Patterns of Thickness Anomaly for Explosive Cyclogenesis over the West-Central North Atlantic Ocean

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ABSTRACT

Hemispheric anomaly patterns of 1000–500 mb thickness were obtained for 67 cases of explosive cyclogenesis over the western North Atlantic Ocean in December–February during 1962–77, beginning between latitudes 30°–40°N and between longitudes 70°–80°W.

Composite patterns for the 26 strongest cases of cyclogenesis differed markedly from those for the 22 weakest. After a filtering to remove the shortest waves, those for the strongest developments showed a prominent negative anomaly area of large scale, centered over western Canada 5 days before the event, moving southeastward to the western Atlantic days after cyclogenesis. No such pervasive anomaly pattern was seen for the weakest cases.

The most intense cyclogenesis occurred when the air over the region of development was slightly colder than the 15-year average, while the least intense occurred in slightly anomalous warmth.

In the zonal average from 25° to 125°W, the strongest cases occurred with warmth in polar latitudes, coldness in middle latitudes and anomalously strong westerly thermal wind in the cyclogenetic area. The weakest cases occurred with cold polar latitudes, warmth in upper middle latitudes, and slightly cold anomalies but no excessive thermal wind in the latitudes of cyclogenesis.

It is implied that both baroclinic forcing and heat and moisture flux from the sea surface were enhanced in the strongest cases, but neither effect was obviously dominant.

1. Introduction

The setting in which explosive cyclogenesis occurs over the western North Atlantic Ocean is reasonably well established. In a study of storms from the period 1981–84, Sanders (1986, hereafter denoted S) found that a necessary predecessor for this event was the presence of a prominent maximum of absolute vorticity at 500 mb, upstream from the location of cyclogenesis at the surface. It further appeared that the intensity of the deepening was positively related to the magnitude of the cyclonic vorticity advection over the surface center, and (Sanders 1987) that the probability of the surface event, given the crossing of the coast by a vorticity maximum of sufficient strength, was as large as 68% when the vorticity maximum was moving fast enough and was flanked by sufficiently strong gradients along the direction of the large-scale flow.

A logical question to ask, then, is what distinguishes the strongest events from those weaker ones that marginally qualify as explosive. Physical reasoning suggests looking at tropospheric temperature patterns, because strong gradients are likely to encourage the development of strong baroclinic forcing and because cold air itself is likely to be associated with reduced static or symmetric stability over the relatively warm ocean, encouraging a strong response to a given forcing. Thus, we identified a sample of cyclones which began a period of explosive deepening between latitude 30° and 40°N, longitudes 70° and 80°W, and examined the hemispheric patterns of thickness of the layer from 1000 to 500 mb from 5 days before to 5 days after the beginning of intensification in each case. This note briefly presents the salient results.

2. The data

The period examined constituted the months of December, January, and February from December 1962 through February 1977, during which archived twice-daily grid-point values of thickness were provided by the National Center for Atmospheric Research. These values were derived from operational analyses of the National Meteorological Center (NMC), on a grid of 4° latitude and 5° longitude. Positions and central pressures of the surface cyclones, at 12-h intervals, were obtained from NMC operational manual analyses.

