

## Statistical Analysis and Updated Climatology of Explosive Cyclones

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### ABSTRACT

A statistical analysis of 12 and 24 hour deepening rates for all surface lows analyzed on at least two successive NMC 12 hourly "front half" hemispheric surface charts was performed for one year of data. Both 12 and 24 hour deepening distributions showed statistically significant (at the 5% level) departures from normality, with the largest deviations occurring along the tail of the distribution associated with most rapid deepening. The sum of two normal curves of different means and standard deviations was successfully fitted to the deepening distributions, suggesting that most cases of explosive cyclogenesis are the result of some additional physical mechanism distinct from ordinary baroclinic instability.

The climatology of explosive cyclones (Sanders and Gyakum) was updated to include the 1979–82 cold seasons, and compared to the previous three-year sample. In addition, a climatology of formation positions, maximum deepening positions and dissipation positions for all cyclones in a one-year data sample was compiled. These studies indicate that the preferred regions of explosive cyclogenesis are primarily baroclinic zones; the climatological and statistical evidence therefore suggests that the explosive mechanism is a combination of the baroclinic process and some other mechanism or mechanisms.

### 1. Introduction

The emphasis of this research on explosively developing cyclones (bombs) has been to obtain some significant statistical evidence that such storms are in some way manifestations of a process or processes above and beyond ordinary baroclinic instability. Gyakum (1983a,b) and Bosart (1981) have addressed this issue through extensive individual case studies. The statistical approach provides a means of addressing the same question in a generalized rather than case specific manner. Inadequate data coverage is often a serious problem in the regions of interest. The statistical analysis of deepening rates is advantageous in this respect since it does not require detailed data. However, this approach necessitates that one forgo any added insights into the physics of the actual deepening process (or processes).

Assuming that such statistical evidence is found, it would provide further incentive to investigate the actual physical mechanism(s) responsible for explosive cyclogenesis, such as the role of convective latent heat release. The climatology of "bombs", updated from Sanders and Gyakum (1980), and expanded to include lesser cyclones, provides a basis for evaluating crudely the relationship between rapid deepeners and more moderate baroclinic disturbances.

### 2. Data base

In order to carry out a statistical analysis of deepening rates and compile a climatology of cyclones, it was first necessary to acquire an adequate data base. All surface lows of a predominantly baroclinic nature (i.e., excluding thermal lows and tropical storms) that were analyzed on at least two successive National Meteorological Center (NMC) 12 hourly "front half" hemispheric surface charts were tracked for the extent of their identifiable existence. The period of record began in February 1980 and ended in January 1981. The skewed one year sample was chosen to minimize the data missing from the Massachusetts Institute of Technology archives, but the resultant break in continuity for the 1979–80 and 1980–81 cold seasons is not believed to be statistically significant.

The latitude–longitude coordinates and central pressure as analyzed on the NMC charts were recorded at 12-hour intervals for as long as each storm was maintained as a distinct entity. The area considered ranged from 130°E eastward to 10°E. Surface lows that moved out of this area, or had transformed from tropical storms to midlatitude baroclinic disturbances were "flagged" for special treatment. The raw data were condensed in the following manner: the formation position, position of maximum deepening and dissipation position were recorded for each system, along with the date, time and magnitude of the maximum 12 and 24 hour pressure falls.

The formation position was taken to be the first

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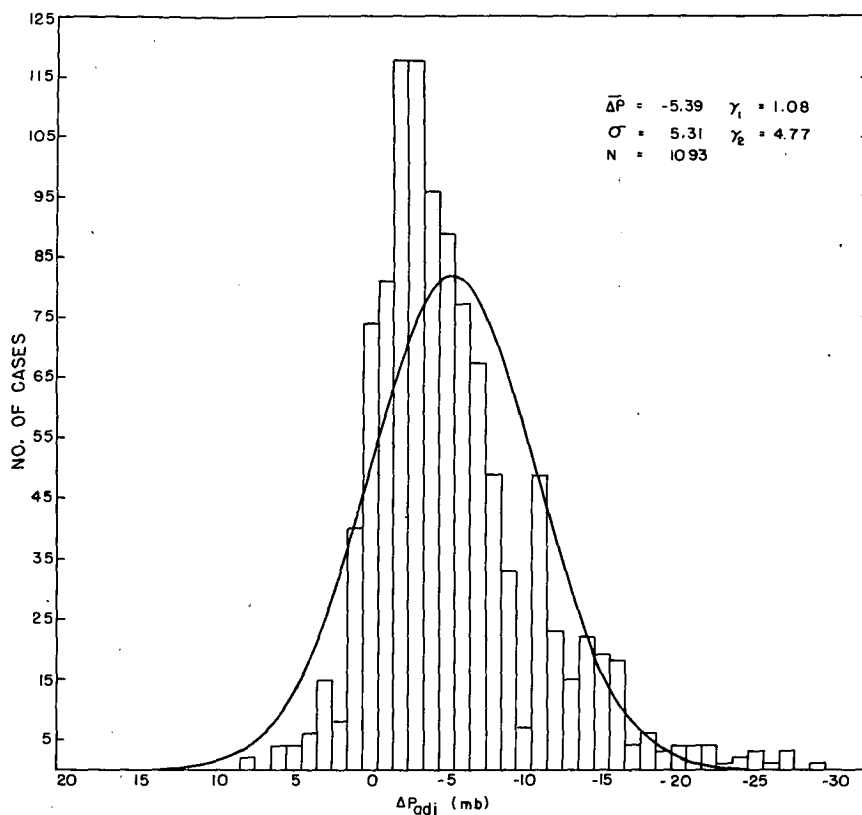


