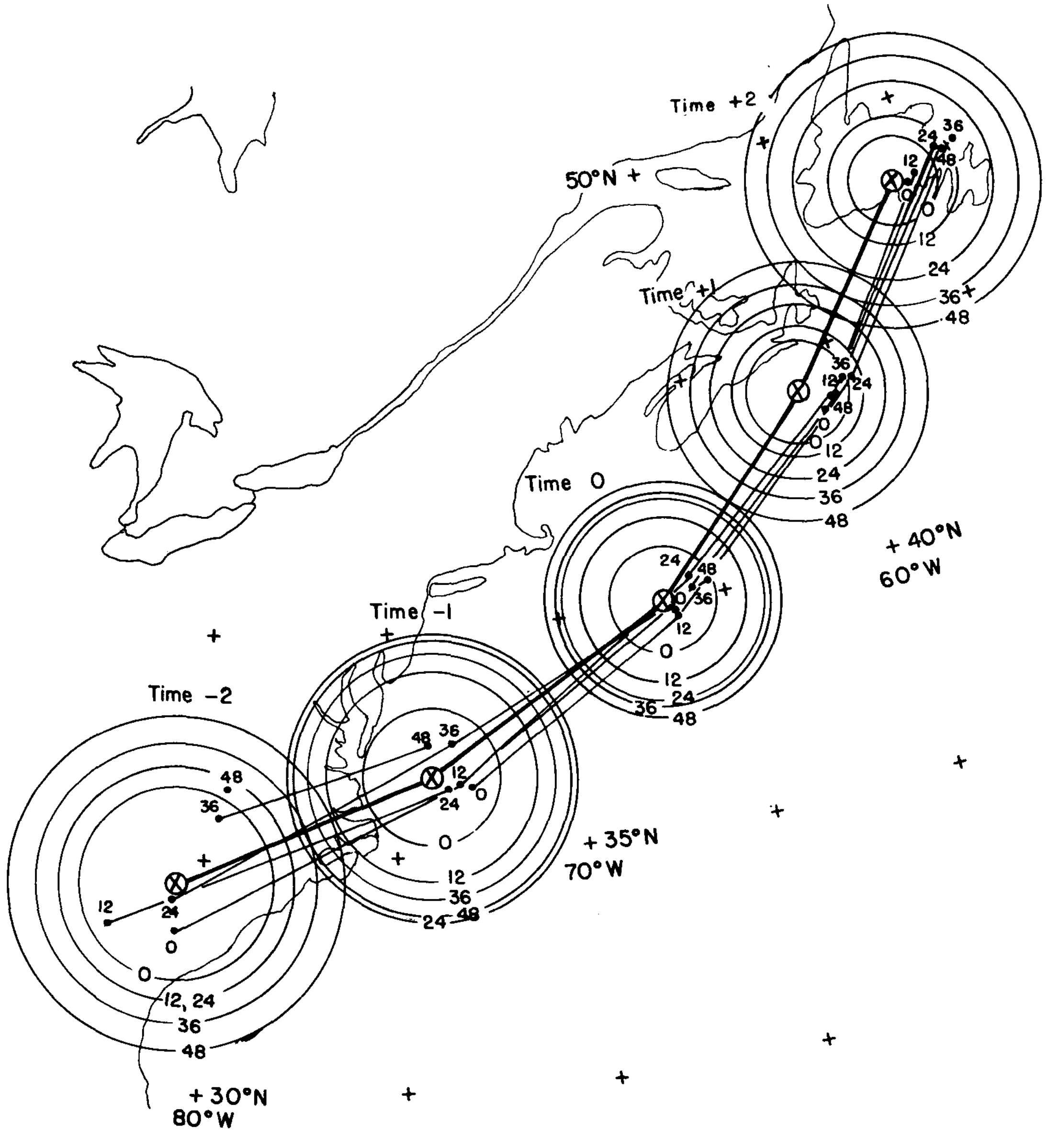

FIG. 2. Errors for indicated times in the history of the analyzed storms for which positions and track are shown by circled X's and heavy straight line segments. The vector mean position of the low center in the LFM predictions at the various times are shown by dots, annotated with the range of the forecast. Light line segments shown the mean predicted tracks, starting between times −2 and +2. The radii of the circle centered on each analyzed position represent the mean magnitude of the position error at the indicated range (referred to the analyzed central position, not the mean predicted position).

