A Study of 500 mb Vorticity Maxima Crossing the East Coast of North America and Associated Surface Cyclogenesis

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ABSTRACT

For assessment of the sufficiency of the approach of an upper-level vorticity maximum as a predictor of explosive surface cyclogenesis in the western Atlantic, a study was made of all 500-mb maxima which crossed the east coast of North America between 5 October 1985 and 4 April 1986. Of 96 such events, 38 produced bombs. This overall likelihood of 40% was greatest (50%) during the period from 19 December through 1 February, when crossings were most frequent.

In the 26 cases when the strength of the vorticity maximum was at least 22×10^{-5} s^{-1}, bomb likelihood was also 50%. When the crossing occurred at or equatorward of latitude 41°N, bombs occurred in 17 of 33 instances (52%). The likelihood rose to 47% when the speed of the upper maximum exceeded 30 kts (15.5 m s^{-1}). The best discrimination was found when this speed was multiplied by a measure of the strength of the vorticity gradients upstream and downstream from the center. On this basis, 16% of the 25 smallest values of this product produced bombs whereas 68% of the 25 largest values did so. Thus it appears that the intensity of the baroclinic forcing influences the probability of an explosive response. The effect of tropospheric stability, static or symmetric, was not examined.

1. Introduction

The importance of a 500 mb vorticity maximum as a predecessor of intense surface cyclogenesis was first noted by Petterssen (1955). Its dominance in the western North Atlantic Ocean has been established by Sanders (1986), and was foreshadowed by a number of summaries and individual case studies (Sanders and Gyakum, 1980; Bosart, 1981; Mullen, 1983; Roebber, 1984; Uccellini et al., 1985; Uccellini, 1986) in this region and elsewhere. The upper-level center of the western Atlantic generally moves from the WNW across the continent and overtakes the growing surface center, which is initiated as the upper center approaches the east coast. While this mean scenario aids in understanding the physical process, the upper predecessor has been shown to be at most a *necessary* condition for explosive cyclogenesis. From the forecasting point of view, the question is whether the approach of the vorticity maximum is a *sufficient* condition for explosive cyclogenesis.

The results are not to be taken as a comprehensive guide to the prediction of explosive cyclogenesis, in which factors other than the upper-level forcing need to be taken into account. In particular, we do not study the static or slantwise stability of the environment of the incipient bomb, which is presumably responsible for the degree of response to the forcing. Nor have we attempted to evaluate the surface forecasts produced by operational models. Presumably, the models would tend to predict cyclogenesis on the occasions when it is indicated from our results, but we have not investigated whether they contribute independently to the forecasts to be inferred from our work.

2. The data

To obtain some information regarding this question, the passage of all significant 500 mb centers across the coast was noted from the archive of the Limited-area Fine-mesh Model (LFM) initial analyses from 5 October 1985–4 April 1986. A significant center was taken to be one in which the central value of absolute vorticity was at least 15×10^{-5} s^{-1}, as suggested by the results of Sanders (1986). In each case, the center was tracked back to long 110°W, the northern limit of the LFM display panel, or the point of origin of the center, whichever was encountered first. It was then tracked forward to the edge of the LFM panel or, on occasion, to the point of disappearance of the center.

At each map time, at 12 h intervals, the central value of absolute vorticity was tabulated, as were the vorticity values at 554 km (5° lat distance) upstream and downstream from the center in the large-scale flow. That is, an 1108 km straight line was marked off and centered on the vorticity maximum with equal 500 mb heights at either end. The difference between the central value and the average of the flanking values thus measured was taken as the intensity of the vorticity system. The intensity indicates the general strength of the vorticity gradients upstream and downstream from the center.

When the LFM analyses were not available on facsimile, from 6 February–18 March, the analyses from the Nested-Grid Model (NGM) introduced at that time were used instead. These more highly resolved analyses generally showed more intense vorticity extrema, and on occasion showed analyses over the ocean which did not appear to be realistic. Since it was not clear how to correct them for better consistency with the LFM data, and since it seemed undesirable to omit this period from the study, data from the NGM analyses were used without adjustment.

A tabulation was also made of the tracks and central pressures of surface cyclones possibly associated with each upper center at some point in its history. Subjective judgment was the basis for determination. The surface center was not considered to be associated if it lay more than a very small distance *upstream* from the vorticity maximum (in the upper flow), if the distance between it and the surface center exceeded about 1500 km, or if another qualifying vorticity center lay closer to the surface cyclone. These criteria are based on physical reasoning and the mean structure found by Sanders (1986). The primary source of information concerning the surface cyclones was the NMC Atlantic analyses, containing plotted data, available routinely on facsimile. The plotted North American surface maps, or the "front-half" surface maps without plotted data, were consulted to fill gaps or clarify an unreadable analysis.

3. Results

a. *Chronology*

As shown in Table 1, 96 upper centers were found. In four instances, the vorticity center first appeared in the initial analysis just offshore and was included because of the possibility that it actually originated over land between map times. During the same period, 38 bombs were identified on the basis of 24-h deepening, normalized for latitude as in Sanders and Gyakum (1980). In 27 instances, explosive cyclogenesis was in progress before or at the time when the upper vorticity center crossed the coast. In all the remaining cases, it began less than 24 h after coastal crossing, and in only three cases was the delay longer than 12 h. Thus, the empirical probability of bomb occurrence at the time of passage of a vorticity maximum across the coast is 28%, rising to 40% if an additional 24 h allowance is made for delayed cyclogenesis. It is clear in either case

TABLE 1. Coastal crossings of vorticity maxima, 1985/86 cold season.

Case	Date	Lat (°N)	Bomb	Case	Date	Lat (°N)	Bomb	Case	Date	Lat (°N)	Bomb
1	8 Oct	44		33	19 Dec	39		65	2 Feb	43	
2	11 Oct	48	*	34	21 Dec	41	*	66	3 Feb	50	(*)
3	12 Oct	44		35	22 Dec	38	(*)	67	6 Feb	49	*
4	17 Oct	49		36	23 Dec	42		68	8 Feb	40	
5	20 Oct	50		37	26 Dec	32		69	9 Feb	49	
6	20 Oct	44		38	27 Dec	60	*	70	11 Feb	47 os	
7	23 Oct	51		39	28 Dec	47		71	12 Feb	40	*
8	26 Oct	45		40	29 Dec	46		72	13 Feb	40	
9	28 Oct	47		41	30 Dec	39	*	73	13 Feb	36	(*)
10	29 Oct	44	(*)	42	30 Dec	44	(*)	74	15 Feb	35	*
11	6 Nov	39		43	31 Dec	56		75	19 Feb	36	
12	9 Nov	48		44	3 Jan	52		76	20 Feb	34	
13	11 Nov	54	(*)	45	4 Jan	42	*	77	22 Feb	40	
14	14 Nov	50	*	46	6 Jan	47	*	78	23 Feb	31	
15	15 Nov	47	*	47	7 Jan	46		79	25 Feb	31	*
16	18 Nov	48		48	8 Jan	41	(*)	80	25 Feb	29 os	
17	21 Nov	55		49	9 Jan	50		81	27 Feb	36	
18	22 Nov	50		50	11 Jan	46		82	1 Mar	30	*
19	24 Nov	50		51	12 Jan	40	*	83	4 Mar	38	
20	25 Nov	48		52	13 Jan	37	*	84	5 Mar	35	*
21	25 Nov	47		53	15 Jan	38	*	85	7 Mar	38	*
22	30 Nov	50		54	16 Jan	44		86	8 Mar	41	
23	4 Dec	55		55	19 Jan	51		87	12 Mar	46	*
24	4 Dec	46 os		56	20 Jan	36		88	15 Mar	42	
25	7 Dec	35	*	57	20 Jan	34		89	17 Mar	42	
26	9 Dec	48	*	58	23 Jan	31		90	18 Mar	44	(*)
27	9 Dec	41		59	24 Jan	50	(*)	91	21 Mar	49	
28	10 Dec	45		60	27 Jan	32	*	92	22 Mar	31	
29	13 Dec	47		61	28 Jan	35	*	93	24 Mar	43	*
30	14 Dec	38	*	62	30 Jan	35	(*)	94	28 Mar	42	
31	17 Dec	46		63	1 Feb	48		95	31 Mar	50	
32	19 Dec	47	*	64	1 Feb	43 os	(*)	96	3 Apr	50	*

