Explosive Cyclogenesis in the West-Central North Atlantic Ocean, 1981–84. Part I: Composite Structure and Mean Behavior

FREDERICK SANDERS*

9 Flint Street, Marblehead, MA 01945

(Manuscript received 4 September 1985, in final form 12 March 1986)

ABSTRACT

Tracks and central values of surface low-pressure centers and 500-mb absolute vorticity maxima were gathered from operational analysis for 48 cases of explosive cyclogenesis in the west-central North Atlantic. The cases were stratified into relatively strong, moderate and weak categories. Tracking was done from 36 h before to 24 h after the time of most rapid surface deepening.

The surface center often first appeared only 12 to 24 h before maximum deepening, but the upper vorticity maximum was present 36 h or more in advance, often many days. Mean motion of the surface low was rapidly northeastward from the southeastern states, or just offshore, to Newfoundland. Intense deepening occurred in a period of no more than 24–36 h. Strong cyclones moved most rapidly and most meridionally, traveled farther over warm water, and deepened dramatically in a single 12-h period while crossing the closely spaced isotherms of sea surface temperature north of the Gulf Stream. The upper vorticity center moved rapidly eastward from an initial position far northwest of the surface low to a final position close by to its south. Modest intensification of this center occurred during overtaking as the surface cyclone deepened explosively. Detailed study of two cases illustrates the range of behaviors as well as problems of oceanic analysis.

A high correlation was found, for the sample means, between upper-level cyclonic vorticity advection over the surface cyclone and simultaneous surface-deepening rate. Thus the explosive maritime cyclone appears to be a fundamentally baroclinic disturbance in which the low-level response to a given upper-level forcing is dramatically large.

1. Introduction

Rapid intensification of extratropical storms over the sea poses a serious threat to life and property both far offshore (Gyakum, 1983; Buckley, 1983) and nearshore (LeBlond, 1984). Although some cases along the coasts of northern Europe were offered by Bergeron (1954) and by Riehl (1980) as examples of "extratropical hurricanes," the first comprehensive surveys of these storm events, denoted "bombs" for convenience, for the Northern Hemisphere were presented by Sanders and Gyakum (1980) and by Roebber (1984). They provided some crude indication of the dynamical mechanism and relationship of these storms to the planetary-scale environment, as well as information on location, season, and frequency of occurrence.

A prominent region of high frequency of explosive cyclogenesis extends northeastward from just east of the Carolina coast into the Atlantic Ocean south of Newfoundland (Roebber, 1984, Fig. 7). Since the data coverage at the surface is reasonably dense in this region and since rawinsondes at Bermuda and Sable Island extend seaward, at least minimally, the good upper-level coverage over North America, this area (Fig. 1) was selected for a more detailed study of the structure and behavior of bombs.

All cases identified here in the 12-hourly operational analyses prepared by the National Meteorological Center (NMC) were collected for the period January 1981 through November 1984. Cases over land were included, provided the maximum deepening did not occur west of the Appalachian mountains. The position of each cyclone at the midpoint of the 24-h period of most rapid deepening was noted, and this 24-h deepening was adjusted for latitude, ϕ, and expressed in bergerons [1 bergeron = 24 mb $(\sin\phi/\sin 60)$]. Results, stratified into categories of intensity, are listed in Table 1 and mapped in Fig. 1. Some were doubtless missed, because of the limitations of surface analysis in regions of sparse data and because of incompleteness, for one reason or another, of the map archive at the Massachusetts Institute of Technology (MIT), which was the primary data source. Of the 54 identified cases, six were discarded because the corresponding initialization maps from the limited-area fine-mesh (LFM) prediction model were missing.

Since 10 of the original 54 cases in this sample produced a maximum bergeron value of 2 or greater, as contrasted with 15 of 109 in the entire Atlantic in Sanders and Gyakum's (1980) sample (cf. their Fig. 5),

---

[*] Former affiliation: Department of Meteorology and Physical Oceanography, Massachusetts Institute of Technology.

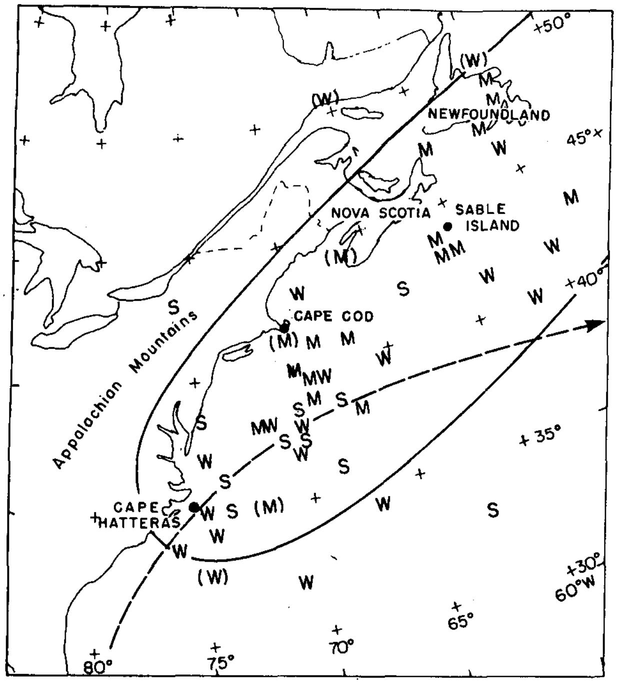

FIG. 1. Locations of bombs January 1981–November 1984. Letter indicates strong, moderate or weak relative intensity and is placed at the position of the cyclone at midpoint of the 24-h period of most rapid deepening. Letters in parentheses denote cases not used. The solid line represents the four-case frequency isopleth from Roebber (1984). Place names in the text are located.

there is some evidence that the present area is particularly prone to especially violent cyclogenesis. This ponderous assertion would come as no surprise to experienced mariners. The geographical distribution of cases looks entirely consistent with Roebber's (1984) distribution (cf. his Fig. 7), also no surprise as nearly half the present sample was contained in his.

2. Mean behavior of the surface low-pressure center and associated 500 mb vorticity center

a. Strong bombs

Tracks of the 12 strong bombs during the period when the deepening rate was at least one bergeron are shown in Fig. 2. There is a notable concentration of tracks more or less along the axis of the Gulf Stream from just east of Cape Hatteras to about 300 km southwest of Cape Cod, thence continuing northeastward across a strong gradient of sea surface temperature to south of Nova Scotia. Even when a portion of the track lay over land, the maximum deepening occurred, with a single exception, when the center was over water.

A composite picture of the behavior of these 12 strong bombs appears in Fig. 3. The position of the low-pressure center at the midpoint of the 24-h period of maximum deepening was chosen as a reference point. This time was denoted time zero and other times

TABLE 1. Dates, times, and locations of identified bombs in the west-central North Atlantic January 1981–November 1984. Strong: >1.8 bergerons; moderate: 1.3–1.8 bergerons; weak: 1.0–1.2 bergerons.

Date	Time (GMT)	North latitude	West longitude	Bergerons
		Strong		
10 Jan 1981	1200	38	68	2.1
3 Mar 1981	1200	33	62	2.0
17 Mar 1981	0000	37	71	2.0
15 Jan 1982	0000	35	74	2.0
13 Feb 1982	1200	36	74	2.8
6 Apr 1982	1200	38	75	2.2
12 Apr 1982	0000	36	68	2.0
6 Jan 1983	1200	38	70	1.9
25 Nov 1983	1200	41	71	2.0
7 Dec 1983	0000	43	76	1.9
24 Dec 1983	1200	37	70	2.4
26 Jan 1984	0000	42	64	2.1
		Moderate		
18 Jan 1981	0000	43	61	1.6
6 Mar 1981	0000	39	69	1.4
15 Mar 1981	0000	44	61	1.4
6 Dec 1981	0000	38	67	1.8
20 Feb 1982	1200	41	67	1.7
24 Feb 1982	1200	43	55	1.4
16 Nov 1982	1200	47	60	1.4
10 Dec 1982	0000	47	56	1.4
12 Feb 1983	1200	40	69	1.4
16 Feb 1983	1200	43	53	1.5
12 Mar 1983	0000	38	72	1.4
25 Oct 1983	1200	43	60	1.4
23 Dec 1983	1200	48	65	1.6
28 Jan 1984	0000	40	70	1.7
31 Jan 1984	1200	41	69	1.4
20 Nov 1984	0000	49	55	1.6
		Weak		
12 Jan 1981	1200	32	71	1.2
29 Jan 1981	1200	42	59	1.2
8 Feb 1981	1200	38	72	1.1
2 Apr 1981	1200	43	69	1.0
16 Dec 1981	0000	37	75	1.2
14 Jan 1982	1200	40	69	1.1
27 Jan 1982	0000	34	67	1.0
22 Feb 1982	0000	38	70	1.2
10 Apr 1982	0000	40	65	1.1
27 Nov 1982	0000	47	65	1.2
11 Jan 1983	1200	44	73	1.0
16 Jan 1983	0000	40	72	1.1
25 Mar 1983	0000	34	76	1.2
1 Apr 1983	0000	34	75	1.2
19 Apr 1983	0000	35	75	1.0
20 Dec 1983	0000	37	63	1.1
3 Jan 1984	0000	40	57	1.1
9 Jan 1984	0000	46	55	1.2
7 Feb 1984	0000	37	70	1.0
4 Jun 1984	0000	42	55	1.0
		Not Used		
2 Jan 1981	1200	41	70	1.5
8 Jan 1981	1200	50	65	1.1
20 Sep 1981	0000	44	66	1.5
26 Sep 1981	0000	50	55	1.2
12 Nov 1981	1200	33	75	1.2
25 Nov 1981	0000	35	72	1.5