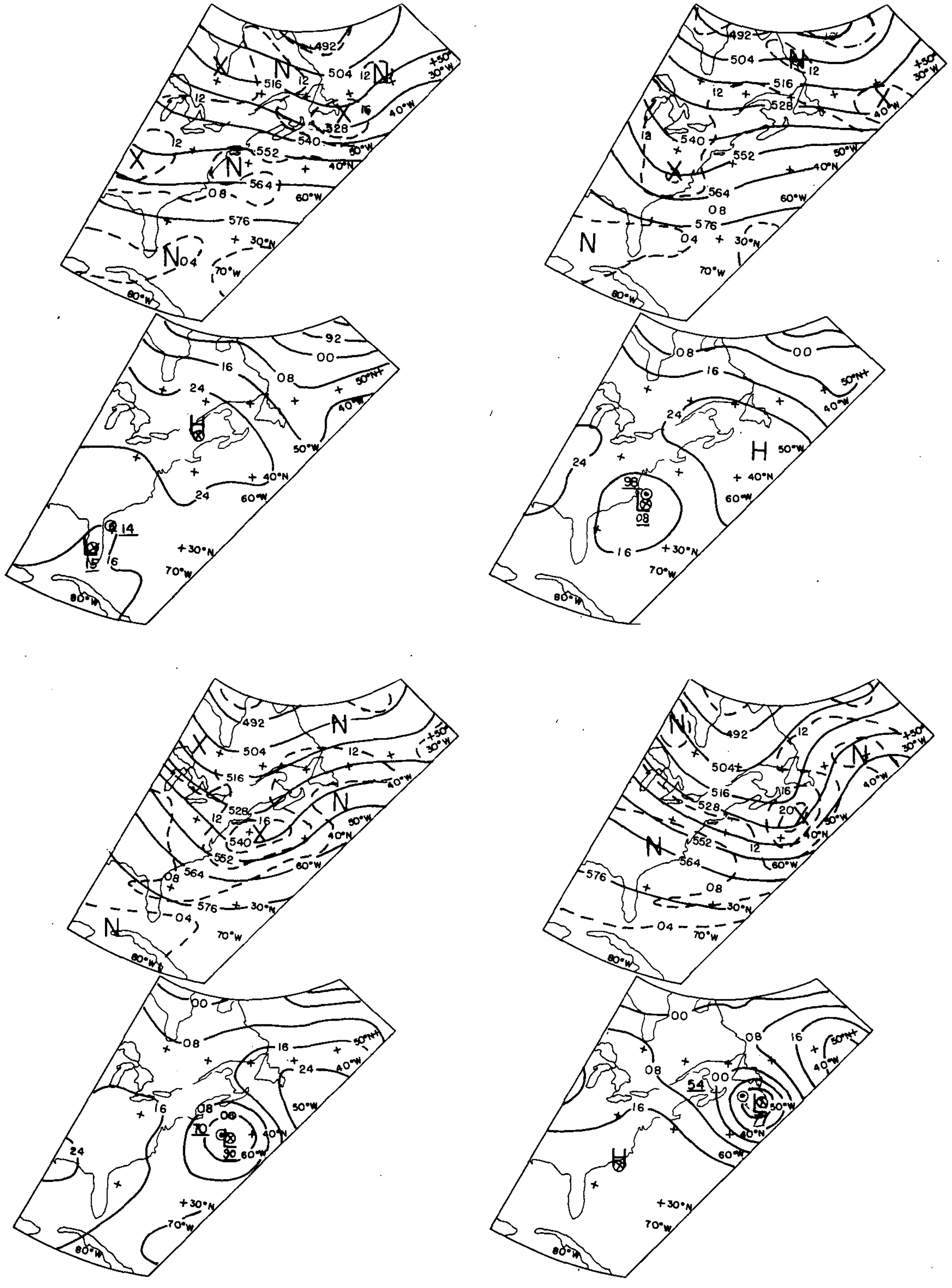

FIG. 3. LFM forecasts from 00 GMT 13 February 1983 (except the forecast for this time, which is from 12 GMT 12 February). Lower panel shows isobars of sea-level pressure at intervals of 8 mb, with centers of high and low pressure. The circled dot indicates the position and central pressure of the main low from subjective analyses. The upper panel shows contours of the 500-mb surface at intervals of 12 dam (solid) and of absolute vorticity at intervals of 4 × 10^{-5} s^{-1} (dashed). Extrema of vorticity are denoted by ×'s and N's. Verifying time: (a) 00 GMT 13 February, (b) 12 GMT 13 February, (c) 00 GMT 14 February, (d) 12 GMT 14 February and (e) for 00 GMT 15 February.