os = initiation offshore
(*) = delayed-action bomb

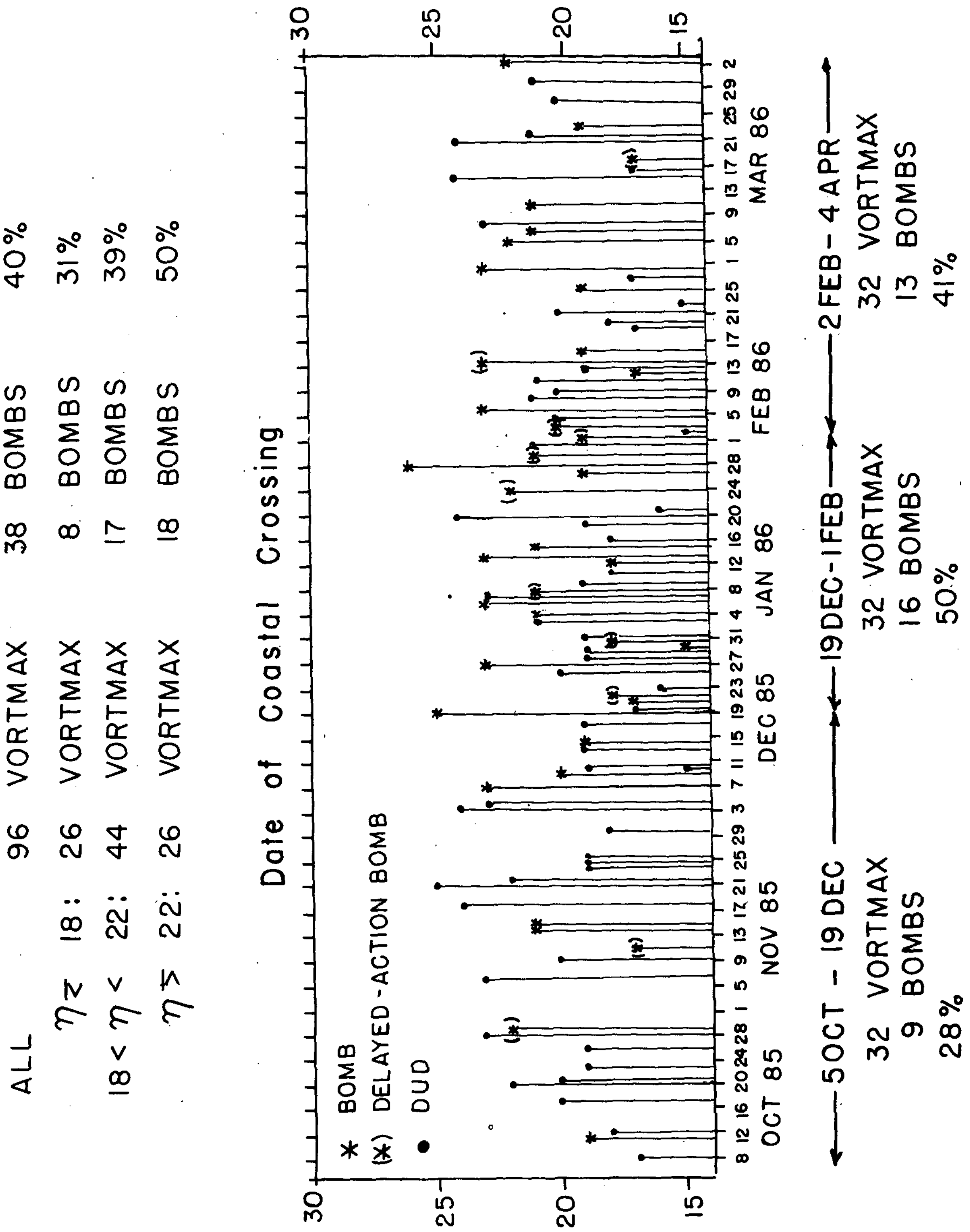

FIG. 1. Chronology of coastal crossings of 500 mb vorticity maxima. Length of line indicates the strength of the maximum at the time of crossing. Asterisk indicates associated explosive cyclogenesis.

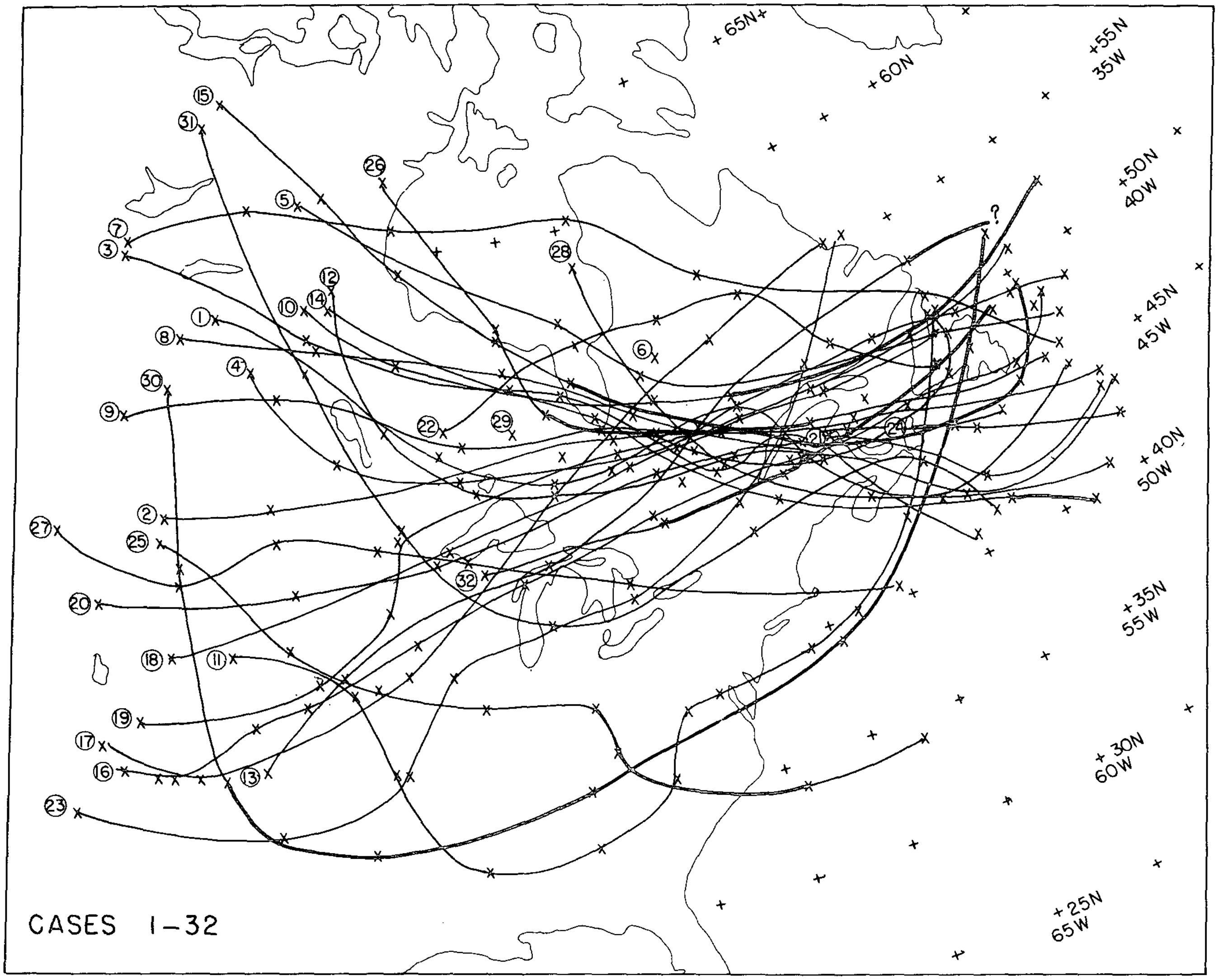

FIG. 2. Tracks of vorticity centers which crossed the coast, with the position each 12 h denoted by "X". Segments of tracks during which explosive cyclogenesis was occurring shown as heavier lines. Case number (see Table 1) indicated at start of track. a) first third; b) middle third; c) last third of cases.

that such a passage is *not* a sufficient condition for a forecast of bomb occurrence.