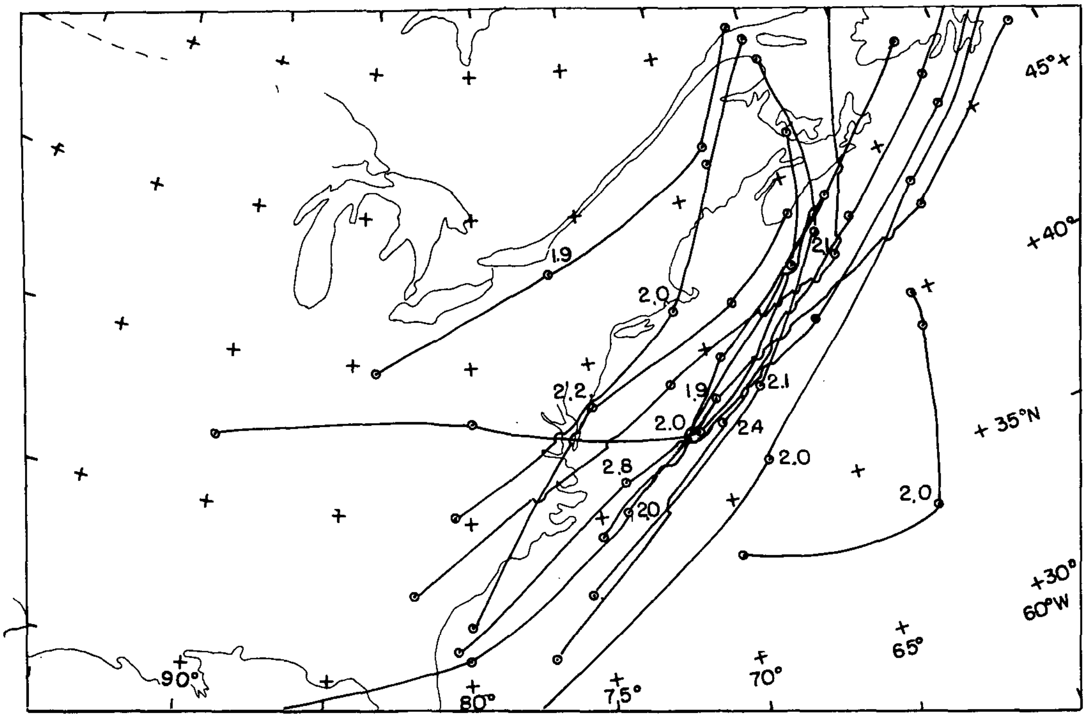

FIG. 2. Twelve-hour positions and tracks of surface low-pressure centers from beginning to end of 24-h period(s) when deepening rate was at least one bergeron. Maximum bergeron value shown. For strong bombs.

were referred to by the number of 12-h increments prior to or subsequent to this time. The mean position of the surface low at the center of the 24-h period of maximum deepening was 37.9°N, 70.2°W. In four instances the low initially appeared only 12 h before time zero, while in only four was initiation time earlier than time −2, prior to which no means were determined. Relatively strong deepening began at time −1 and continued until time +2, after which little further occurred. An extraordinary mean fall of 24 mb was observed in the 12 h following time zero, as the center crossed the region of strong gradient of sea surface temperature (SST) on the north flank of the Gulf Stream. Gyakum's (1983) study of the *QEII* storm of 10 September 1978 shows spectacular deepening while crossing SST isotherms, consistent with this result.

The mean surface cyclone moved generally northeastward on a cyclonically curving path at a speed of about 18 m s^{-1} (35 kt) while deepening most rapidly, slowing only after time +1. This speed is faster than the typical 13 m s^{-1} (25 kt) rate of cyclones and anticyclones during the winter season. Quasi-geostrophic theory (e.g., Sanders, 1971) indicates that the rapid motion is due to strong overall baroclinicity and small effective static stability. However suspect this theory may be in dealing with storms in which the relative vorticity is not small compared to the Coriolis parameter, and whatever difficulties it may have in accounting for the large deepening rates, the importance of large baroclinicity, and perhaps of small stability, in the speed of advance of the cyclone is confirmed by everyday experience.

Sanders and Gyakum (1980) pointed to the typical presence of a mobile trough at 500 mb west of the deepening center. For each bomb in the present sample each 500-mb absolute vorticity maximum possibly associated with the surface cyclone was extracted from the LFM (Newell and Deaven, 1981) operational initializations. At the time of first appearance of the surface low there was sometimes uncertainty about which vorticity center would enjoy the ultimate association. On occasion one center was associated with the early stages of the surface cyclone, only to give way to a more powerful one approaching from the west at higher latitudes as explosive deepening occurred. In a few instances the mean position of two closely spaced centers of equal intensity was taken as the nominal position. The associated vorticity center, or the more intense one in cases of ambiguity, was tracked, with mean positions appearing in Fig. 3.

At time zero this center lay on the average 635 km (345 n mi) west of the intensifying surface low center and was associated with strong cyclonic vorticity advection of $+19 \times 10^{-10}$ s^{-2} by the geostrophic wind over the surface cyclone. (This advection was obtained from the LFM initialization by multiplying the 500-mb geostrophic speed by the difference in vorticity at the ends of a 1000-km alongflow line segment centered

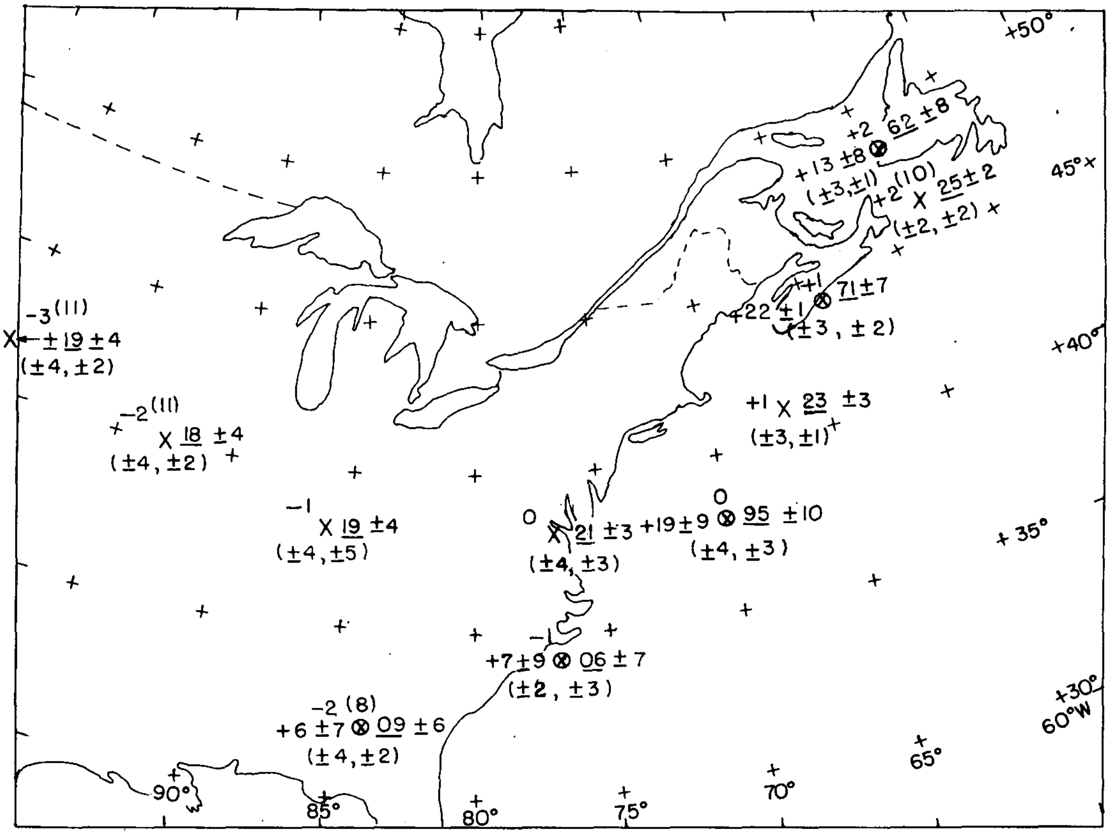

FIG. 3. For strong bombs, composite 12-hourly positions of surface low-pressure center (circled X's) and 500-mb absolute vorticity maximum (uncircled X's). Time zero, at upper left, is central time of 24-h period of maximum deepening. Mean absolute vorticity advection at 500 mb over the surface center in units of 10^{-10} s^{-2} is to left of the center position. To the right of the circled X's are tens and units digits in mb of mean central pressures, and to the right of X's are central values of mean vorticity maximum in units of 10^{-5} s^{-1}. Below are mean location information in longitude and latitude for low at time zero, otherwise in incremental longitude and latitude from position 12 h earlier. Mean positions of vorticity maxima are indicated, below, in longitude and latitude relative to concurrent surface low, except for times −2 and −3, when they are referred to positions 12 h earlier. Standard deviations are given for all mean quantities in parenthesis. Unsigned numbers in parentheses indicate number of cases available in the MIT archives, if fewer than the total number in the sample.

on the surface low.) To elaborate on the variability of this relationship beyond the bare standard deviations, Fig. 4a shows the positions of each of the 12 vorticity centers relative to the surface cyclone, which is plotted at the sample mean position. The bearings from low to vorticity maximum varied between southwest and northwest, while ranges between 210 and 1355 km (115 and 735 n mi) were observed. This vorticity center is clearly associated with the mobile trough noted by Sanders and Gyakum (1980).