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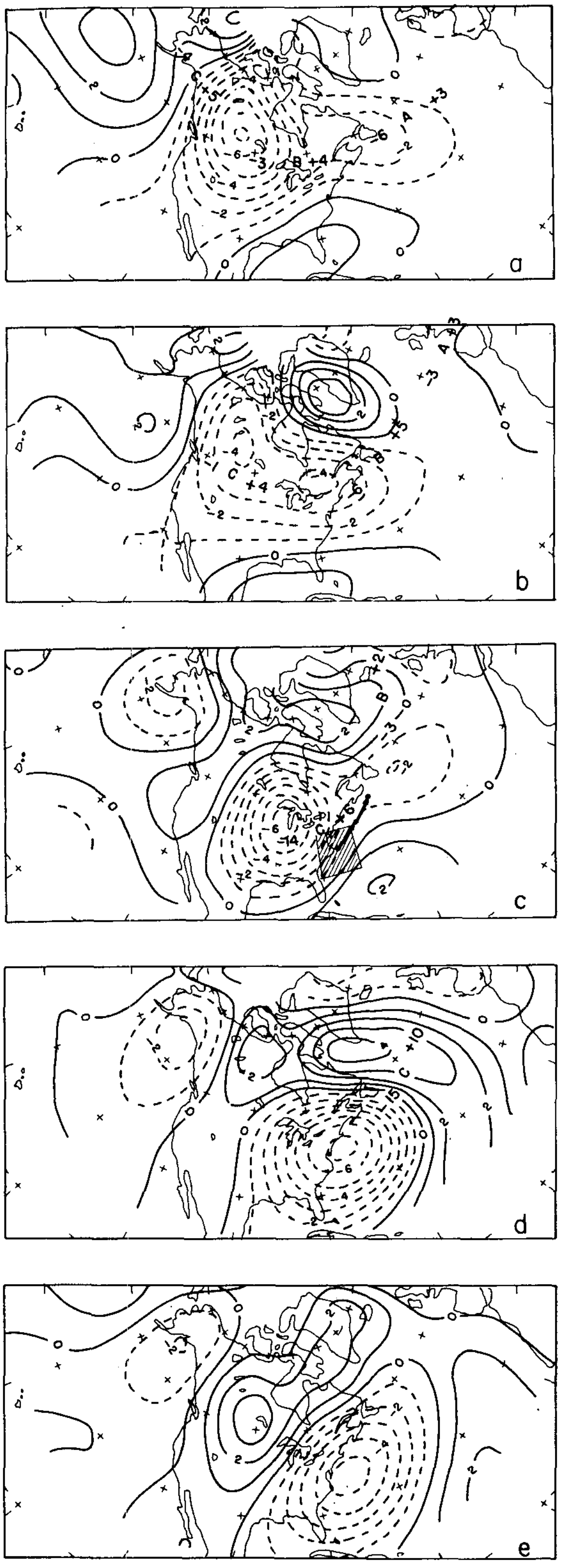

FIG. 1. Composite patterns of departure of thickness of the layer 1000–500 mb from the long-term mean, for the strong cases of explosive cyclogenesis. Isopleths are at intervals of 2 dam, those for negative values being dashed. (a) Day −4, (b) Day −2, (c) Day 0, (d) Day +2, (e) Day +4. The regions of cyclogenesis and the mean positions of the cyclones in the sample are indicated in (c). Heavy signed values show values and positions of selected local maxima and minima of 24-h change of unfiltered composite thickness, in dam, associated with the implied mobile synoptic systems denoted by letters.

TABLE 1. Mean positions and central pressures of cyclones.

Time (days)	Latitude (°N)	Longitude (°W)	Central pressure (mb)
	Strong cases (N = 26)		
0	35.8 (2.4)	74.9 (2.6)	1004.3 (7.8)*
0.5	40.0 (2.7)	66.4 (4.6)	985.5 (8.8)
1	44.3 (3.4)	60.2 (5.8)	965.2 (8.7)
	Moderate cases (N = 19)		
0	35.1 (2.8)	75.4 (2.8)	1006.5 (7.0)
0.5	39.0 (2.9)	68.6 (5.0)	991.6 (8.2)
1	42.7 (3.3)	63.2 (8.0)	980.6 (6.5)
	Weak cases (N = 22)		
0	36.5 (2.5)	74.0 (2.9)	1004.5 (8.5)
0.5	39.6 (2.7)	67.7 (4.0)	992.5 (10.4)
1	43.6 (4.0)	61.4 (6.8)	983.9 (9.5)

* Numbers in parentheses are standard deviations about the means.

Only cyclones in which the maximum deepening, beginning in the specified area, exceeded one bergeron as defined by Sanders and Gyakum (1980) were considered. Time zero for each cyclone was taken at the beginning of the qualifying deepening. Thickness data were obtained over the interval from 120 hours before to 120 hours after this time.

A total of 67 cases was found in the 46 months examined. This represented only half the frequency found by S for the same months during 1981–84, the discrepancy being due mainly to the larger area studied. A stratification into strong (>1.8 bergerons), moderate (1.7–1.4 bergerons), and weak (<1.4 bergerons) cases was made, with limiting values slightly different from those chosen by S, to divide the sample more evenly. (One bergeron is 24 mb per 24 h, multiplied by the ratio of the sine of the latitude divided by the sine of 60°.) Mean positions and central pressures for each category are shown in Table 1. Comparison with S's data shows less variation between categories in the mean tracks, but still the fastest motion for the strong cases. The strong cases in this sample did not show especially rapid deepening in a single 12-h period, but the mean position at time 0.5 (the middle of the 24-h period of maximum deepening) was within the zone of maximum gradient of sea-surface temperature. The earlier study showed strongest deepening in a 12-h period that crossed this zone. Had the same deepening in this location occurred in this sample, it would have been masked by the timing.