The chronology of these passages appears in Fig. 1. Crossings were most frequent from mid-December through mid-February and most infrequent prior to this time. During this active period, there were only four gaps of three or more days between passages. The values of the vorticity maxima showed no particular trend, with both the strongest and the weakest maxima observed during the busy period. (The three cases with center value smaller than 15 × 10^{-5} s^{-1} at time of crossing were included because of their greater strengths before or after crossing.) Some indication of regimes in which bombs are either encouraged or suppressed is seen in the record. From 16 November–6 December, for example, no bombs were observed, despite the passage of nine prominent vorticity maxima across the coast. On the other hand, five of the six crossings from 24 January–1 February were associated with intense cyclogenesis.

Bombs (whether concurrent or delayed) were most numerous during the active period, occurring in 50% of the instances from 19 December–1 February, and occurred least often prior to this time, when only 28% of the coastal crossings produced explosive cyclogenesis. Bomb likelihood responded to the central vorticity value, ranging from 31% when this value was 18 or lower through 39% for the midrange, to 50% when the value was 22 or higher. The use of NGM analyses during the period 6 February–18 March does not appear

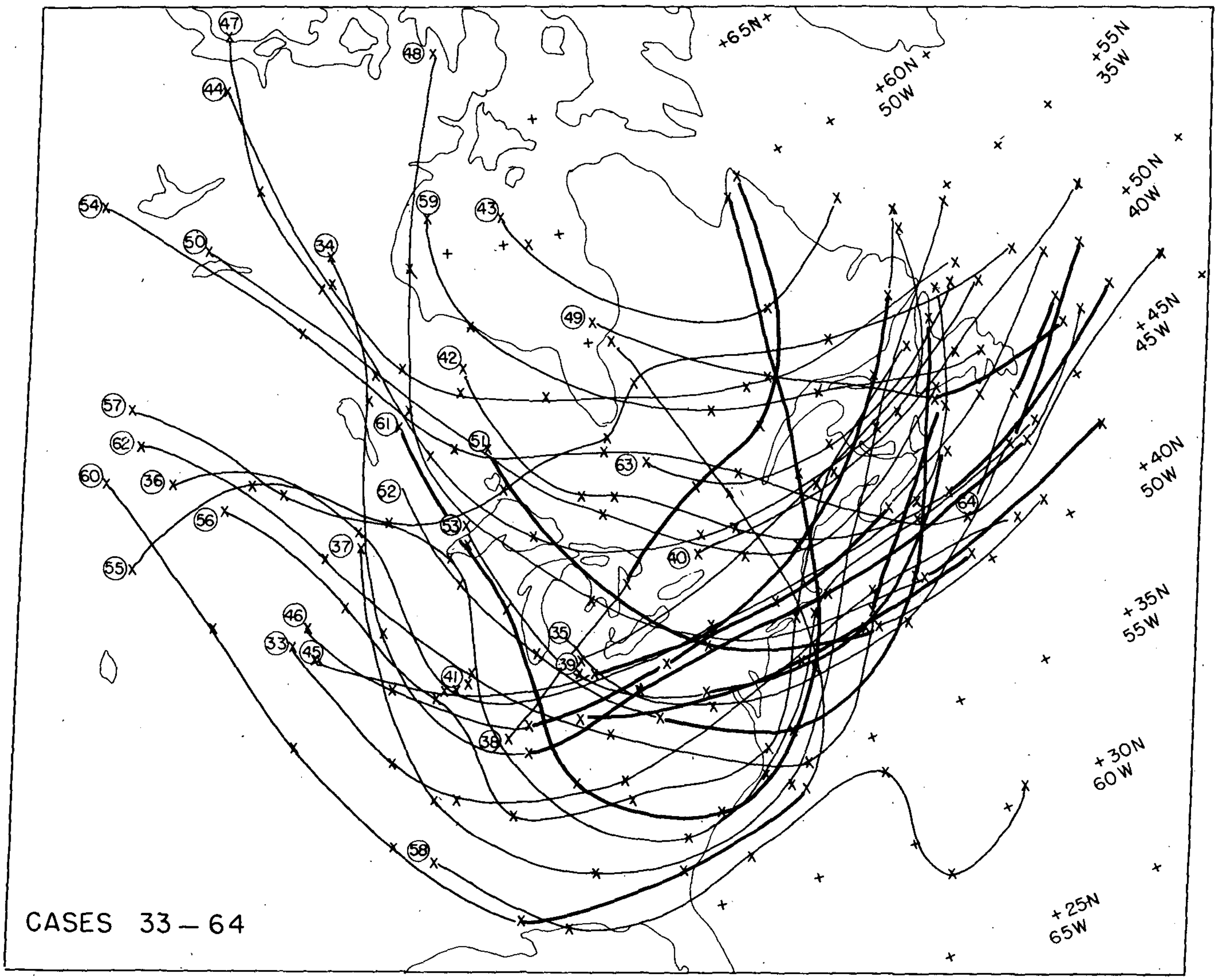

FIG. 2. (*Continued*)

to have produced a visible anomaly in the strength of centers (see Fig. 1), although subtle effects may be present.

b. Tracks

The tracks of the upper centers are mapped in Fig. 2, which displays a wide variety of behavior. Some flow regimes are detectable: for example, the early part of the season (Fig. 2a) was dominated by WNW–ESE tracks crossing the continental coast between lat 45°N and lat 50°N; during the busy period (Fig. 2b), the tracks were widely dispersed with little concentration, but with a number displaying a strongly meridional orientation, implying a deep quasi-steady, planetary-scale trough in eastern North America; in late winter (Fig. 2c), the tracks were more zonal but with a mean south of that prevailing earlier. The relative frequency of bomb occurrence was broadly related to the latitude at which the vorticity maximum crossed the coast. As seen here and in Table 1, there were 21 bombs in 63 crossings (33%) at or poleward of lat 41°N, and 17 bombs in 33 crossings (52%) at or equatorward of lat 40°N.

Examination of the early portions of the tracks subsequently associated with bomb occurrence, as shown in Fig. 2, does not disclose anything particularly distinctive. During the late-November respite noted previously, there was a change in the regime, with centers originating for the first time in the southwestern United States. These systems were often associated with vigorous cyclogenesis in the center of the continent rather than in the western Atlantic. Conversely, in the active period at the end of January noted previously, the vor-