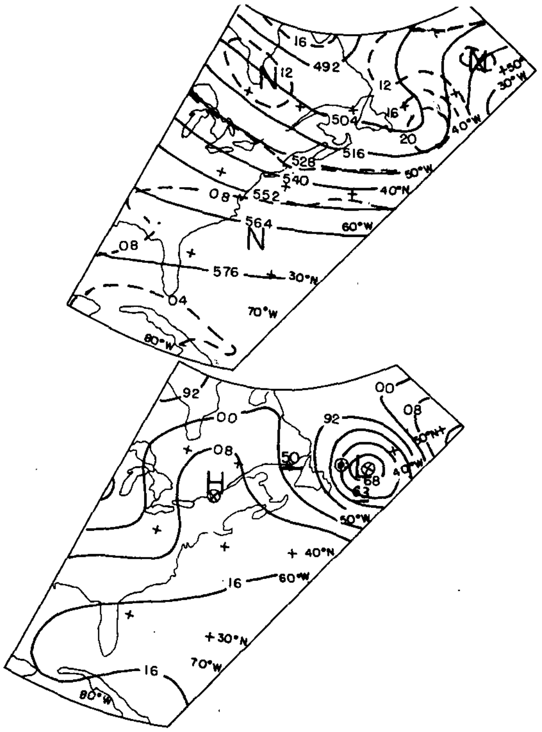

FIG. 3. (*Continued*)

initial southward bias changed to northward by 24 h and grew. Since the storms moved northeastward, it is apparent that predicted speeds were slightly too fast, on the average. This small bias, scarcely more than 1 kt (0.6 m s^{-1}) from initialization to 48 h, thus reverses and nearly eliminates the substantial slow bias reported by Leary (1971) and Druyan (1974) for the earlier, coarse-mesh, models.

More detailed patterns of error in the sample of predicted bomb tracks are shown in Fig. 2, stratified by time in the history of the storms, but not by bomb intensity. The characteristics of the observed tracks, stratified by intensity, have been described by Sanders (1986).

Note that errors were especially large, at all ranges including initialization, at time −2. Both analyzed and predicted centers, when present, were weak and ill defined. On occasion it was not clear whether a predicted center could be identified with the analyzed one, or whether the case should be regarded as one in which the LFM failed to detect the nascent cyclone. Continuity was used in making a decision, and in no case were lows separated by more than 650 n mi (1200 km) considered to represent the same center.

Errors at all ranges became smaller until time zero, when the storm was intensifying most rapidly. It often seemed that the model atmosphere knew better where to produce cyclogenesis than how to get a preexisting low to that spot, if we may be permitted a second anthropomorphism. After time zero, errors remained the same or shrunk at ranges less than 24 h, owing probably to increasing definition of the center. Error growth was the rule at longer ranges from time zero to +2.

Comparison of observed with mean predicted track segments shows close agreement between times −2 and −1 and between +1 and +2. From −1 to time +1, on the other hand, the predicted track does not curve as sharply northward as the observed one, thus confirming Abe Rosenblum's Rule[1] (personal communication, third hand). We would venture a speculation that a sufficiently intense prediction of the interaction between surface and upper-level systems (cf. Sanders, 1986) would simultaneously solve the problems of insufficient depth of central pressure and of rightward motion.

At all times the mean vector error in the initialized position lay in the southeast quadrant, away from the dense data coverage over the North American continent and coastal waters. Evidently the analysis algorithm urges the extreme feature, the intense cyclone, toward the data-poor vastness of the open ocean. A small improvement over the raw LFM-predicted position might be effected in the mean by correcting for the displacement of the initialized central position from the analyzed position of the cyclone. Well away from the coast, we would not expect this error to occur, since data are sparse in all directions.