At the beginning of the period of explosive deepening, 12 h earlier, Fig. 3 shows the mean vorticity center about 925 km (500 n mi) west-northwest of the surface low. The large standard deviation in latitude is attributable, as can be seen in Fig. 4b, to three instances in which the vorticity center lay far to the northwest, 1830 km (990 n mi) in the extreme case. The association with the surface cyclone was tenuous in these cases and could be mooted. At the other extreme, one center lay 480 km (260 n mi) west-southwest of the cyclone. In the mean, the vorticity advection over the surface low was cyclonic but weak.

Figure 3 shows that in all instances (save one in which the LFM maps were not available) a prominent vorticity center existed before the appearance of the nascent bomb. They were thus similar to cases described by Petterssen (1955) over the central United States and later denoted Type B (Petterssen and Smebye, 1971). These authors repeat the assertion of Petterssen et al. (1962) that Atlantic storms are of a contrasting Type A, in which there is no predecessor trough at upper levels and which develops simultaneously at all levels. Our results do not support that assertion.

Looking at the history of the mean vorticity center itself, we see brisk motion toward the east-southeast at 15 m s^{-1} (30 kt) from 36 to 12 h prior to time zero.

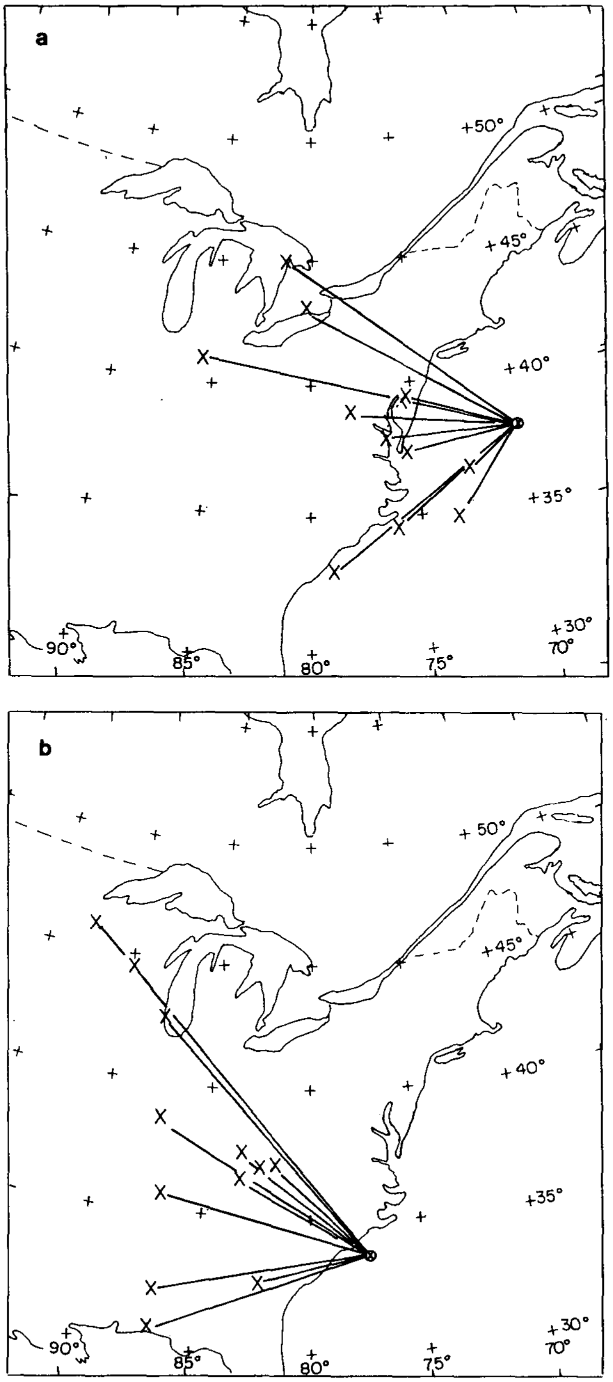

FIG. 4. For the strong bomb case, individual positions of 500-mb absolute vorticity maxima relative to surface low, plotted in its sample-mean position. (a) Time zero; (b) Time −1.

Then, when interaction with the intensifying surface storm had begun, the upper center advanced rapidly at 20 m s^{-1} (38 kt) eastward and then northeastward, overtaking and passing just south of the intensifying bomb at a distance of 220 km (120 n mi) at the end of rapid deepening. The smallness of the standard deviations of the positions of the vorticity maxima after interaction indicate that the mean is reliable there and that the large scatter in Fig. 4 was no longer present. The track of the vorticity maximum suggests a quasi-stationary planetary-scale trough between 80° and 85°W.

During this time, the mean central vorticity value at 500 mb changed little from its initial value of 19 $\times 10^{-5}$ s^{-1} prior to interaction with the bomb, then intensified to a peak of 25 $\times$ 10^{-5} s^{-1}. The implied growth of relative vorticity at upper levels was about 6 $\times$ 10^{-5} s^{-1}, or about $\frac{2}{3}$f, doubtless much smaller than the surface boundary-layer vorticity growth in the bomb.

The mean absolute vorticity advection over the surface low was cyclonic throughout, weakly so at first (when anticyclonic advection was noted in a few individual instances, possibly attributed to analysis uncertainty), peaking at the end of the period of explosive deepening, and finally weakening substantially as the 500-mb vorticity center passed by. The growth of this advection was partly due to intensification of the vorticity minimum in the downstream ridge.

The mean behavior of this strong-bomb sample resembles that reported by Chen et al. (1985) for a western Pacific cyclone development along the Kurishio. They remarked on lack of initial association with an upper-level trough, but noted later interaction with an advancing trough in higher latitudes as major intensification (apparently a moderate bomb of 1.4 bergerons in our terms) took place. Although they judged that baroclinic instability was not a factor in initial formation, close examination of their Fig. 4c suggests cyclonic vorticity advection over the nascent surface low, just west of a confluent 500-mb ridge. Thus weak baroclinic forcing appears to have been present in this Pacific case, as in our sample, even in the initial phase.

Recent theoretical work by Farrell (1984, 1985) suggests that configurations similar to those seen in this study can be analyzed as initial-value problems. Solutions show large transient growth of nonmodal waves and efficient excitation of normal modes even though the latter might not themselves be exponentially unstable.

b. Moderate bombs

The tracks of the moderate bombs during explosive deepening are shown in Fig. 5. Comparison with the tracks of strong bombs (Fig. 2) shows no similar concentration over the warm water near 38°N, 70°W. Rather, the tracks tended to lie over colder water farther north where the opportunity for transit across the strongest SST gradients is reduced.

The mean position at time zero, at 42.9°N, 63.4°W, was substantially northeast of the comparable position for strong bombs, as seen in Fig. 6. Eleven of the 16

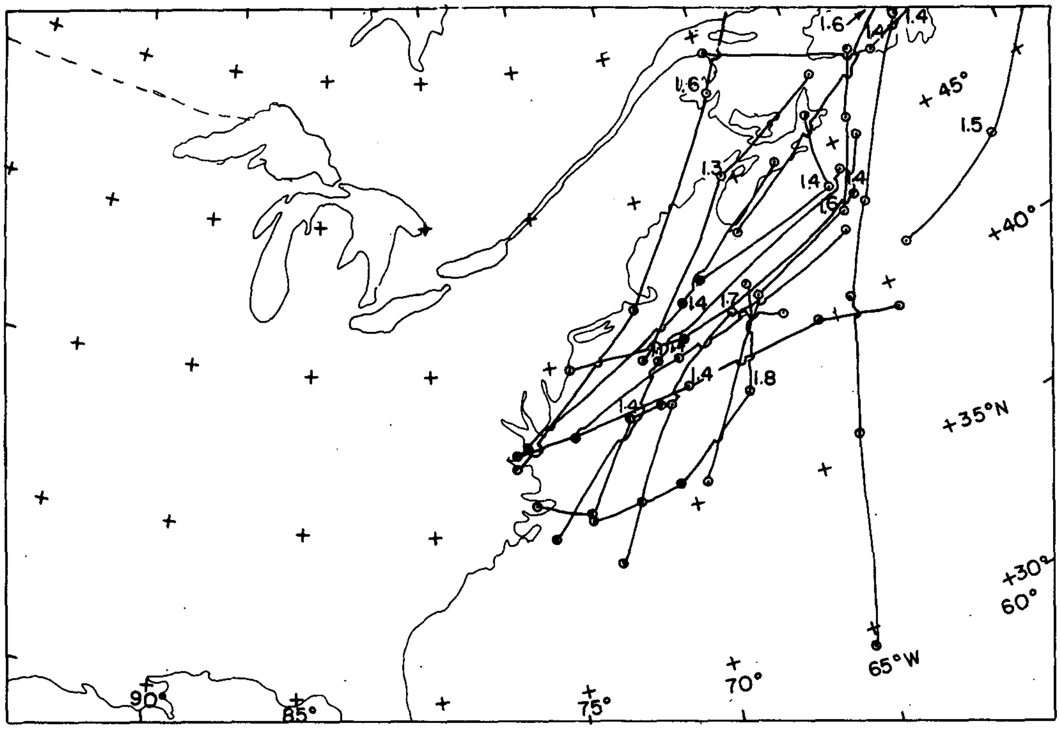

FIG. 5. As in Fig. 2 except for moderate bombs.