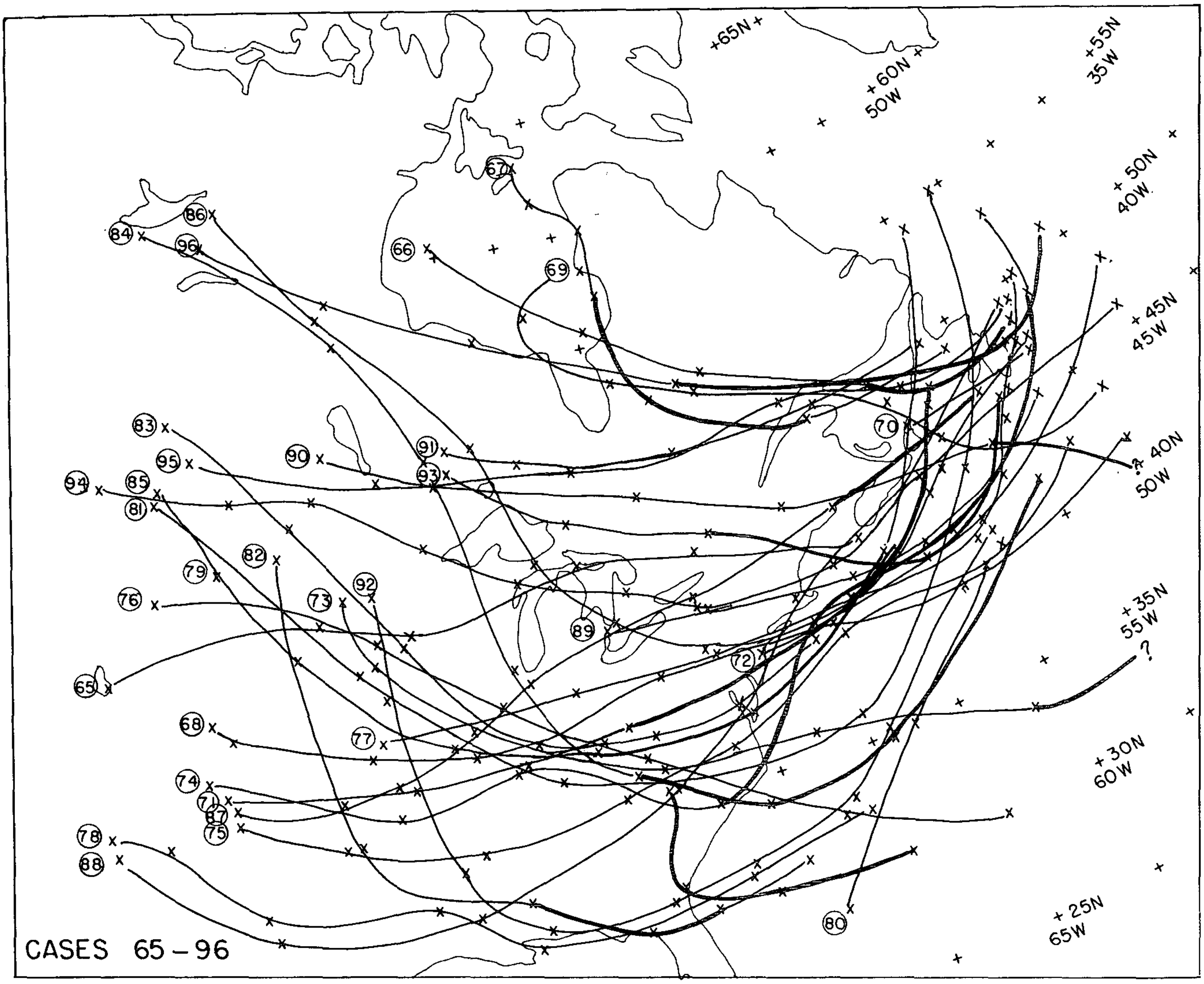

FIG. 2. (*Continued*)

ticity centers moved southeastward around a large planetary-scale trough, with surface cyclogenesis occurring on the east side. One can readily find counterexamples, however, and it is difficult to formulate any concise forecast guidance.

The tracks of the surface cyclones themselves, while they were deepening intensively, are shown in Fig. 3. They are consistent with the distribution of positions of maximum deepening shown by Roebber (1984) for a 6-year sample, except that in the most recent season, a relatively large number of cases occurred east of Newfoundland. Another departure from previous experience, as reported by Sanders (1986), is the lack of particularly strong bombs in the western Atlantic. As can be seen in Fig. 3, cases with maximum Bergeron values of 1.9 or greater (with a single minimally documented exception in the subtropics) lay east of Newfoundland. Since the bombs in this recent season are, in some respects, anomalous, we must resist drawing more than preliminary conclusions from this sample of cases.

4. Forecast considerations

From earlier work (Sanders, 1986), we found that the speed of advance of the vorticity maximum is largest for the most rapidly deepening storms. Thus, the speed of the maximum at the time of coastal crossing might be related to the probability of bomb occurrence. Experience further suggests that large-scale maxima with only modest vorticity gradients on the smaller-scale of the developing surface storm may not be ef-

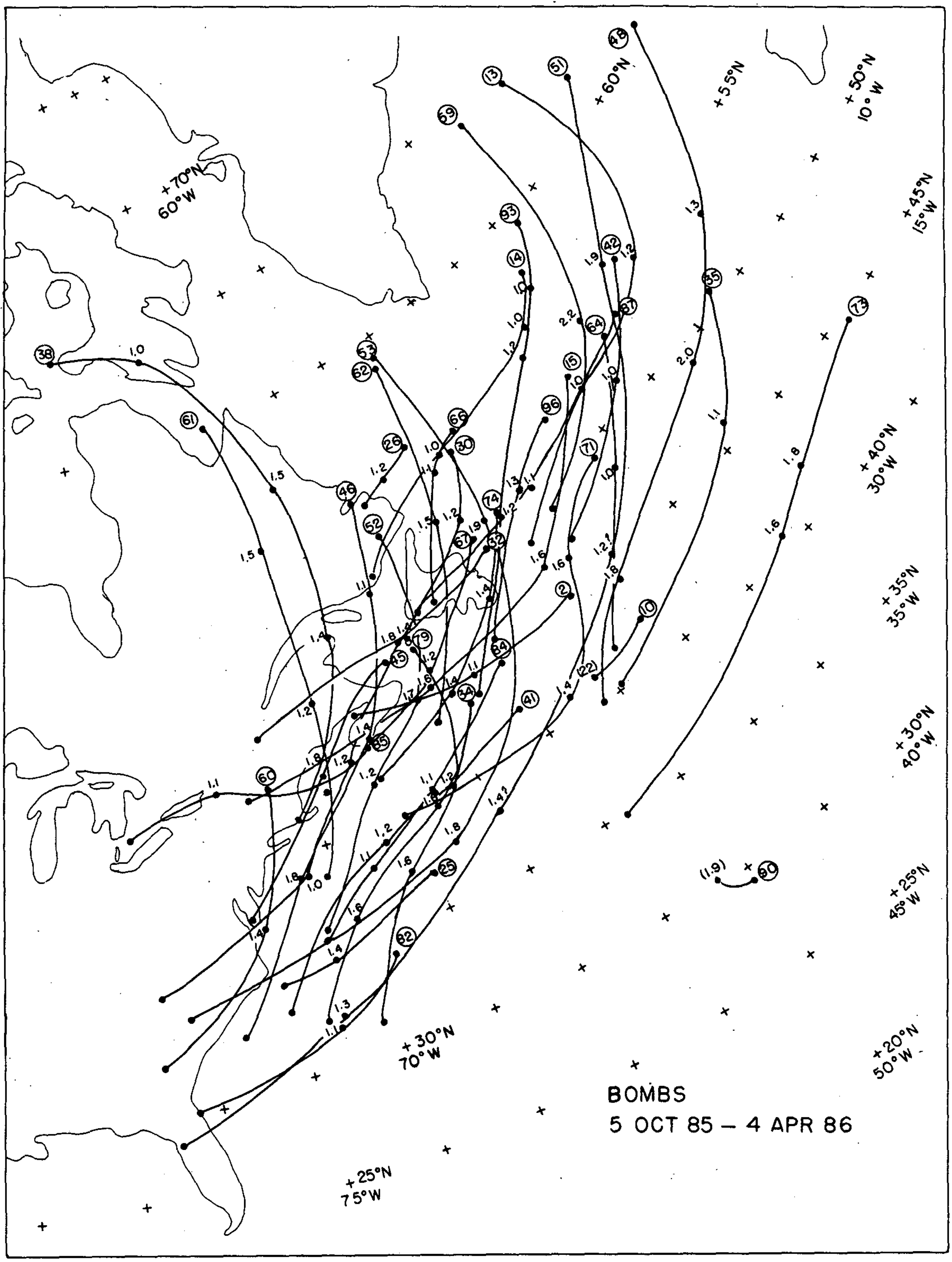

FIG. 3. Tracks of bombs during explosive cyclogenesis. Dots show position each 12 h. The maximum Bergeron number (see Sanders and Gyakum, 1980) is shown for each storm. Case number is indicated at end of track segment.