Stratification into strong, moderate and weak categories of bomb intensity confirms for each sample the characteristics described above. The moderate-intensity cases showed decidedly smaller position errors than the others. The value averaged over all ranges was 112 n mi (208 km), compared to 135 n mi (250 km) for strong bombs and 151 n mi (279 km) for weak bombs. When this averaged error is expressed in proportion to the mean speed of the storms in the corresponding samples, the relatively slow-moving moderate bombs fare worst and the strong ones best. It seems likely that these differences represent chance effects in small samples.

4. Two forecasts

a. 13–15 February 1983

This storm was probably the most intense and the most rapidly deepening cyclone in the sample (Sanders, 1986), and the LFM predictions for it suffered their largest absolute errors in central pressure. By way of example, Fig. 3 shows the forecast from 00 GMT[2] on the 13th (except that the 12-h forecast from the preceding run replaced the missing initialization maps). Corresponding verification maps appear in Fig. 4.

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[1] In its purest form: "The intensifying low moves to the left of the predicted track." This profound insight was thought initially to reflect purely human frailty, although Leary (1971) presented some evidence to the contrary.

[2] Synoptic times in two digit hours.

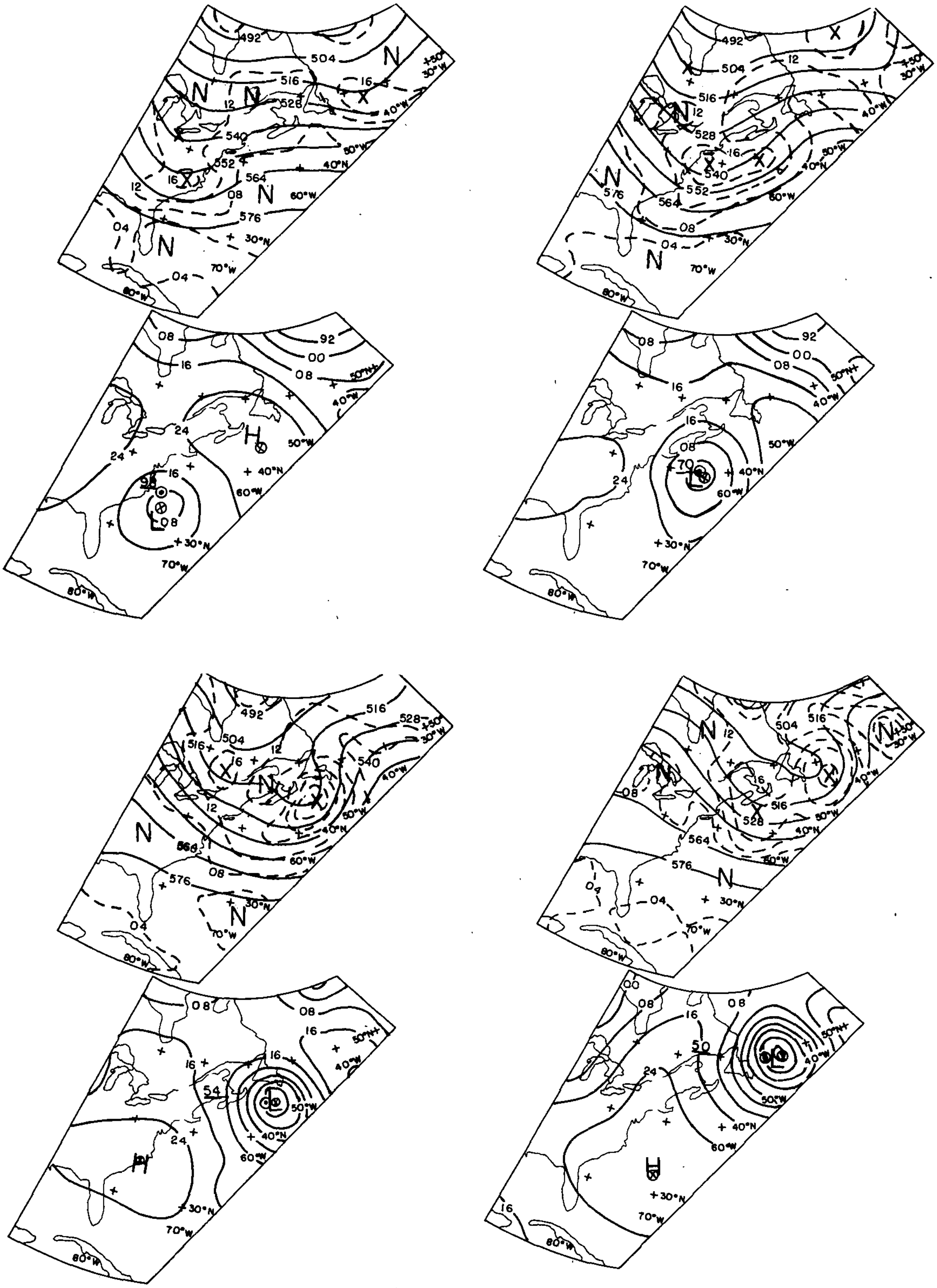

FIG. 4. LFM initializations, in same format as Fig. 3, for (a) 12 GMT 13 February, (b) 00 GMT 14 February, (c) 12 GMT 14 February and (d) 00 GMT 15 February.