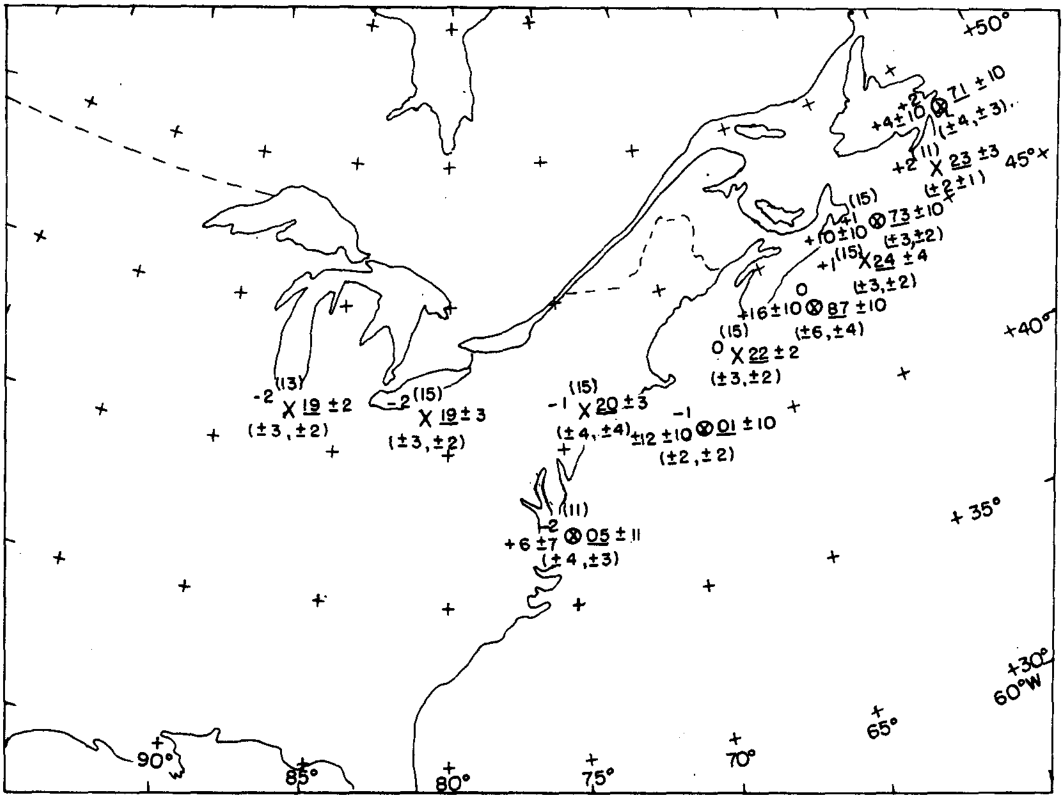

FIG. 6. As in Fig. 3 except for moderate bombs.

cyclones had appeared 24 h earlier but only five prior to that time. The mean speed was distinctly slower than for strong bombs and the mean track was decidedly more zonal. Thus the mean point of origin at time -2 was northeast of the point for strong bombs, but by time $+2$ it lay to the east. These differences probably represent the chance effects of sampling.

The mean deepening of the moderate bomb was comparable to that of the strong bomb, except for the lack of the 12-h period of extraordinary pressure fall as the strong center traversed the region of intense gradient of SST. The somewhat lower pressure of the mean moderate bomb through time zero and its generally northeastward position indicate that by chance the moderate sample represented a slightly later time in the life history of the event than was the case with strong bombs.

The mean associated 500-mb vorticity center likewise started farther north and moved more slowly and more zonally than its strong-bomb counterpart. Similarly, it overtook the surface cyclone and ended south of it at a modest distance of about 200 km.

Until time zero, the mean intensity of the vorticity center was slightly but insignificantly greater than for the strong-bomb sample. Its subsequent increase was not as rapid, however, and terminated more quickly, confirming that this sample was taken somewhat later in the deepening episode and suggesting that much of the interaction occurs in a single 12-h period.

The individual positions of vorticity centers relative to the surface center at time zero (Fig. 7a) shows a smaller scatter than in Fig. 4a. In fact, the distribution 12 h earlier (Fig. 7b) more nearly resembles the time-zero distribution for strong bombs. The outliers far to the north-northeast of the surface center in Fig. 7b illustrate the range of possibilities. The case producing the extreme one of this pair will be discussed later.

Vorticity advections over the surface cyclone started out at time -2 as in the strong-bomb cases. A substantial increase from $+6$ to $+12$ ($\times 10^{-10}$ s^{-2}) occurred, however, at time -1, reflecting the later point in the process of overtaking of the surface system by the 500-mb maximum. Peak values fell substantially below those for strong bombs, despite a comparable strong vorticity maximum. It appears that the overall horizontal temperature gradients were likely somewhat weaker in the moderate bomb case, accounting for both the smaller peak vorticity advection at 500 mb and the slower track speeds of the surface cyclone and the 500-mb center.

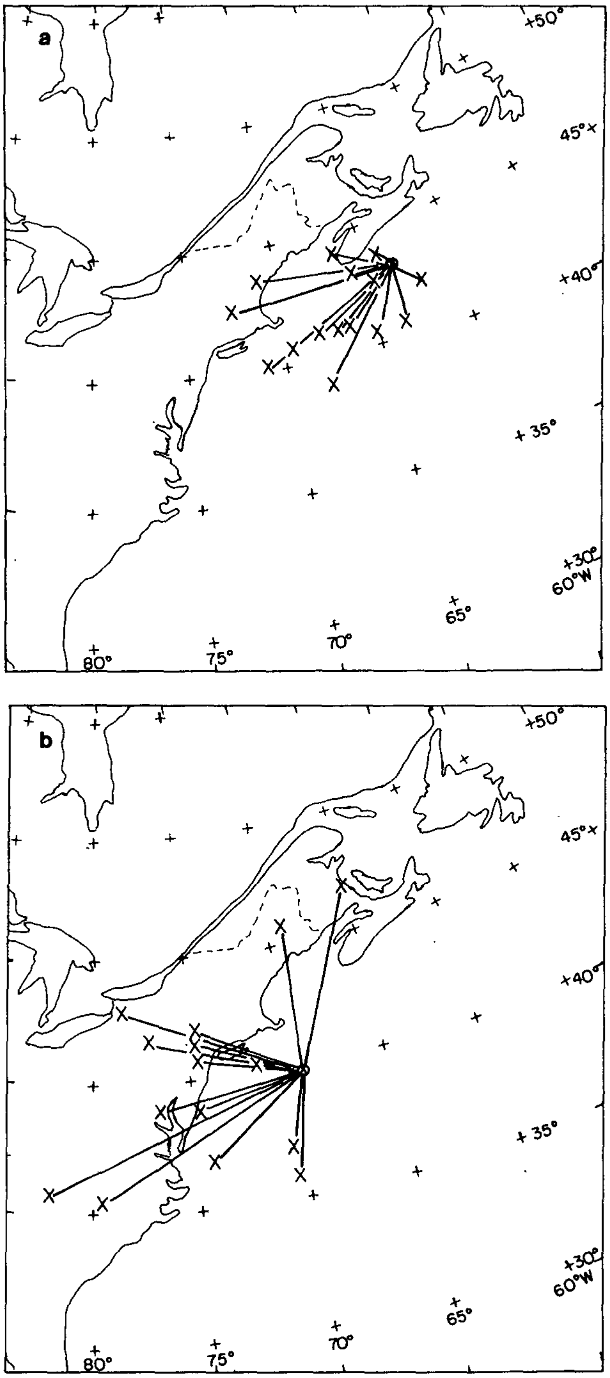

FIG. 7. As in Fig. 4 except for moderate bombs.

c. Weak bombs

The 20 remaining bombs with growth rates not exceeding 1.2 bergerons followed the tracks shown in Fig. 8. They were widely scattered. About a third never experienced the warm water in and southwest of the Gulf Stream, while another third traversed the region of strong SST gradient on its northern flank without the extreme deepening seen in the strong-bomb sample.