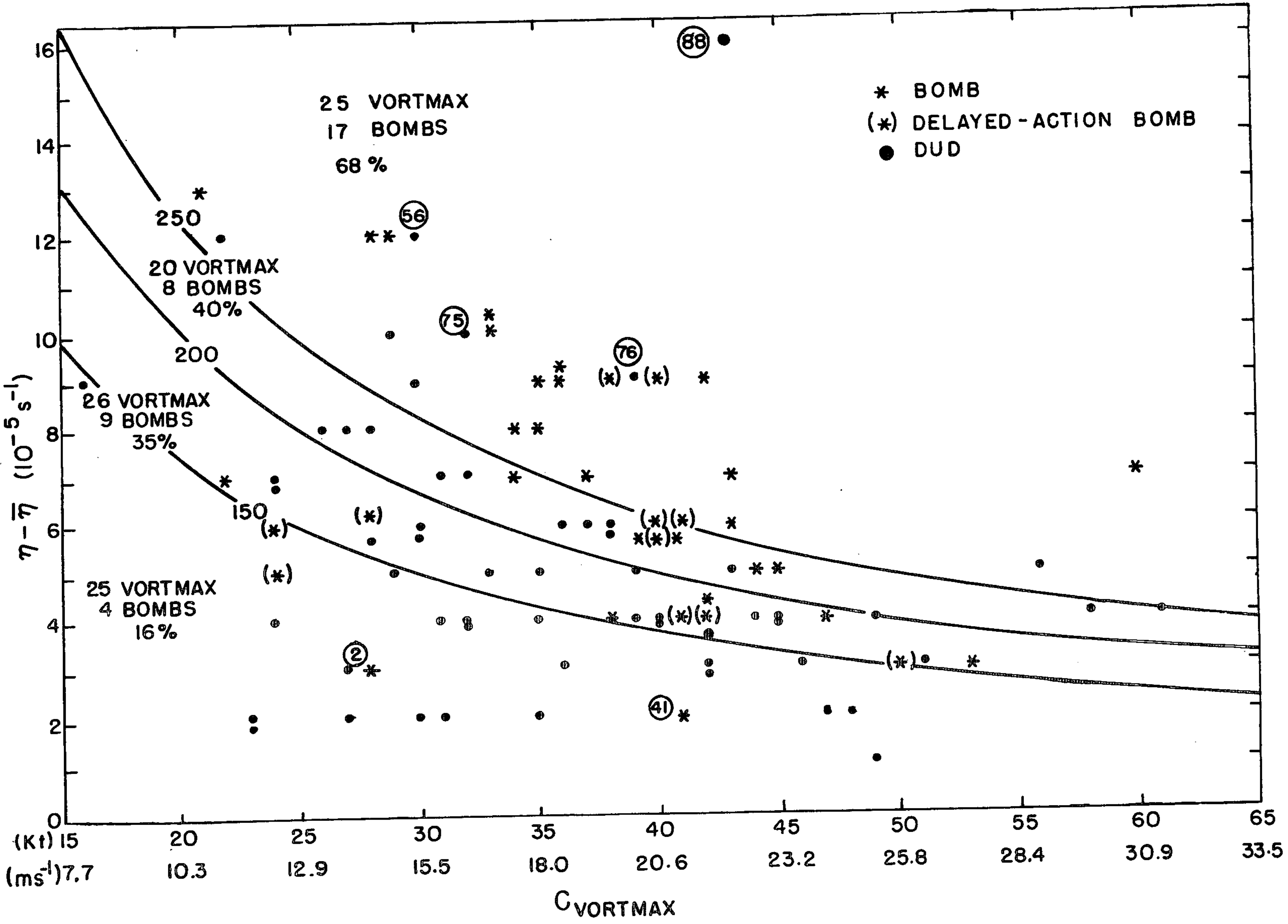

FIG. 4. Speed of vorticity maximum along abscissa, and intensity, $\eta - \bar{\eta}$, along ordinate, at time of coastal crossing. Asterisks and dots indicate whether or not explosive cyclogenesis occurred in response. Hyperbolic lines are shown for values of the product of 150, 200 and 250 × $10^{-5}\ s^{-1}$ (0.8, 1.0 and 1.3 × $10^{-3}\ m\ s^{-2}$).

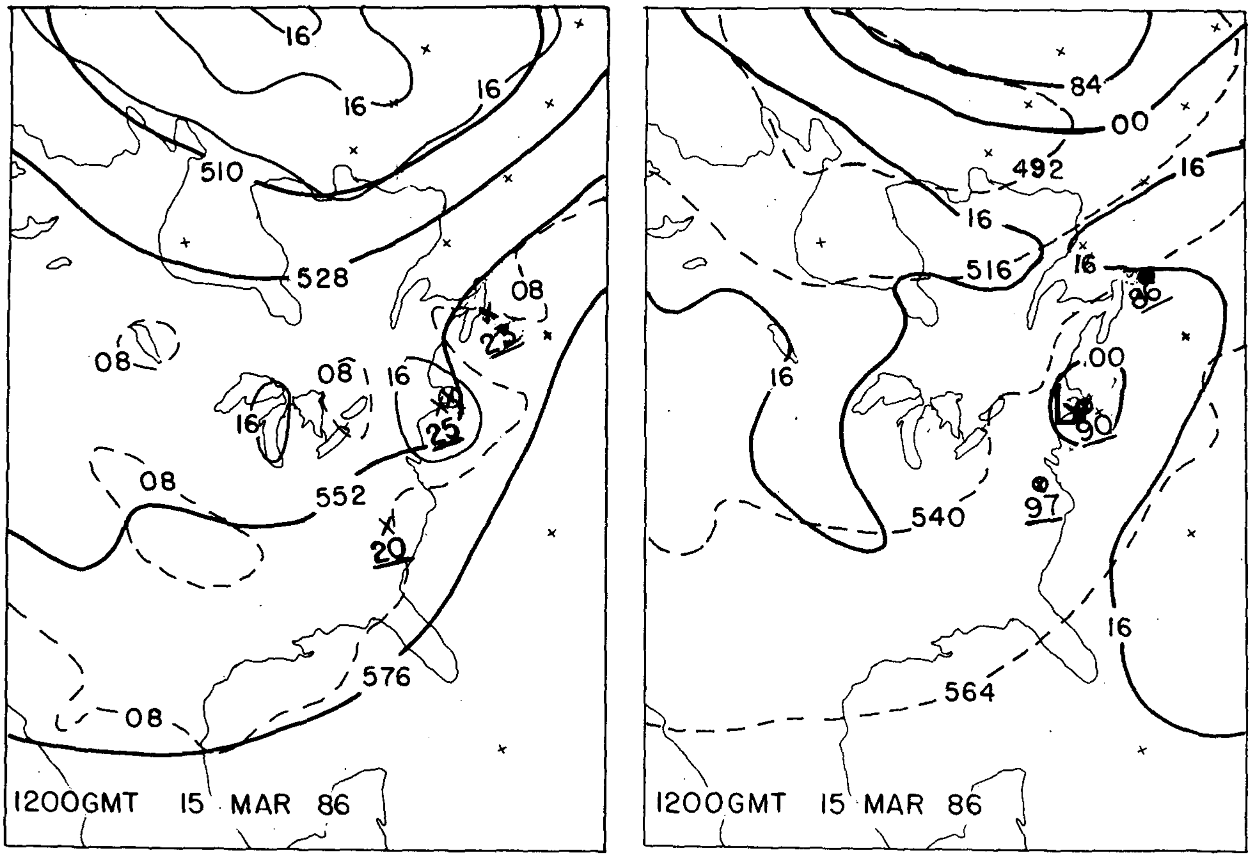

FIG. 5. (a) 500-mb and (b) sea level analyses for 1200 UTC 15 March 1986. In (a) heavy solid lines are height contours labeled in dam; the thin solid and dashed lines are absolute vorticity isopleths for 16 and 8 × 10^{-5} s^{-1}, respectively; and the X's denote the positions of the vorticity maximum at time of coastal crossing and 12 h before and after, with strength indicated. The position of the sea level low at the central time is shown by a small circled x. In (b) the heavy solid lines are sea level isobars labeled in mb (hundreds and thousands digits omitted) and the heavy dashed lines represent thickness of the layer from 1000 to 500 mb, labeled in dam. Positions of sea level low center at the central time and 12 h earlier and later is indicated by the small circled x's, with central pressure value denoted in mb. For the central time, the superposed position of the upper vorticity maximum is shown by a large X.

fective in forcing explosive cyclogenesis. Thus, the intensity of the vorticity system on the 1108 km scale, measured as described earlier, might be related to the probability of bomb occurrence.

Motivated by this reasoning, we find in this sample that the relative frequency of bomb occurrence is weakly related to speed of the vorticity maximum; it is 26% for speeds of not more than 31 kt (16.0 m s^{-1}), 47% for speeds between 31 and 41 kt (21.2 m s^{-1}), but only 45% for speeds equal to or greater than this upper limit. In the case of vorticity intensity, the relative frequency of bombs is 23% when $\eta - \bar{\eta}$ is no more than 4 × 10^{-5} s^{-1}, 46% when it is between 4 and 7, and 54% when it is at least 7 of these units. This sensitivity is comparable to results found for other parameters.