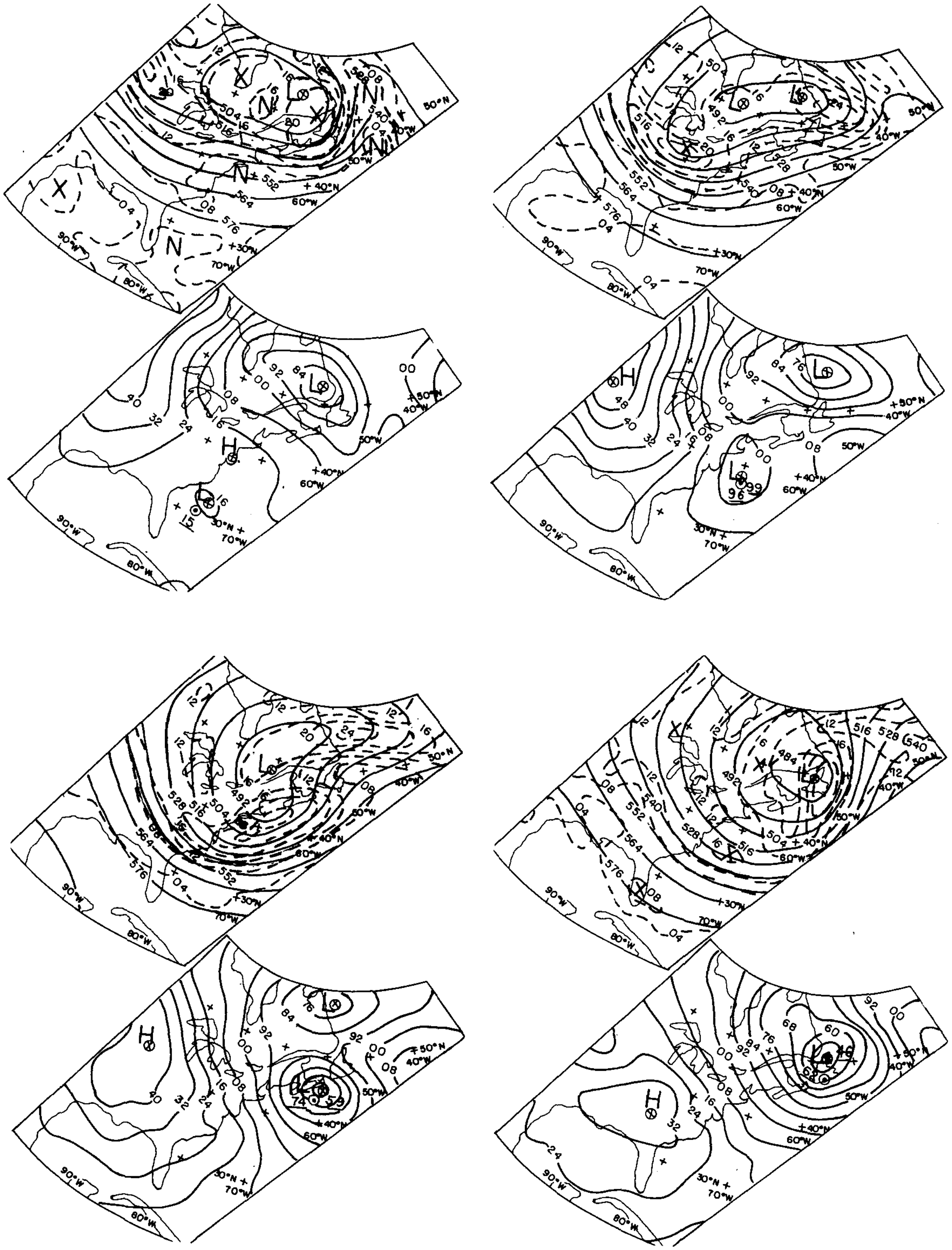

FIG. 5. LFM initialization and forecasts from 00 GMT 24 December 1983, as in Fig. 3: (a) 00 GMT 24 December, (b) 12 GMT 24 December, (c) 00 GMT 25 December, (d) 12 GMT 25 December and (e) 00 GMT 26 December.

At the start, there was the usual difficulty in correct location of the center. By 12 GMT of the 13th and afterward, however, when the storm was a prominent feature, analyzed, initialized and predicted positions were quite close. The typical eastward bias was clear, as was the usual counterclockwise rotation of the dis-

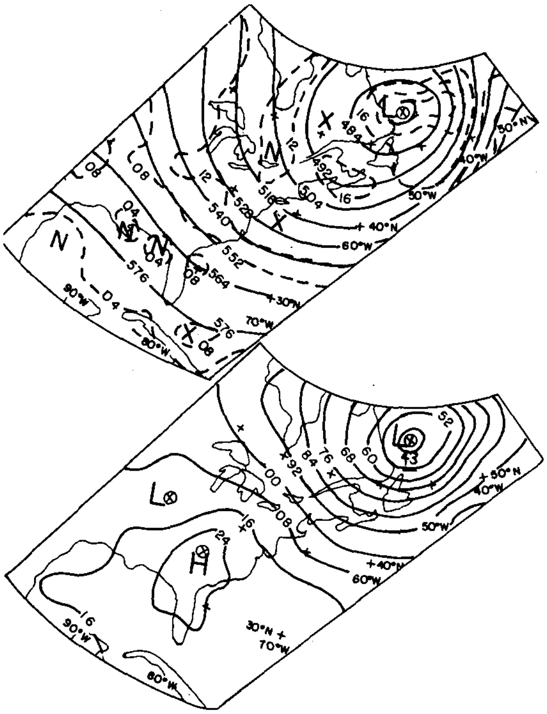

FIG. 5. (*Continued*)

placement vector with time. Neither predicted nor initialized central pressures were deep enough, as customary. There was a remarkable 27-mb discrepancy between analyzed and initialized central values at 00 GMT on the 14th, as noted by Sanders (1986). The 24-h forecast for this time was considerably better, in respect to central pressure, than the initialization. Larger errors on the 14th and 15th were found in LFM forecasts from the poor initialization for this time, as would be expected.

At 500 mb a modest but distinct vorticity maximum of about 15×10^{-5} s^{-1} intensified, particularly during close interaction as it overtook the surface cyclone, to a final value near 26×10^{-5} s^{-1}. Predictions showed a more modest growth to near 23×10^{-5} s^{-1}. The predicted positions were only slightly in error, showing the typical overtaking and passage to the south of the deepening surface center.