The composite in Fig. 9 shows mean tracks for both surface and 500 mb centers, which more nearly resemble their counterparts for the strong-bomb than for the moderate-bomb sample. The surface track in this weak-bomb picture, however, started perhaps 200 km farther

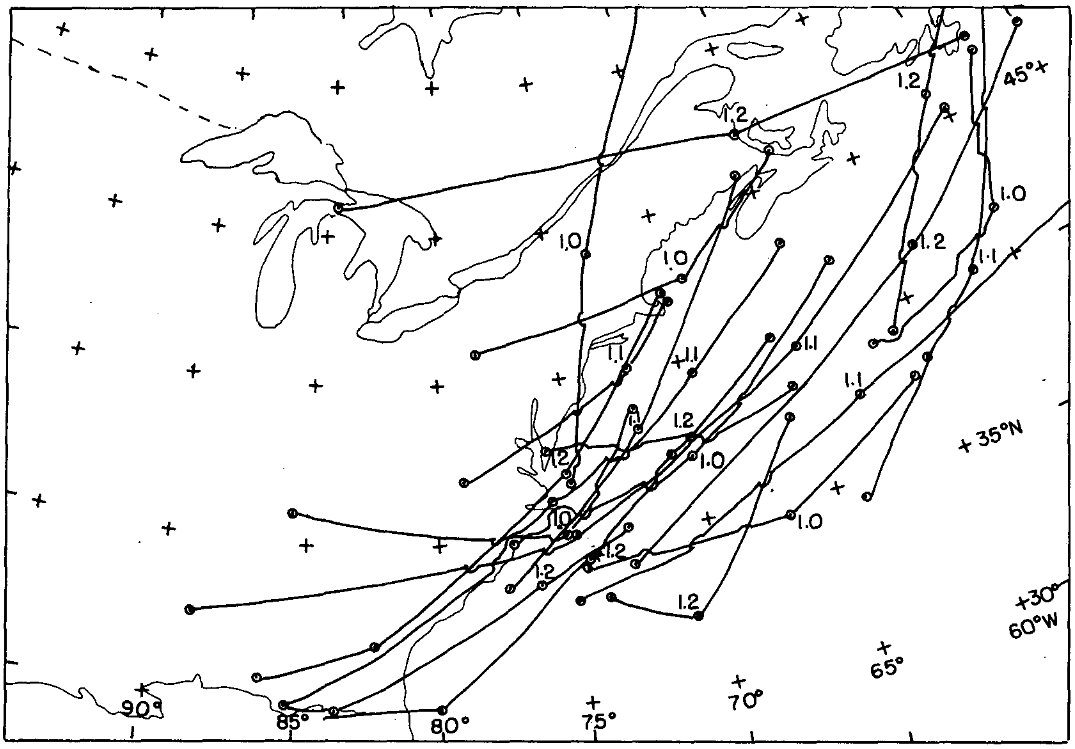

FIG. 8. As in Fig. 2 except for weak bombs.

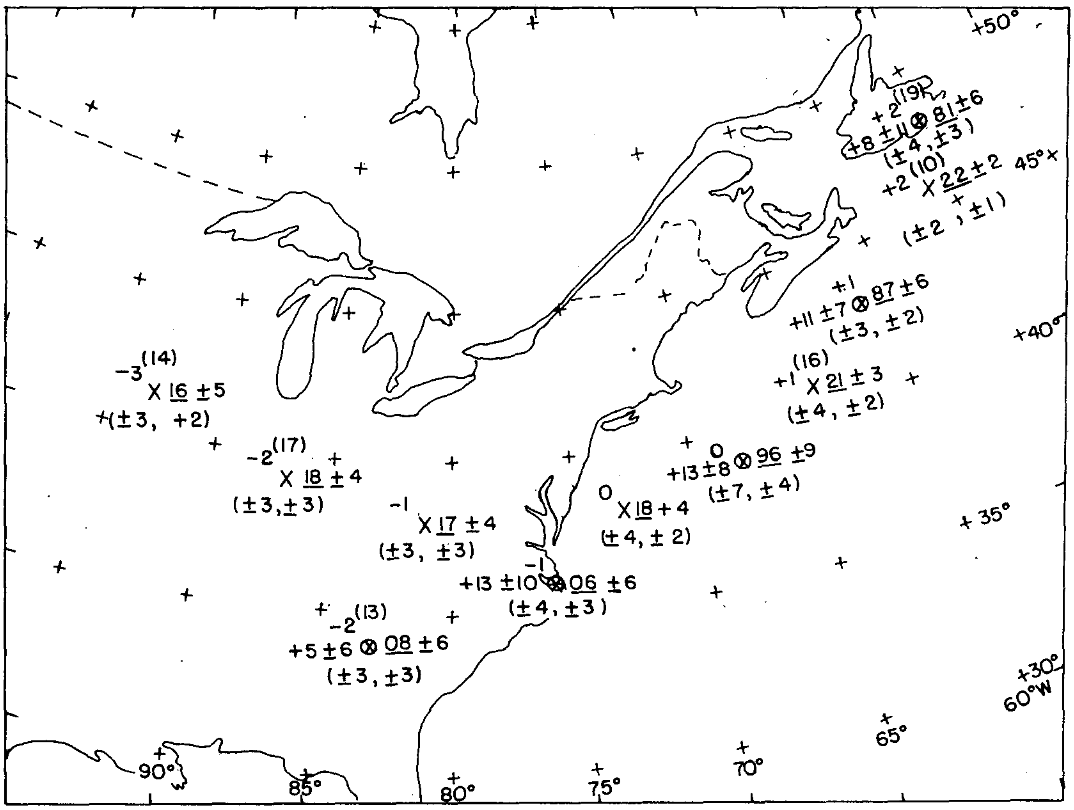

FIG. 9. As in Fig. 3 except for weak bombs.

north at time -2, indicated a somewhat more zonal direction and slower speed, and spent less time over warm water. In 10 of the 20 cases, the low existed prior to this time. At the upper level, the vorticity center on the average followed a track almost identical to that for the strong bombs, but at a speed about 2.5 m s^{-1} (5 kt) slower. Thus, this sample, as well as the one for moderate bombs, suggests somewhat less overall baroclinicity. As with the other samples, the vorticity maximum could be identified at least as early as time -3, provided it was within the map area and the LFM maps were available.

As with the other samples, the mean 500-mb vorticity center tended to overtake the surface cyclone, as the orientation between the two rotated clockwise from northwest–southeast to south–north. Close comparison of Figs. 3 and 9 suggests that the weak-bomb sample also represented a slightly later time in the development than did the strong cases. The individual cases depicted in Figs. 10a and 10b resemble their counterparts in Figs. 4a and 4b, except for a slight clockwise rotation of the whole group and the presence of numerous vorticity maxima in the weak cases closer to the surface center than the closest of the strong cases. The weaker cases were also characterized by a smaller distance separation of upper and lower features at time -2. The intensity of the mean vorticity maximum for the weak cases was substantially weaker than for the other samples through the period. The upper-level vorticity advection over the surface center started with the same modest cyclonic mean value, increased to $+13 \times 10^{-10}$ s^{-2} at time -1 but then increased no further. The sequence of vorticity advections and surface central pressures behaved very similarly to the corresponding features in the moderate-bomb sample, but with smaller overall intensity.

3. Summary of mean behavior

The behavior described above is summarized in Figs. 11–13. In the first of these, the 12-h period of extraordinary deepening from time zero to +1 sets the strong bombs apart from the others. The relative lack of vigor of the weak bombs is matched by the relative weakness of the associated 500-mb absolute vorticity maximum.

Figure 12 makes explicit the motion of this vorticity center relative to the surface cyclone. The relative track for each of the three samples is an inward spiral beginning northwest of the nascent bomb and ending nearby to the south of the developed storm. The strong cases are distinguished from the others by the substantially greater initial separation distance and the greater relative speed of the vorticity maximum.

The mean 500-mb geostrophic vorticity advection over the surface center, averaged at the beginning and end of a 12-h period, is plotted in Fig. 13 against the mean deepening of the surface center over the same period, for each of the three samples. The relationship is surprisingly close in view of the limitations of analysis at upper levels over the ocean. The uncertainties have doubtless been reduced by averaging results for a number of cases within each sample, but there is little evidence of bias. The regression line illustrated the relationship

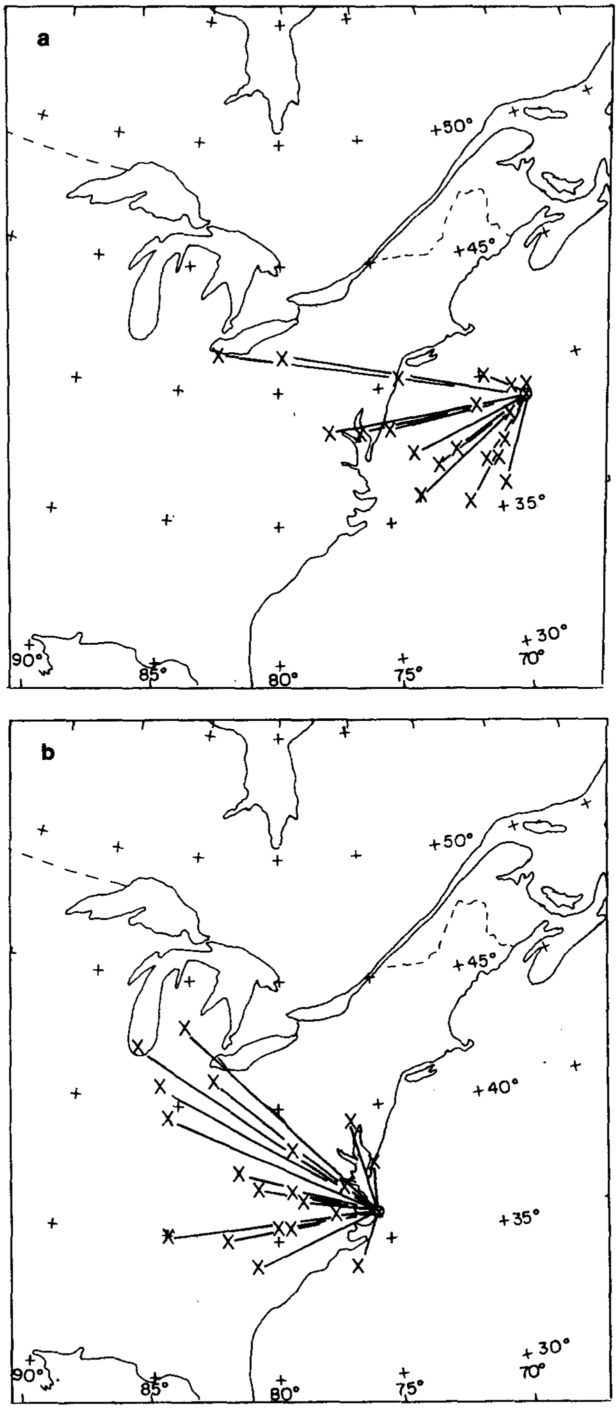

FIG. 10. As in Fig. 4 except for weak bombs.