A better discrimination is found when the values of the speed and the vorticity intensity are jointly plotted, as in Fig. 4. A broad measure of the strength of the vorticity advections (hence the forcing) associated with the upper-level system can be obtained by assuming that it moves with a steering flow near 500 mb. Multiplication of this speed by the vorticity intensity (recall that it reflects the magnitude of the gradients flanking the center) should then represent the strength of the advections at 500 mb. From Fig. 4 we see that when this product is less than 150 × 10^{-5} kt s^{-1} (0.8 × 10^{-3} m s^{-2}), the relative frequency of bombs is only 16%. When the product exceeds 250 × 10^{-5} kt s^{-1} (1.3 × 10^{-3} m s^{-2}), the relative frequency rises to 68%. Intermediate values yield results not far from the overall sample frequency. The importance of baroclinic effects shown by Sanders (1986) is thus reinforced. Evidently, the likelihood of bomb occurrence, as well as the rate of deepening given that explosive cyclogenesis is under way, is quite sensitive to the vorticity advection associated with the upper-level system.

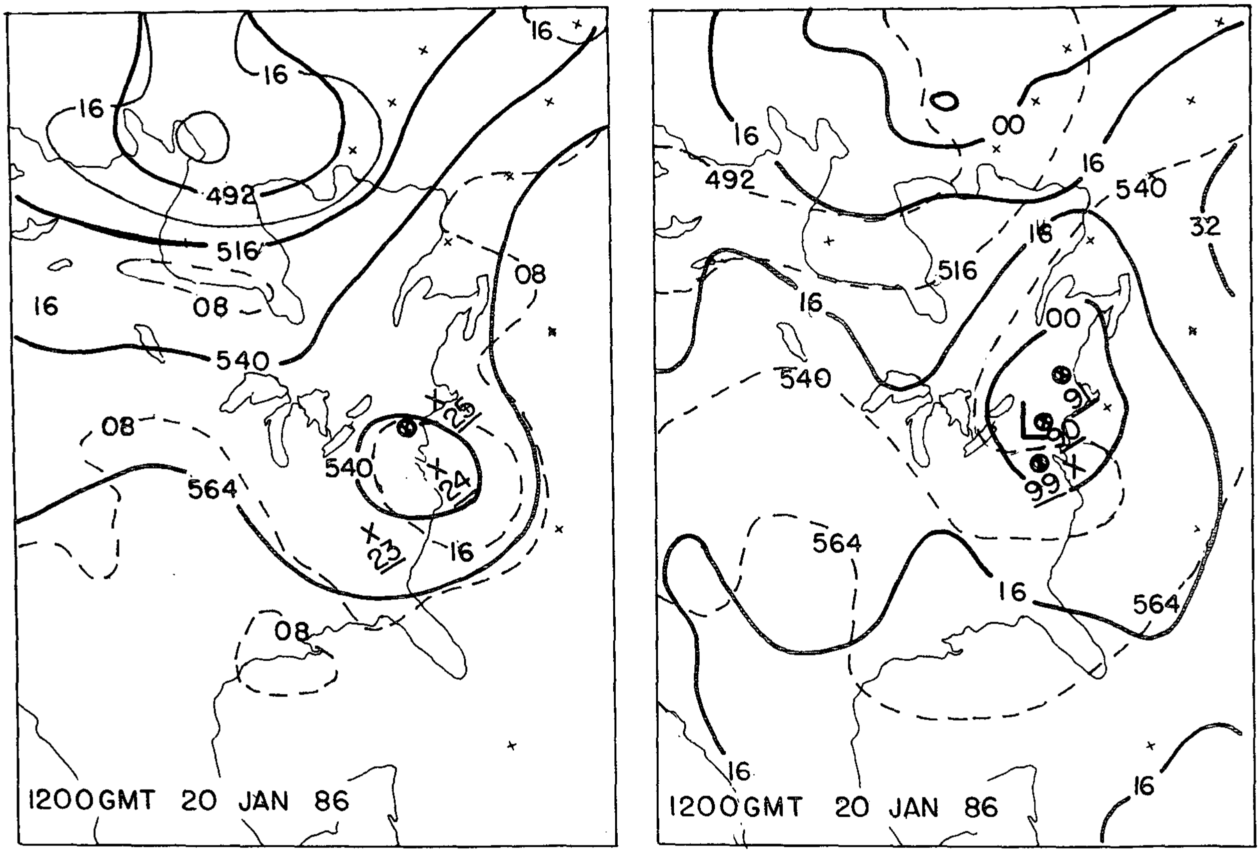

FIG. 6. As in Fig. 5 except for 1200 UTC 20 January 1986.

5. Limitations

As Fig. 4 shows, errant points do exist, reminding us that the real atmosphere (at least as represented in operational analyses) is probabilistic in this frame of reference. Case 88, the extreme outlier, is illustrated in highly simplified form in Fig. 5. An intense surface cyclone was located very near the position of the upper-level center. It had never quite achieved bomb status, perhaps owing to a track over land rather than water. Two other egregious "forecast busts," illustrated in Figs. 6 and 7, show something of a similar character. The vorticity maximum in these cases, however, was not so close to the surface cyclone. In case 56 (Fig. 6), the track was over land and might have represented a bomb 12 h earlier had a separate low-pressure center been identifiable 24 h earlier (not shown). In case 75 (Fig. 7), the surface center deepened to 982 mb in the analysis 24 h later (not shown). Had this deepening occurred 12 h later, a possibility not ruled out by the sparse data coverage at that time, this case would have been classified as a bomb. In a fourth dissident case 76 (Fig. 8), a surface low was near the upper-level center 12 h prior to coastal crossing. Just after crossing, the upper vorticity maximum was analyzed to lie decidedly *east* of the surface system, a rare configuration that ought to be accompanied by pronounced weakening of the existing system. This weakening was observed to occur at the surface. The vorticity center aloft, however, strengthened at least temporarily, thus casting doubts on the credibility of the 500 mb analysis.

In the two cases (2 and 41) in Figs. 9 and 10, instances when bombs were observed despite modest values of the implied 500 mb vorticity advection, overall baroclinicity was quite strong and an analysis showing only a slightly stronger vorticity analysis would have yielded a substantially larger value of the product. This was particularly true of case 2, in which the analyzed center was stronger 12 h before and after coastal crossing than at the critical time.

From this recitation of chagrin, we conclude 1) further bomb occurrence is unlikely if a pronounced surface center lies close to the position of the 500 mb vorticity maximum at the time of coastal crossing, and 2) uncertainty in oceanic analysis is always with us and will produce some contrary cases. We note further that in three of the four instances of unexpected failure of bomb occurrence, the output of the Nested-Grid Model (NGM) was the basis of the vorticity measurements.