At a range of 48 h the largest errors in sea-level pressure and 500-mb height were not associated with the storm. Rather, they were found in the east-central United States as part of a very large-scale deficiency which is understood to be typical of the LFM when strong westerlies are blowing, as in this case, across the Rocky Mountains (not shown). This broad error notwithstanding, LFM-predicted 500-mb heights were insufficiently deep at 48 h south of Nova Scotia, where a severely underestimated cold outbreak was occurring.

On the whole, the error in prediction of the storm was one of degree, not of kind. That is, the LFM anticipated the development of a major cyclone from very small beginnings, with a respectable track forecast and a reasonably accurate forecast of the behavior of the vorticity maximum at 500 mb.

b. 24–26 December 1983

Can the LFM produce an intense vortex, comparable to those appearing in operational manual analysis? Indeed so, as this case shows. At the initialization time for the forecast starting at 00 GMT on the 24th (Fig. 5a), the central United States was suffering from an unprecedented severe December cold wave (Quiroz, 1984) and a weak low had formed over the warm water off shore from the southeastern States. At 500 mb a broad trough containing a 25×10^{-5} s^{-1} vorticity maximum over the north-central United States was flanked by extremely strong westerlies. The forecast indicated extraordinary deepening (including, from 12 GMT on the 24th to 00 GMT on the 25th, the 35-mb outlier in Fig. 1), with the storm moving rapidly northeastward into the Canadian Maritime Provinces. Thus were the hopes of the New England snow lovers kindled, for they had every statistical right to expect an even more intense cyclone moving leftward of the predicted track.