The departures of all thickness values from the appropriate half-month mean for the 1962–77 period were calculated at each synoptic time. Then composite thickness anomaly fields were prepared for each category of cyclone strength. These showed planetary scale features as well as features associated with the smaller synoptic features. To suppress the effects of the latter, the anomaly values were filtered by application of an operator whose general form is described by Haltiner (1971). The operator was applied to eliminate the two-dimensional waves with length twice and 5 times the grid mesh length, and then once again to remove the shorter waves. This filtering operation removes at least 85% of the amplitude of waves shorter than 6 times the mesh length (about 2700 km in the zonal direction at latitude 35°N), but no more than 20% of waves larger than 16 times the mesh length. Appropriate modification of the smoothing was applied near the southern boundary. The filtered fields appear in Fig. 1 for the strong cases and in Fig. 2 for the weak cases.

3. Results

The most striking feature of Fig. 1 is the large region of negative anomaly which moved at an average speed of 4.5 m s^{-1} from western Canada southeastward across the Great Lakes and into the western North Atlantic over the 10-day period centered on the beginning of explosive cyclogenesis. The anomaly at the center of this cold mass was the largest of either sign throughout the hemisphere until the fifth day after Day 0. This result might have been expected around the central time because of the focusing on a fixed geographical area in the selection of cases, but the dominance of this anomaly 4 days earlier and later attests to its strength and persistence. Close examination of the daily series of maps discloses that two cold centers occurred within the envelope of the large anomaly, each moving at about 10 m s^{-1}, the first losing its identity in the western Atlantic area while the second became defined over the continent. This process is seen in the irregularities in Figs. 1b and 1c. The positive anomaly over the Davis Strait southwest of Greenland, starting 2 days before the cyclogenesis, is a characteristic precursor noted by synoptic analysts.

For the weak cases, in Fig. 2, a weak cold anomaly center was seen, moving erratically in central and eastern North America throughout the period, but only at time zero, and 24 h earlier was it the strongest anomaly on the map.

Over the center itself at Day 0, the filtered anomalous thermal wind for the strong cases was southwesterly at about 6 m s^{-1}. For the weak cases, it was southerly at about 4 m^{-1}. In the filtered patterns, cyclones began explosive intensification in air slightly colder than average for the location in the strong cases and slightly warmer than average in the weak cases. Similar dis-