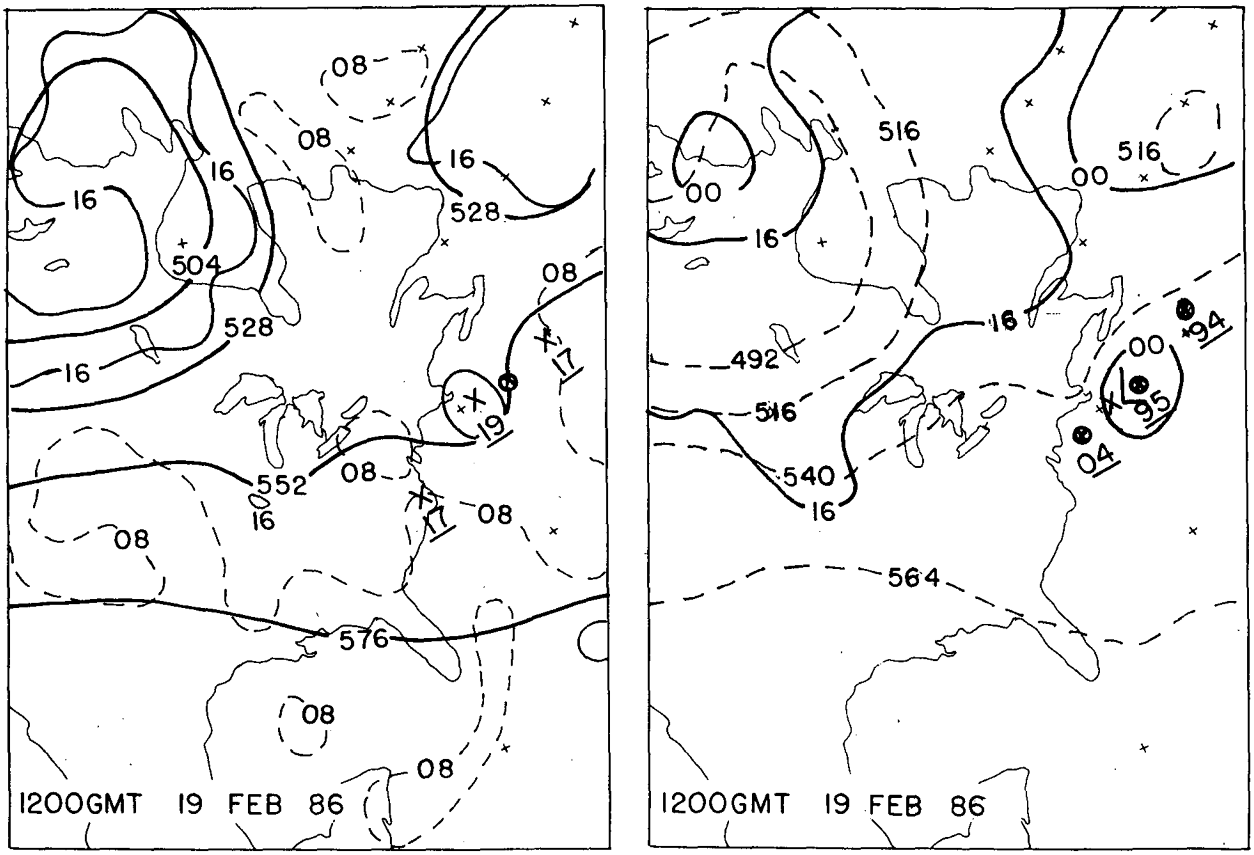

FIG. 7. As in Fig. 5 except for 1200 UTC 19 February 1986.

Since this model typically shows vorticity extrema, both maxima and minima, to be somewhat stronger than as seen in the LFM analyses, the results we have presented here, as they relate to the strength and the intensity of the vorticity centers, may not be applicable to analyses other than LFM. They may, in fact, be somewhat contaminated by the inclusion of a data from a number of NGM analyses.

As a speculative comment, it appeared on a number of occasions that when strong low-level northwesterlies with cold advection existed over the coast and adjacent Atlantic waters at the time of coastal crossing of the upper vorticity center, bomb occurrence, if it happened at all, was likely to be delayed and to occur a considerable distance offshore. This impression is consistent with Petterssen and Smebye's (1971) observation that significant cold advection must not be present if low-level development is to begin in response to the advance of a pre-existing upper trough.

Finally, it should be noted that we have examined only the baroclinic forcing that appears to be a crucial ingredient of these storms. We have not addressed the question of the static or symmetric stability, which should strongly influence the degree of response to a given forcing, and which has been shown by Reed and Albright (1986) to be extremely important in an eastern Pacific case.

6. Concluding summary

It is known that explosive cyclogenesis in the western Atlantic is accompanied by the approach from the west of a prominent vorticity center at 500 mb, which typically has a considerable history prior to the appearance of the surface cyclone. It is not known to what extent the approach of an upper-level center is a sufficient condition for surface cyclogenesis.

Some information on this point was obtained by noting and tracking all prominent vorticity centers, as shown almost exclusively in the LFM initial analyses, which crossed the coast of North America between lat 29°N and 60°N during the 26 weeks from 5 October–4 April 1986. There were 96 such centers, of which 27 were accompanied by explosive cyclogenesis at the time of coastal crossing or before, and 11 within 24 h after the time of crossing. Thus, 38 of 96 cases (or 40%) produced bombs. The approach of an upper center is

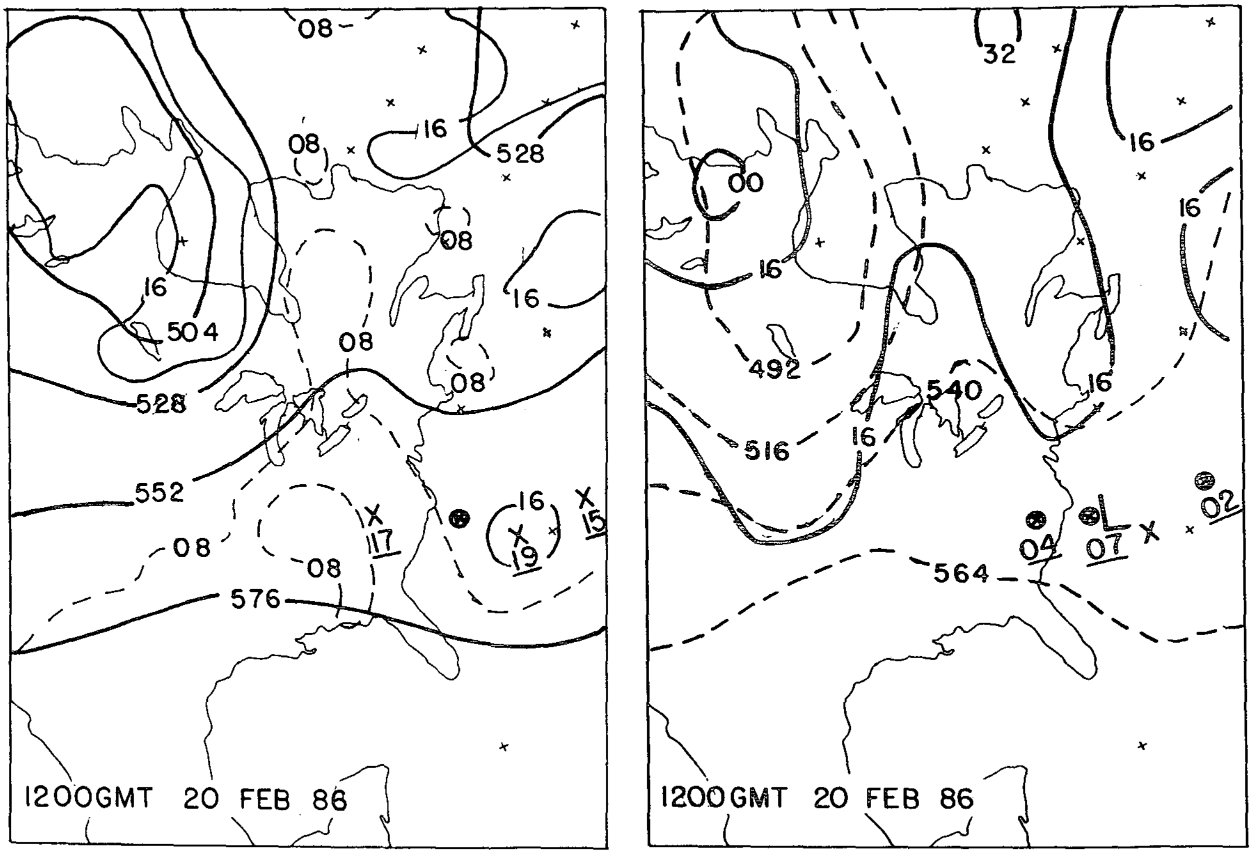

FIG. 8. As in Fig. 5 except for 1200 UTC 20 February 1986.