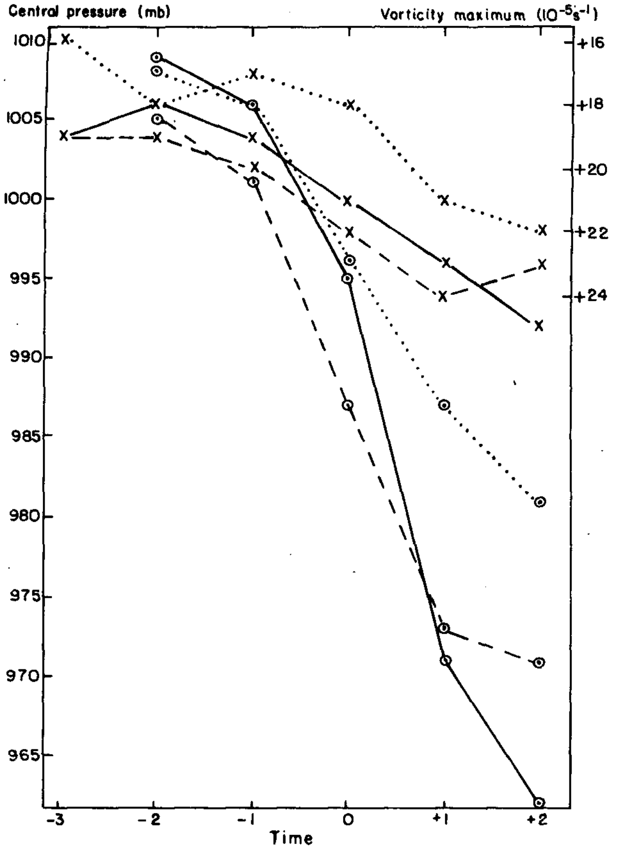

FIG. 11. Central pressure of mean surface bombs (circled dots) and values of mean 500-mb absolute vorticity maximum (X's) from time −3 to time +2. Strong-, moderate- and weak-bomb samples are indicated by solid, dashed and dotted lines, respectively.

$$y = -6.73 + 1.31x; \quad r = 0.872$$

where x is the 12-h surface deepening in mb, y is the estimated absolute vorticity advection over the surface center in units of 10^{-10} s^{-2}, and r is the correlation coefficient. If the two outlying points (for strong bombs at times zero and +1) are disregarded, the regression equation becomes

$$y = -8.87 + 1.552x; \quad r = 0.924.$$

One might have expected the points for the 12-h period beginning at time +1, when the cyclone was mature, to lie to the lower right of the regression line. That is, common experience indicates that a certain amount of baroclinic forcing is required to sustain an intense cyclone against surface dissipation, and Petterssen and Smebye (1971) found in an analysis of the energetics of two North American storms that this dissipation constituted an effective brake on development. Our results, except for the strong-bomb sample, failed to show this effect. It is possible that the mature and intense oceanic cyclone is sustained in part by deep, perhaps slantwise, convective flux of latent and sensible heat received from the sea surface, as recently argued for tropical cyclones by Emanuel (1986).

These considerations aside, Fig. 13 constitutes strong evidence that oceanic bombs are essentially baroclinic disturbances forced by the same mechanism that operates over land. A similar finding was presented by Rogers and Bosart (1986) in a study of intense cyclogenesis mainly in the central North Atlantic. That the response to the baroclinic mechanism is so large, as found by Sanders and Gyakum (1980) and by Anthes et al. (1983), is likely due to more exotic physical effects.

It should be emphasized that the sample-mean results shown in Figs. 11–13 cannot be uncritically applied to individual cases. They refer to means of samples of modest size in which the vagaries of individual cases, whether due to inadequacies of analysis or to variations in atmospheric behavior, have been smoothed out. A typical case and an anomalous case are next presented in some detail.

4. Two cases

a. 12–15 February 1982

This storm, at 2.8 bergerons the most explosive in our sample of bombs, was responsible for the destruction of the oil rig *Ocean Ranger* east of Newfoundland

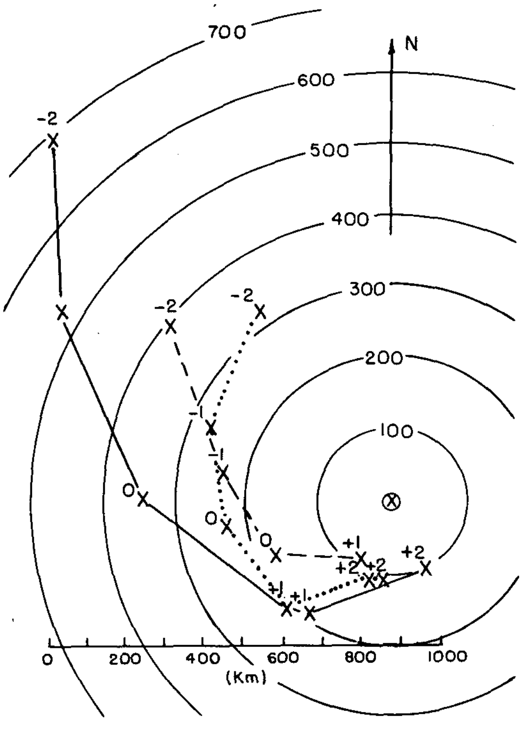

FIG. 12. Position of 500-mb absolute vorticity maximum relative to surface cyclone center from time −2 to time +2. Strong-, moderate- and weak-bomb samples are denoted by solid, dashed and dotted lines, respectively. Range circles are at intervals of 100 m (185 km), and a kilometer scale is provided. The motion of the surface cyclone relative to the upper level vorticity center can be visualized by rotating the figure 180° and interchanging the identities of the centers.

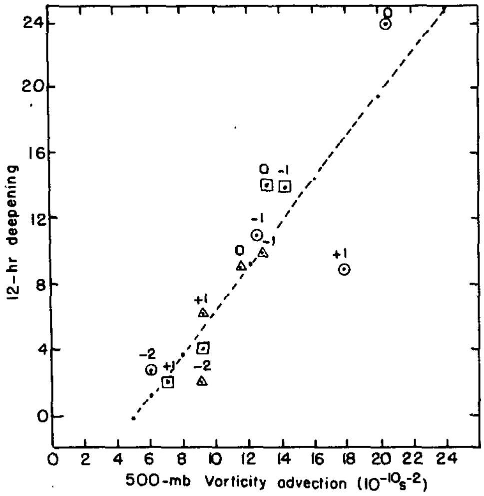

FIG. 13. Mean 500-mb absolute vorticity advection over the surface cyclone center averaged over 12-h periods versus 12-h drop in central pressure. The time period is denoted by the value at its beginning. Strong, moderate and weak samples are indicated by circles, squares and triangles, respectively.

and the sinking of the nearby Soviet container ship, *Mekhanik Tarasov,* with a total loss of 116 lives. The structure and behavior of this storm is illustrated by the series of LFM initial patterns of sea level pressure and thickness of the layer from 1000 to 500 mb in Fig. 14.

At 1200 GMT 12 February a trough of low pressure over Mexico extended over the western Gulf of Mexico, while an unrelated 500-mb trough lay over the south-central United States, with maximum absolute vorticity of 17 × 10^{-5} s^{-1}, rather unimpressive for a nascent strong bomb. This maximum had originated several days earlier above strong downslope easterlies in the Alaska Panhandle, had migrated southward along the west coast of North America and then had moved eastward across the continent. Only weak surface structure had accompanied this system. The flow was broadly confluent over the central and eastern United States, and overall thickness gradients were stronger near the East Coast than elsewhere.

Twelve hours later, the LFM model had correctly predicted eastward motion of the vorticity maximum at about 15 m s^{-1} (30 kt) with little change in intensity. The model had also correctly indicated the appearance of a weak new surface low, but at a position about 400 km (220 n mi) southwest of the correct location, shown by coastal and ship's observations to lie just offshore in the Atlantic along the strong temperature gradient flanking the Gulf Stream. Although the strongest cyclonic vorticity advection associated with the upper trough likely lay well northwest of both the predicted and actual center, substantial advection was indicated by the barotropic initialization (the 500-mb LFM panel being unavailable), and interaction with the upper feature appeared to be under way at an early stage.