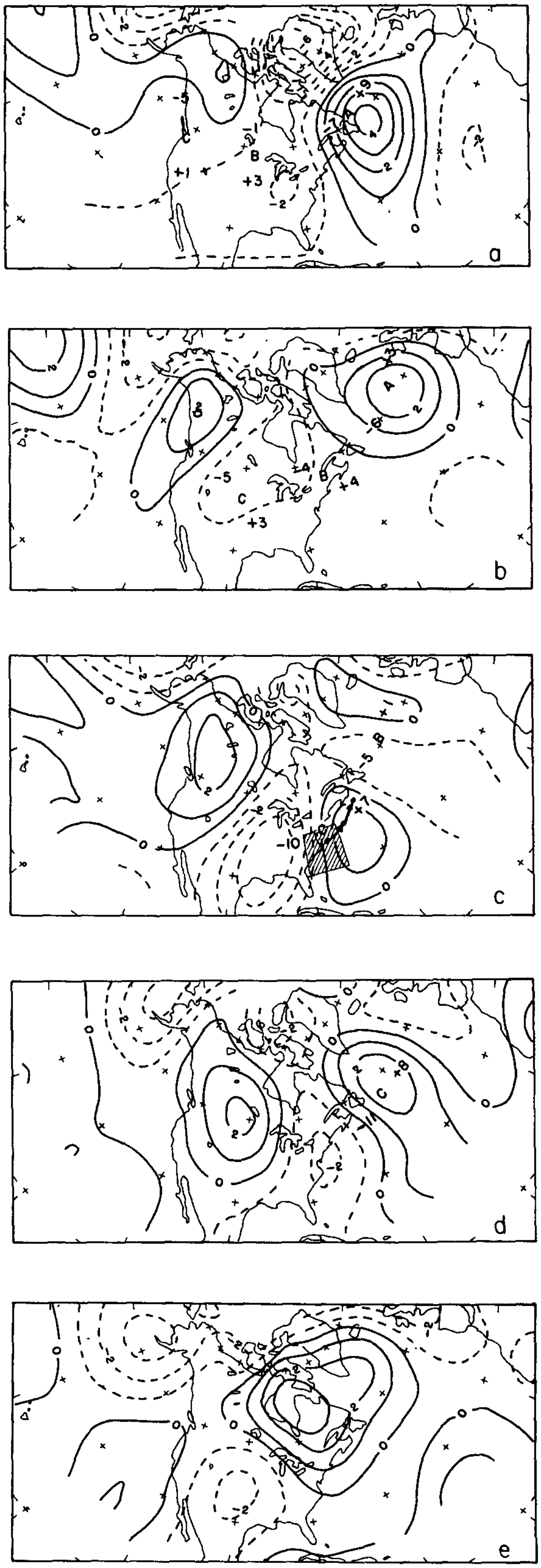

FIG. 2. As in Fig. 1, but for weak cases of explosive cyclogenesis.

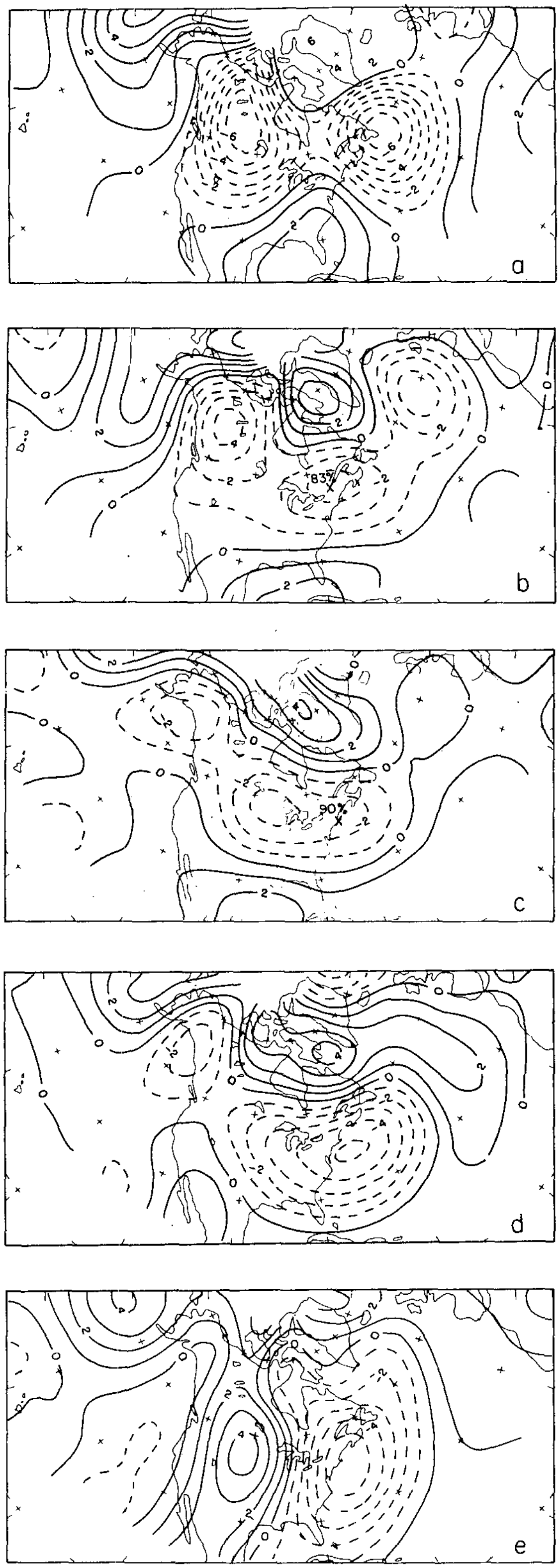

FIG. 3. As in Fig. 1, but for the difference of the anomalies, those for the strong cases minus those for the weak cases. The values at the points marked X are maxima of statistical significance.

tinctions characterized the areas traversed by the cyclones in the 24-h period of deepening.

The differences of the anomaly patterns for the two intensities of cyclogenesis are shown in Fig. 3. Relative coldness over the continent and the adjacent western Atlantic was the rule for the strong cases, interrupted by a weak brief relatively warm episode over the cyclogenetic area 3–4 days before the event and by developing warmth over the central United States a few days after the event, when the main mass of colder air had moved out over the ocean. The relative coldness over the Atlantic several days prior to cyclogenesis was due to modest coldness in the strong cases contrasted with prominent warmth in the weak ones. Note that the strong cases occurred in an environment of relative coldness and failed to produce relatively high filtered thicknesses except over the central and eastern Atlantic, despite undoubtedly intense advection patterns on the synoptic scale.