On this singular occasion, however, the real atmosphere could not meet the challenge posed by the model. A strong bomb ensued, but not as strong as predicted in the area of study. At this time the observed track was to the *right* of the predicted one, in apparent violation of Rosenblum's Rule, but suggesting as a modification of it that the *more strongly* intensifying cyclone moves to the left. During this time the predicted track speed was somewhat excessive, as it was found to be on the average. Evidently this bias is not dependent on intensification. Between 36 and 48 h [Figs. 6c) and d)] the observed storm deepened markedly as it passed east of Labrador, to overtake the central pressure of the predicted low. The observed position, however, was substantially east (to the right) of the forecast position.

At 500 mb the predicted vorticity center, like the surface center, moved somewhat too rapidly. After 12 h its intensity was slightly too large. Elsewhere, errors similar to those in the preceding case are seen. The forecast surface anticyclone was much too weak, and in this instance much too far to the east.

Predicted sea-level pressures and 500-mb heights over the central United States were again much too high. The amplitude of the 500-mb trough along the East Coast, and the intensity of the associated cold outbreak, was substantially understated.

As in the preceding case, the errors in prediction of the storm were of degree rather than of kind. In this case the amount of overprediction by the LFM was a singular event. It is instructive to compare the forecast 500-mb vorticity advections with the initialized advections over the surface center during the 12-h period