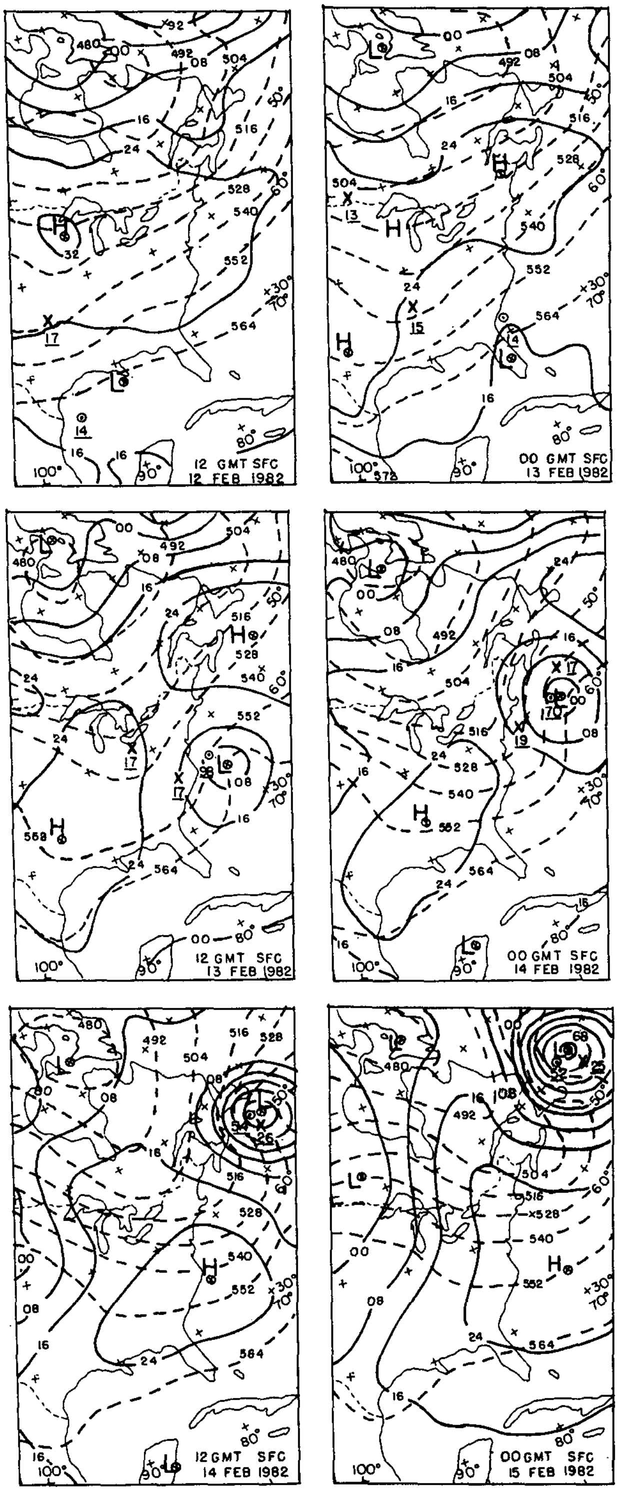

FIG. 14. LFM initializations of sea level isobars at intervals of 8 mb (solid) and of isopleths of thickness 100–500 mb at intervals of 12 dam. Times are as indicated from 12 to 15 February 1982. Patterns for 0000 GMT 13 February are 12-h forecasts. The X's with underlined digits show the position and intensity of relevant vorticity maxima. The dots and underlined digits show the position and central sea level pressure of surface lows as derived from manual analyses. Units of vorticity are 10^{-5} s^{-1} and of pressure the tens and units digits are in mb.

Rapid 18 m s^{-1} (35 kt) motion eastward at 500 mb and northeastward at the surface, with strong development at sea level, characterized the next 12 h. By 1200 GMT 13 February the surface cyclone lay east of the oncoming upper vorticity maximum. At this time the LFM initialization showed a low center of 1004 mb, but ship's observations with winds up to 20 m s^{-1} (40 kt) and pressures as low as 1001 mb indicated without question a position substantially northwest and a pressure substantially lower than shown in the LFM initialization. This time turned out to be time zero. The resemblance to the pattern in Fig. 3 is close, aside from the location southwest of the mean and the continuing lack of impressiveness in the 500-mb vorticity center. An additional atypical feature in this instance was a second vorticity maximum northwest of the one being tracked. This second feature had moved rapidly from the west-northwest and was about to merge with the first.

The next initialization, for 0000 GMT 14 February, showed accelerating motion of the bomb toward the northeast at about 20 m s^{-1} (40 kt). A manual surface analysis placed the low center about 100 km (55 n mi) north of the initialized position, in quite good agreement, but the analyzed pressure minimum of 970 mb was not even approached by the initialized value of 997 mb. No ship reported close to the center, the lowest transmitted value being 990 mb about 220 km (120 n mi) southeast of the initialized center position. Six hours earlier a ship had observed 996 mb with a southwesterly wind of 30 m s^{-1} (60 kt), and 6 h later the Sable Island observation showed 974 mb and gale-force winds, so there can be little doubt that the initialization was seriously deficient.

At 500 mb the two aforementioned vorticity centers were shown as merged into a somewhat enhanced one atypically far west of such a strongly developed surface cyclone. Worse, a new center of nearly equal strength was depicted northeast of the surface low, so that the calculated vorticity advection over it was only 7×10^{-10} s^{-1}, by far the smallest value in the strong-bomb sample at time +1. Thus the initialization was suspect at upper levels as well as at the surface.

By 1200 GMT of the 14th the initializations were in better agreement with both the manual surface analysis and the strong-bomb composite (Fig. 3). The subjectively analyzed minimum pressure of 954 mb, still 16 mb deeper than the initialized value, was not supported by any direct observation near the center, but 983 mb with northwesterly winds of 40 m s^{-1} (80 kt) at an oil rig just east of Sable Island and easterlies of 35 m s^{-1} (70 kt) on the east coast of Newfoundland, with pressure of 984 mb, implied a very deep low. The oil rig, moreover, reported a 23-mb pressure rise in the preceding 3 h, implying a 960-mb value there at 0900 GMT. The pressure and change at Sable Island (988 mb with a rise of 29 mb) similarly implied a 959-mb value there at 0900 GMT. Thus there was much indirect evidence for a pressure at least as low as that analyzed. Analyzed and initialized positions of the bomb were in reasonable agreement.

The upper-level vorticity maximum had now increased to a typically large value and was shown in the initialization a typically small distance south of the surface bomb.

At 0000 GMT of 15 February the initialized central pressure has finally come into approximate agreement with the analyzed one. The position of the initialized 500-mb vorticity maximum appeared reasonable, but the corresponding surface low center again lay distinctly southeast of the analyzed one. A report of west-southwesterly winds of 38 m s^{-1} (75 kt) was received from a position close to that of *Ocean Ranger,* with the analysis implying northwesterlies at least as strong just to the northwest. This sector of an intense cyclone was found by Buckley (1983) and by Hamilton (1980) to be favored for the production of extreme waves. These were presumably responsible for the casualties, which occurred shortly after the time of this initialization.

b. 24–26 October 1983

The preceding example, qualifications aside, displayed a structure and behavior in generally good agreement with the composite in Fig. 3. Lest it be thought that application of the composites be a panacea, however, we present now a moderate bomb of relatively little strength recommended mainly on account of its bizarre relationship to the 500 mb vorticity field. Maps appear in Fig. 15.

At 0000 GMT 24 October a weakly defined surface low lay in the Carolinas, North or South depending on whether one prefers analysis or initialization. At 500 mb a modest absolute vorticity maximum was found about 740 km (400 n mi) to the west. The surface feature had moved northeastward over the preceding day while the 500 mb maximum had moved slowly east-southeastward, having been in existence for a number of days. That development was sluggish was attributable to the general weakness of temperature gradients as shown by the thickness pattern in the central and eastern United States. A separate vorticity center lay far to the north-northeast, associated with a cold trough over eastern Canada.

The next initialization shows the surface low on the Atlantic coast with no change in central pressure, while the analysis places it again about 300 km (160 n mi), again to the northeast. At the upper level, the southern vorticity maximum continued slowly east-southeastward while the northern one remained about 1440 km (780 n mi) north-northeast of the surface low, with slowly growing intensity. The baroclinic zone between these two had strengthened perceptibly.