There was substantial case-to-case variability in both samples, so that statistical significances of the patterns of difference, based on a 2-sided *t*-test, are not impressive. Their continuity in time and their physical reasonableness, however, adds credibility.

The patterns differed on a scale larger than that of the filtered cold anomaly. The anomalies were averaged zonally from longitude 25° to 125°W, separately for the strong and weak cases, yielding the time–latitude sections shown in Fig. 4. For the strong cases, a prominent sector-wide cold anomaly starting at latitude 54°N moved slowly equatorward to 38°N during the period, with anomalous warmth occupying an increasingly large portion of higher latitudes. Slight warmth edged northward from the subtropics at the time of cyclogenesis, giving a 1.8 m s^{-1} anomalous westerly component of thermal wind over the sector between latitudes 30° and 40°N. In the weak cases, cold air dominated the Arctic and the region south of 40°N, while a warm strip was found in higher middle latitudes. Gradients were extremely weak, however, over the belt from 30° to 40°N.

The moderate cases of explosive cyclogenesis were briefly examined, and appeared to show characteristics intermediate between those described. That is, there was a cold anomaly center moving from Canada into the western Atlantic, with more character than that shown for the weak cases, but without the strength and dominance displayed by the patterns for the strong cases.

The day-to-day changes in the unfiltered thickness anomalies (not shown) displayed numerous centers of rise and fall, representing the effects of the mobile disturbances of synoptic scale. In the patterns for both the strong and the weak cases, three doublets of warming followed by cooling could be tracked across North America and the Atlantic, as seen in Figs. 1 and 2. The third in each case corresponded to the explosive cyclo-

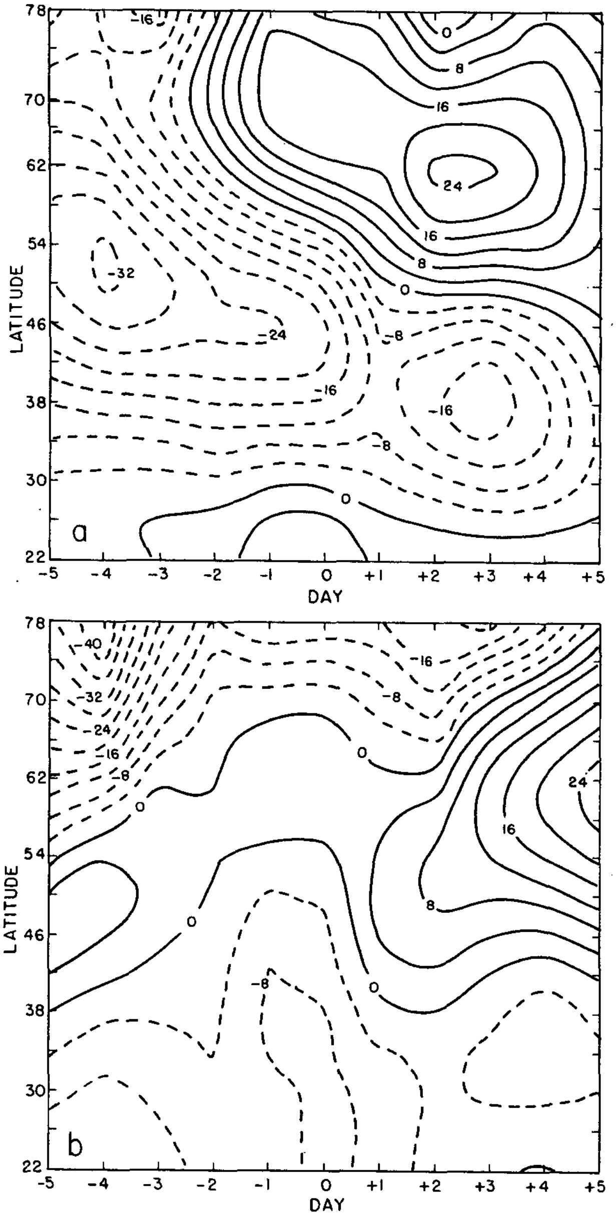

FIG. 4. Time series of the zonal mean of the filtered thickness anomalies, averaged from longitude 25° to 125°W. Isopleths are at intervals of 4 m, negative values being dashed. (a) For the strong cases, (b) for the weak cases.

genesis on Day 0, but could be seen on Day −4 (and earlier), representing the predecessor disturbance at upper levels discussed by S. By Day +4, the doublets were no longer identifiable. Track speeds for the identifiable doublets averaged 13.7 and 12.3 m s^{-1}, respectively, for the strong and weak cases, reflecting implicitly a slightly stronger overall baroclinicity for the strong cases, as also suggested by the patterns in Fig. 4.