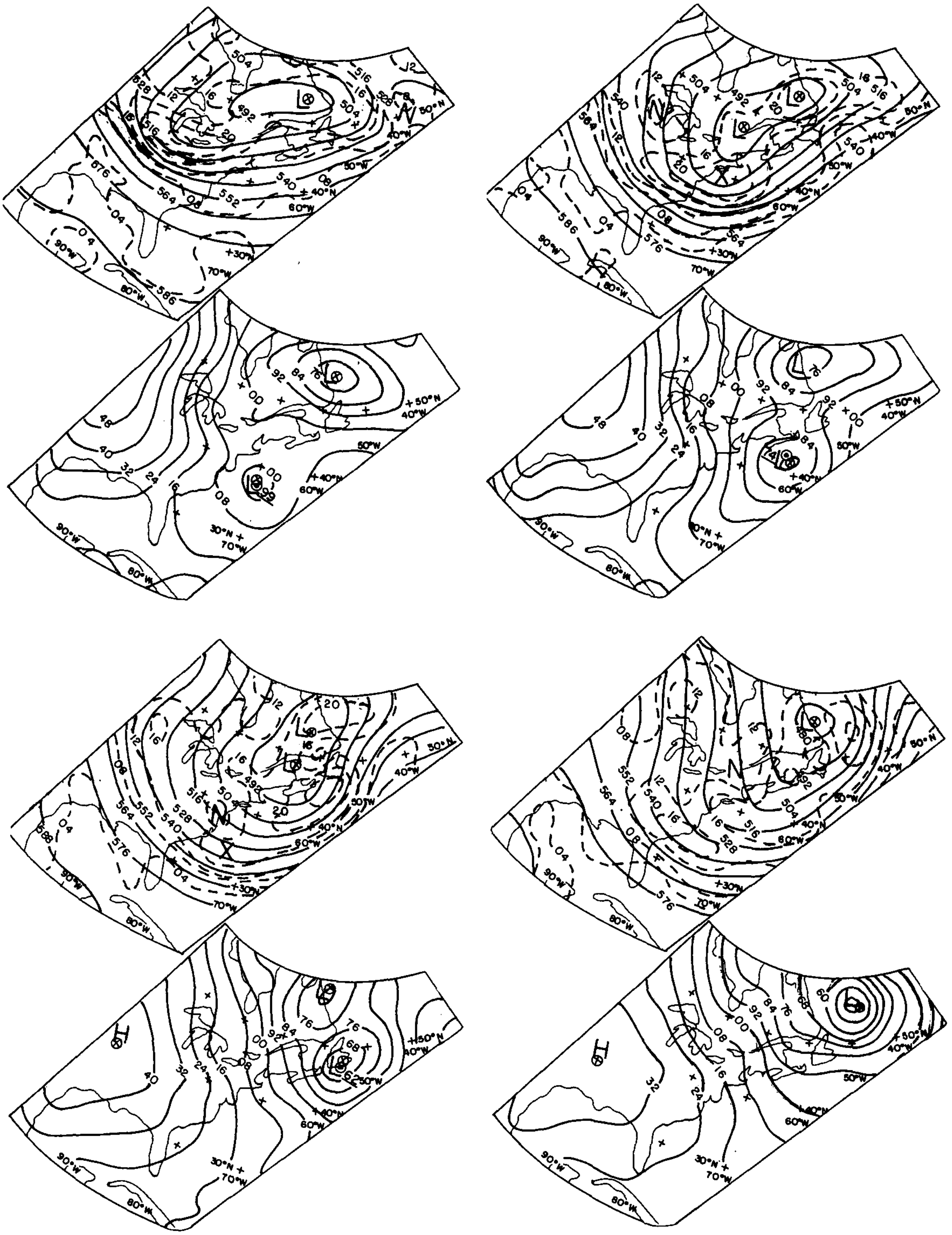

FIG. 6. LFM initializations: (a) 12 GMT 24 December, (b) 00 GMT 25 December, (c) 12 GMT 25 December and (d) 00 GMT 26 December.

of extreme deepening. From Figs. 5b and 5c we estimate a predicted value of $+16 \times 10^{-10}$ s^{-2} at 12 GMT of the 24th, rising to an extraordinary $+65 \times 10^{-10}$ s^{-2} 12 h later. From Figs. 6a and 6b we find corresponding initialized values of +5 and +33 ($\times 10^{-10}$ s^{-2}), about half the forecast amount. The deepening in the initializations was about half that in the LFM forecast, although the deepening in the analyses was substantially more. It seems that the extreme forecast deepening was attributable to the extraordinarily large value of the upper-level forcing (cf. Sanders, 1986, Fig. 13), as the surface system was overtaken by the intense 500-mb vorticity center in an extremely baroclinic situation. Why the center in the real atmosphere failed to match the forecast behavior is a matter of details in the 500-mb flow pattern (to argue legalistically), but we have no idea what the physical interpretation of the failure is or how it might have been predicted.

5. Concluding summary

We have examined the recent performance of the LFM in dealing with explosive cyclogenesis in the west-central North Atlantic. A study of 51 instances in which the deepening rate from manual analyses was at least 10 mb in 12 h showed that the LFM at 12–24 h range captured 58% of the analyzed deepening, on the average, but accounted for only about 30% of the variance of the analyzed deepening in individual cases. This shortfall notwithstanding, the performance of the LFM represented a distinct improvement over that of earlier operational models with relatively coarse mesh lengths. A comparison of central pressures of the cyclones from the manual analyses with those given by LFM predictions (and initializations) showed little systematic difference until rapid deepening began. Then the LFM displayed insufficiently deep centers, the discrepancy increasing from about 4 mb in the initializations to about 10 mb in the forecasts for ranges of 36 to 48 h. In individual cases the discrepancy tended to vary directly with the strength of the storm.

The path of the storm was reasonably well predicted, once the LFM was able to identify the nascent center. The earliest appearance of the center in the manual analyses was not detected by the model in a substantial fraction of cases. This flaw aside, magnitudes of position errors (assuming the manual analyses to be correct) increased from about 75 n mi (140 km) in the initializations to about 185 n mi (340 km) in the 48-h forecasts. The mean vector error in the LFM was initially slightly southeast of the manually analyzed center and finally east-northeast at a distance of about 65 n mi (120 km). Thus the predicted speed was very slightly too fast and the predicted track direction slightly to the right of the manually analyzed one.

Two individual case studies show that the LFM forecasts were correct in at least a qualitative sense even when the observed storm was 25 to 30 mb deeper than the predicted one, and even in the rare case when the LFM prediction showed a far more rapidly intensifying storm than the real atmosphere was able to produce. We take this as evidence that the "bomb" is essentially a baroclinic phenomenon, that the LFM is able to capture the essentials of the baroclinic process, and that the amount of response to baroclinic forcing remains intractable.

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