This frontogenesis in the path of the surface center continued as the surface low moved slowly eastward close to the 40th parallel by 0000 GMT on the 25th. The southern vorticity maximum moved even more

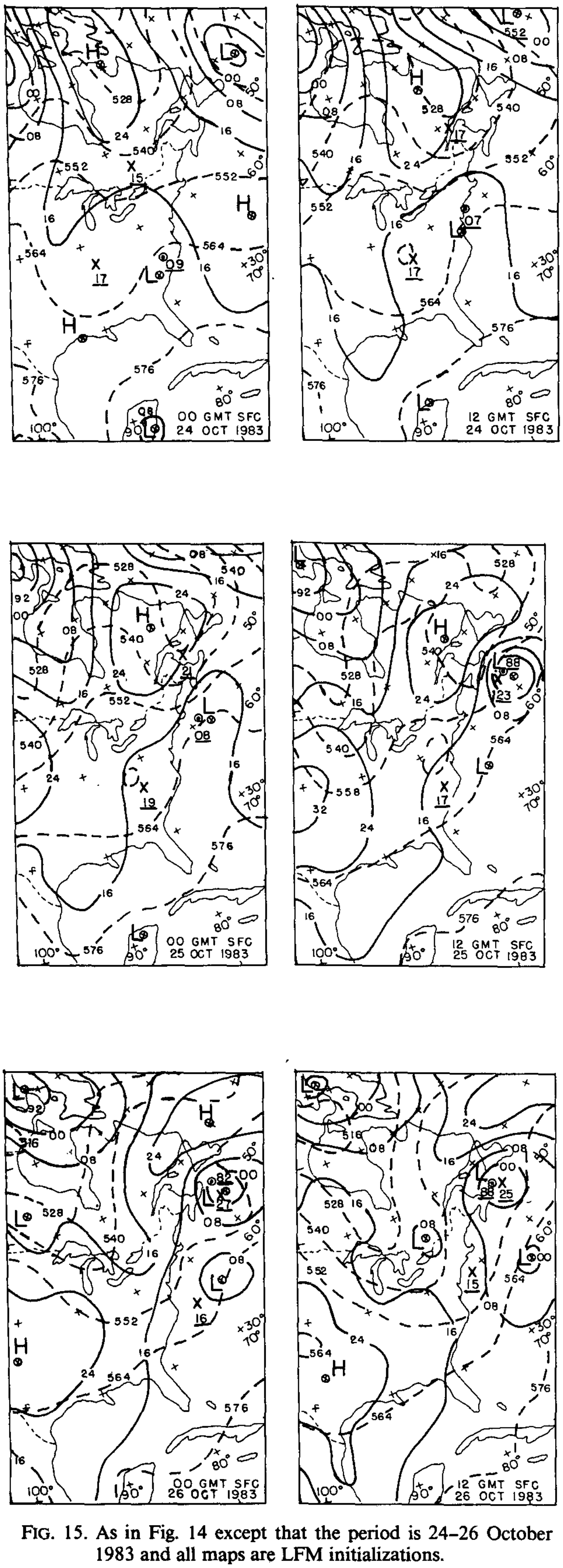

FIG. 15. As in Fig. 14 except that the period is 24–26 October 1983 and all maps are LFM initializations.

slowly, so that its association with the surface low appeared at an end. This type of situation is characterized by a "breakaway" low, which propagates rapidly eastward along the isotherms without much change of intensity, leaving the old upper-level system behind. The northern vorticity center in this case continued to grow as it approached the cyclone from the north-northeast.

Explosive deepening then suddenly and unexpectedly occurred, accompanied by strong interaction between the surface system and the northern vorticity center. By 1200 GMT 25 October the surface bomb was near Sable Island (rather nearer and deeper in the manual analysis than in the LFM initialization), and the growing 500-mb vorticity center was close by to the west. The old vorticity center was approaching the mid-Atlantic coast and had produced a new, weak cyclone over the warmer water to the east.

There was little motion of either the surface low or the vorticity center near Sable Island over the next 24 h. At 0000 GMT on the 26th there was 13 mb discrepancy between the initialized and the more intense analyzed surface pressure center. It appears that the observation from Sable Island had little effect on the initialized pattern. At 500 mb the vorticity maximum became very intense, then weakened as the surface center filled by 1200 GMT on the 26th.

It is noteworthy that the manual analysis placed the surface low north of the initialized position on all six maps of this series (and on most of the maps in the February 1982 series as well). It seems that the automated system seeks to smooth gradients by moving the center away from the region of intense gradient toward the region of sparse data coverage.

5. Conclusions and comments

We have studied explosive cyclogenesis over the west-central North Atlantic, a region infamous for the violence of its storms, from 1981 to 1984. Identifying bombs according to Sanders and Gyakum's (1980) criterion, we stratified them into samples of 12 strong, 16 moderate and 20 (relatively) weak cases. Composite patterns of motion and depth of the surface center are comparable for each of the three samples.

1) There was rapid northeastward motion, particularly fast and particularly meridional for strong bombs.

2) Strong bombs traveled a somewhat greater distance over warm water east and south of the Gulf Stream.

3) Rapid deepening occurred over a period of 24–36 h. Strong bombs displayed a spectacular mean deepening of 24 mb in 12 h while crossing the region of strong SST gradient on the north flank of the Gulf Stream.

4) This behavior is consistent with Sanders and Gyakum's (1980) identification of the north and west flanks of the Stream and of the Kuroshio as preferred

bomb locations. The relationship to warm water and strong SST gradient seems contributory although not crucial to deepening, since numerous bombs occur in the northeastern portions of the Pacific and Atlantic where the sea is relatively cool and isothermal, and since one can find individual exceptions also in our area of study.

5) A prominent absolute-vorticity maximum at 500 mb approached the bomb during deepening along a relative path of spiral form, starting far to the northwest and ending close by to the south.

6) This vorticity maximum preexisted the surface cyclone in all cases. The initial surface development seemed on occasion independent of the maximum but was characterized in any event by weak cyclonic vorticity advection overhead.

7) The upper vorticity maximum strengthened during interaction with the surface storm, but the vorticity growth at 500 mb was much smaller than that in the surface boundary layer.

8) For the three sample means, the average vorticity advection at the beginning and end of a 12-h period was highly correlated with the simultaneous 12-h deepening for periods starting 24 h before maximum deepening and ending 24 h afterward. Attributing much scatter in individual cases to uncertainties of oceanic analysis, we find this result to be strong evidence of the fundamentally baroclinic character of the bomb. The large response to the baroclinic forcing is likely due to small effective static stability brought about in the first instance by fluxes of latent and sensible heat from the sea surface, together with small dissipation over the relatively smooth sea surface.

9) From detailed analysis of two individual cases it is clear that many bombs may behave close to the sample mean, but an occasional one may be quite aberrant in its relationship to the 500-mb vorticity field. It is also clear that good analysis is not as easily achieved over the ocean as over a midlatitude continent. The effort is necessary, however, if satisfactory prediction of bombs is to be achieved.

Acknowledgments. The author wishes to acknowledge the benefit of discussions with William H. Buckley of the David W. Taylor Naval Ship Research and Development Center, Kerry Emanuel of MIT and Brian Farrell of Harvard University. He is grateful to Isabelle Kole for the drafting of figures and Laura Doughty for the processing of these words. This research was supported by the Office of Naval Research, under Contract 00014-84-C-0660.

REFERENCES

Anthes, R. A., Y.-H. Kuo and J. R. Gyakum, 1983: Numerical simulation of a case of explosive marine cyclogenesis. *Mon. Wea. Rev.*, **111**, 1174–1188.

Bergeron, T., 1954: Reviews of modern meteorology—12: The problem of tropical hurricanes. *Quart. J. Roy. Meteor. Soc.*, **80**, 131–164.

Buckley, W. H., 1983: A study of extreme waves and their effects on ship structures. Rep. No. SSC-320. David W. Taylor Naval Ship Research and Development Center, Bethesda, MD 20084, 82 pp. [Available through National Technical Information Service, Springfield, VA 22161].

Chen, T.-C., C.-B. Chang and D. J. Perkey, 1985: Synoptic study of a medium-scale oceanic cyclone during AMTEX'75, *Mon. Wea. Rev.*, **113**, 349–361.

Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585–604.

Farrell, B., 1984: Modal and nonmodal baroclinic waves. *J. Atmos. Sci.*, **41**, 668–673.

——, 1985: Transient growth of damped baroclinic waves. *J. Atmos. Sci.*, **42**, 2718–2727.

Gyakum, J. R., 1983: On the evolution of the *QEII* storm. I: Synoptic aspects. *Mon. Wea. Rev.*, **111**, 1137–1155.

Hamilton, G. D., 1980: Buoy capsizing wave conditions. *Mariners Wea. Log*, **24**, 165–173.

LeBlond, P. H., 1984: Final report of the investigation on the storm of October 11–12, 1984 on the west coast of Vancouver Island. Report to Minister of the Environment, House of Commons, Ottawa, Ontario, Canada, 314 pp.

Newell, J. E., and D. G. Deaven, 1981: The LFM-II model—1980. NOAA Tech. Memo. NWS NMC 66, 20 pp. [Available from Environmental Science Information Center (D822), NOAA 6009 Executive Blvd., Rockville, MD 20852.]

Petterssen, S., 1955: A general survey of factors influencing development at sea level. *J. Meteor.*, **12**, 36–42.

——, and S. J. Smebye, 1971: On the development of extratropical cyclones. *Quart. J. Roy. Meteor. Soc.*, **97**, 457–482.

——, D. L. Bradbury and K. Pedersen, 1962: The Norwegian cyclone models in relation to heat and cold sources. *Geophys. Publ.*, **24**, 243–280.

Riehl, H., 1980: Some aspects of the advance in the knowledge of hurricanes. *Pure. Appl. Geophys.* **119**, 612–627.

Roebber, P. J., 1984: Statistical analysis and updated climatology of explosive cyclones. *Mon. Wea. Rev.*, **112**, 1577–1589.

Rogers, E., and L. F. Bosart, 1986: A investigation of explosively deepening oceanic cyclones. *Mon. Wea. Rev.*, **114**, 702–718.

Sanders, F., 1971: Analytic solutions of the nonlinear omega and vorticity equations for a structurally simple model of disturbances in the baroclinic westerlies. *Mon. Wea. Rev.*, **99**, 393–407.

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