Doublet B for the strong cases may have had a special significance. On Day −2 the trough was just southeast of Newfoundland (Fig. 2b), and in its wake a substantial mass of cold air moved out over the waters where the explosive cyclogenesis subsequently occurred. Negative unfiltered thickness anomalies persisted in the region of deepening through 12 h prior to its onset. For the weak cases, doublet B had no such effect. It reduced the thicknesses over the cyclogenetic region only to values near zero, and by Day −1 substantial positive unfiltered anomalies were present there.

4. Concluding discussion

Others have found cold air in the path of a maritime cyclone to be characteristic of strong intensification. This circumstance might be interpreted in two ways: increased baroclinicity along the southern edge of the cold anomaly, and reduced static stability in the cold air itself, owing to enhanced flux of heat and moisture from the sea surface. Bosart and Lin (1984), in synoptic diagnosis, and Uccellini et al. (1987), in numerical modeling, have stressed the importance of fluxes from the sea surface into the air in the path of a major cyclone. Namias (1987), on the other hand, shows an enormous and persistent cold anomaly over the northwestern North Atlantic during an entire month prior to the "design cyclone" that developed there in December 1986. He points to the enhanced baroclinicity between this anomaly and simultaneous persistent warmth to its south. We have noted, in addition, that during the day or two immediately preceding this extraordinary cyclogenesis, virtually every observation across the North Atlantic east of North America and north of 50°N noted swelling cumulus or cumulonimbus clouds and showers of rain or soft hail. Thus there is evidence supporting interpretations in terms of both enhanced baroclinicity and reduced stability.

Our results do not resolve this question. The difference in baroclinicity between the strong and the weak cases is slight, but so is the thickness difference in terms of mean tropospheric temperature over the cyclogenetic area. If the stability is small, however, a small change could have a large effect.

The speed of the larger-scale cold anomaly in the composite patterns for the strong cases was only about one-third the speed of the synoptic doublets. The cold anomaly represented something larger and more slow-moving than the individual cyclone/anticyclone disturbances, but did not clearly resemble any of the teleconnection patterns of long time scale and planetary space scale described by a number of authors in the past several years. Thus it appears to represent an additional complication in the study of interaction between important synoptic events and other scales.

The forecasting implications of Figs. 1 and 2 are obvious. If a case of explosive cyclogenesis is predicted to occur in the next few days, its intensity may be foreshadowed by the planetary-scale temperature patterns. Massive coldness over North America indicates an extreme event, while pronounced warmth over the western Atlantic makes it unlikely. Our findings, however, are in the nature of necessary conditions, not sufficient ones. Common experience shows that it is possible to have frigid air in the right regions and yet apparently no predecessor vorticity maximum at upper levels to provide a catalyst. In these circumstances, the accuracy of the upper-level forecast is exceptionally important.

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REFERENCES

Bosart, L. F., and S. C. Lin, 1984: A diagnostic analysis of the Presidents' Day storm of February 1979. *Mon. Wea. Rev.*, **112**, 2148–2177.

Haltiner, G. J., 1971: *Numerical Weather Prediction.* Wiley and Sons, p. 270.

Namias, J., 1987: Factors relating to the explosive North Atlantic cyclone of December 1986. *Weather,* **42,** 322–325.

Sanders, F., 1986: Explosive cyclogenesis over the west-central North Atlantic Ocean. Part I: Composite structure and mean behavior. *Mon. Wea. Rev.*, **114,** 1781–1794.

——, 1987: A study of 500-mb vorticity maxima crossing the east coast of North America and associated surface cyclogenesis. *Wea. Forecasting,* **2,** 70–83.

——, and J. R. Gyakum, 1980: Synoptic–dynamic climatology of the "bomb". *Mon. Wea. Rev.*, **108,** 1589–1606.

Uccellini, L. W., R. A. Petersen, K. F. Brill, P. J. Kocin and J. J. Tuccillo, 1987: Synergistic interactions between an upper-level jet streak and diabatic processes that influence the development of a low-level jet and a secondary coastal cyclone. *Mon. Wea. Rev.*, **115,** 2227–2261.