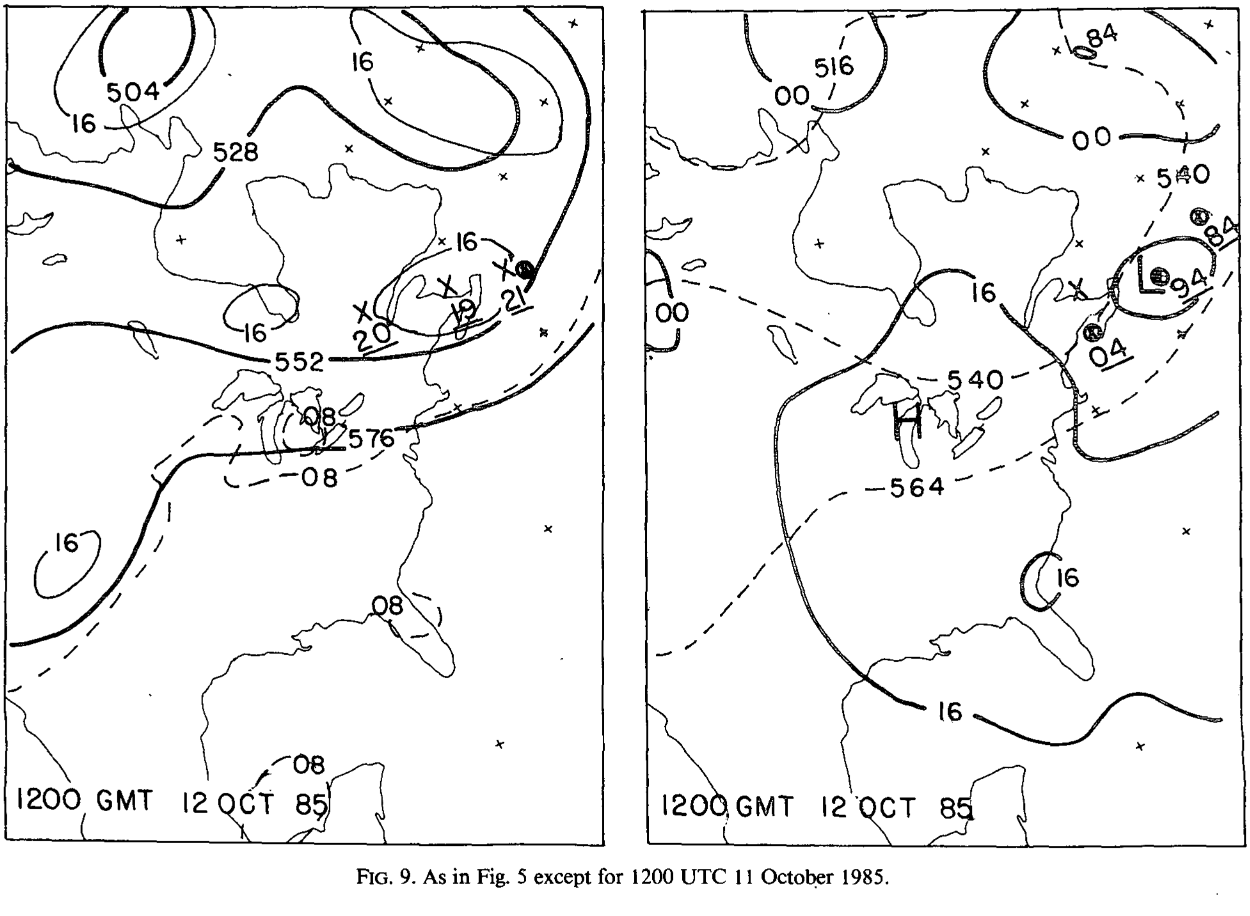

FIG. 9. As in Fig. 5 except for 1200 UTC 11 October 1985.

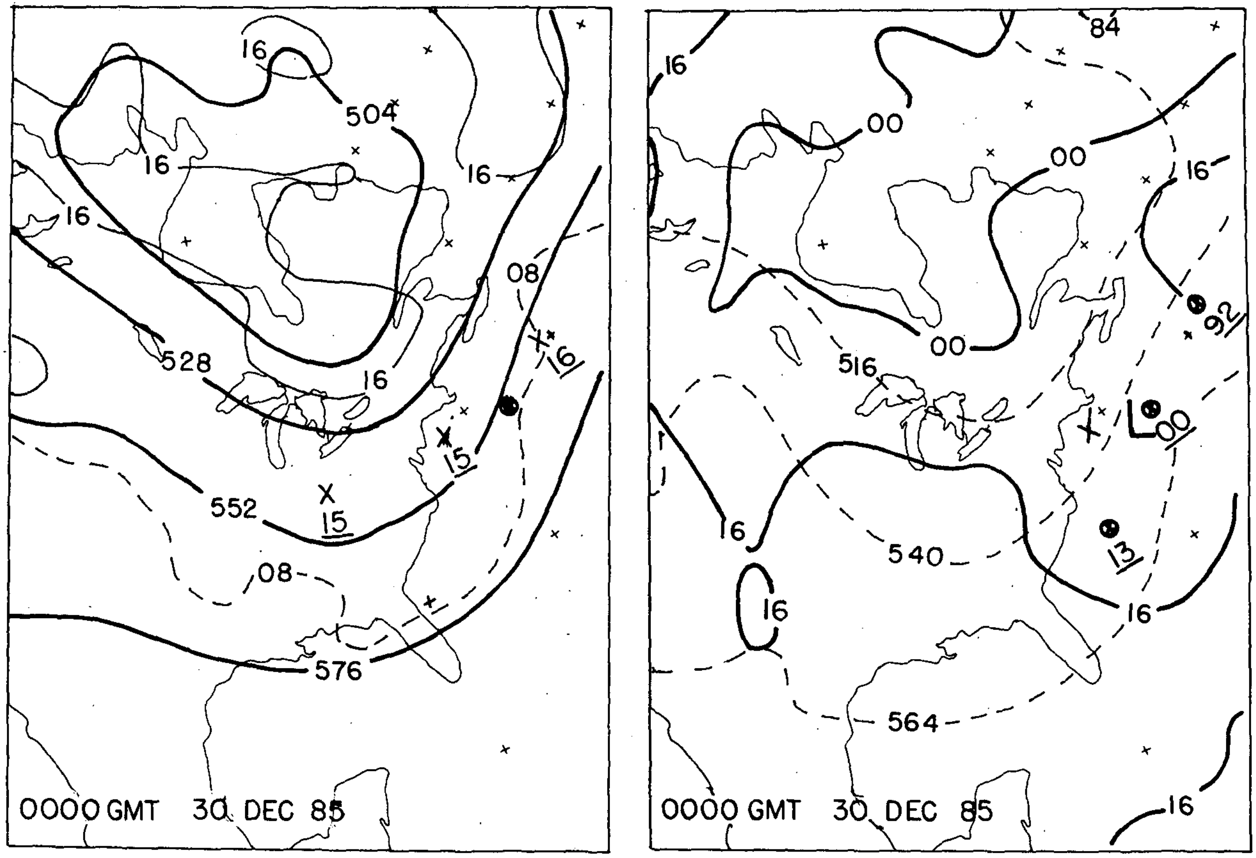

FIG. 10. As in Fig. 5 except for 0000 UTC 30 December 1985.

far from a sufficient condition for explosive cyclogenesis.

During the cold season, the earliest 32 crossings occurred from 8 October–19 December and only 28% produced bombs. The next 32 occurred in the relatively short period from 19 December–1 February, producing bombs in 50% of the cases. The data suggested shorter periods of suppressed or enhanced activity, implying the influence of a planetary-scale regime. This aspect was not examined, however. Some latitude dependence was seen: for upper centers crossing the coast poleward of lat 40°N, the proportion producing bombs was 26%, whereas for the 33 cases of centers crossing to the south the proportion was 52%.

The central absolute-vorticity value at coastal crossing was related to bomb likelihood. In 26 cases when this value was no more than $18 \times 10^{-5}\ \mathrm{s}^{-1}$, 31% produced bombs, while in 26 cases when the value was at least $22 \times 10^{-5}\ \mathrm{s}^{-1}$, the proportion was 50%.

A better discrimination was obtained when the speed of the upper center at coastal crossing was multiplied by the excess of central vorticity over the average 300 nmi (554 km) upstream and downstream. This product is a measure of general strength of upper-level vorticity advection, reflecting the degree of baroclinic forcing. In the 25 cases when the product exceeded 250×10^{-5} kt s^{-1} ($1.3 \times 10^{-3}\ \mathrm{m\ s}^{-2}$), bombs occurred 17 times (68%), while in the 25 cases when the product was less than $150 \times 10^{-5}\ \mathrm{s}^{-1}$ ($0.8 \times 10^{-3}\ \mathrm{m\ s}^{-2}$), bombs occurred in only 4 instances (16%).

Examination of the cases when bombs failed to occur despite large value of the product found that close proximity of the upper center and a strong surface cyclone at the time of coastal crossing was unfavorable for further bomb development. If strong northwesterly flow and cold advection were occurring in the extreme western Atlantic at time of crossing, cyclogenesis was likely to be delayed 12–24 h and to occur relatively far offshore.

A number of these failures occurred during the interval when the new NGM model, with stronger analyzed-vorticity gradients, was the only source of analyses. These analyses typically show vorticity extrema to be somewhat stronger than they appear in LFM analyses. Thus, the present results, as they relate to the strength and intensity of the upper vorticity center, may not be applicable to other than LFM analyses.

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