FIG. 1. Twelve-hour deepening distribution, one-year data:  $\Delta P$  and  $\sigma$  are the sample mean and standard deviation;  $N$  is the total number of cases;  $\gamma_1$  and  $\gamma_2$  are the coefficients of skewness and kurtosis, respectively, measures of the relative centeredness and peakness of the distribution. The solid line represents the least-squares fit Gaussian distribution.

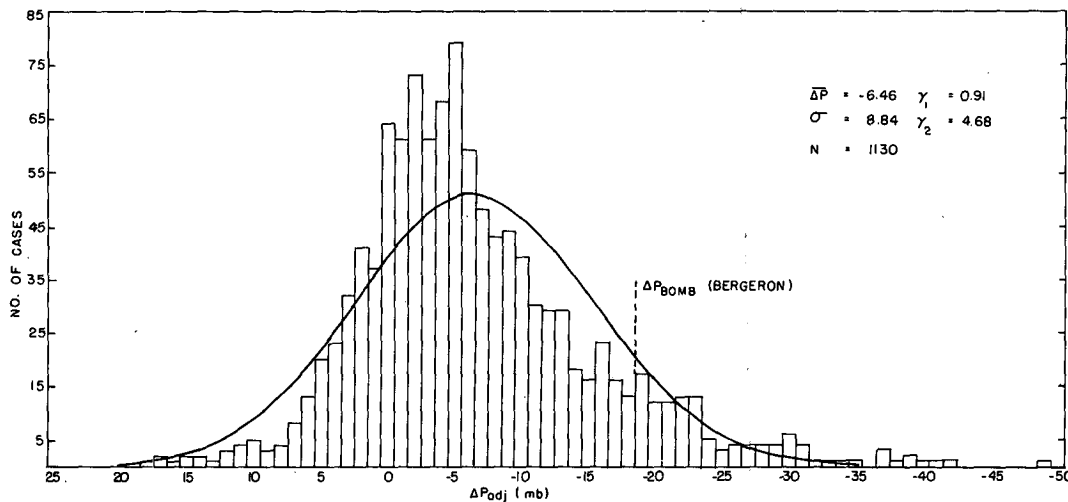


FIG. 2. Twenty-four hour deepening distribution, one-year data. The dashed line indicates the Bergeron definition of a bomb; points to the right of the line are bombs.

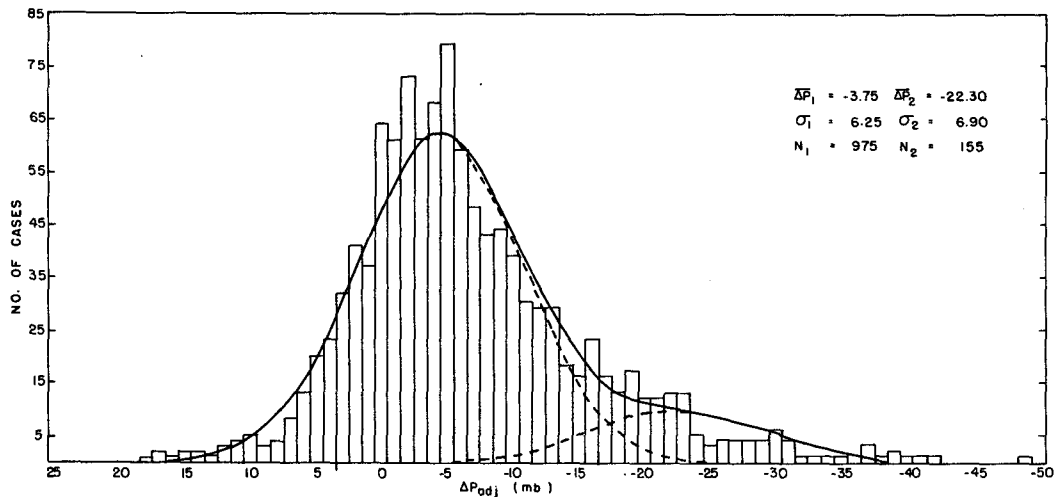


FIG. 3. Twenty-four hour deepening distribution, one-year data. The solid line indicates the sum of two normal curves, the dashed lines indicate the two separate curves.

analyzed position of the storm, provided it was determined that it had not simply moved from a previous location off the map. Any system that formed out of the range of coverage was not included in the compilation of formation positions. Cyclones that were transformed in nature from that of a tropical storm

to a baroclinic disturbance were also excluded from the formation position data.

The maximum deepening position was taken to be the position of the storm centered over the 24-hour interval of most rapid deepening; thus, the position of maximum 24-hour deepening was the position of the

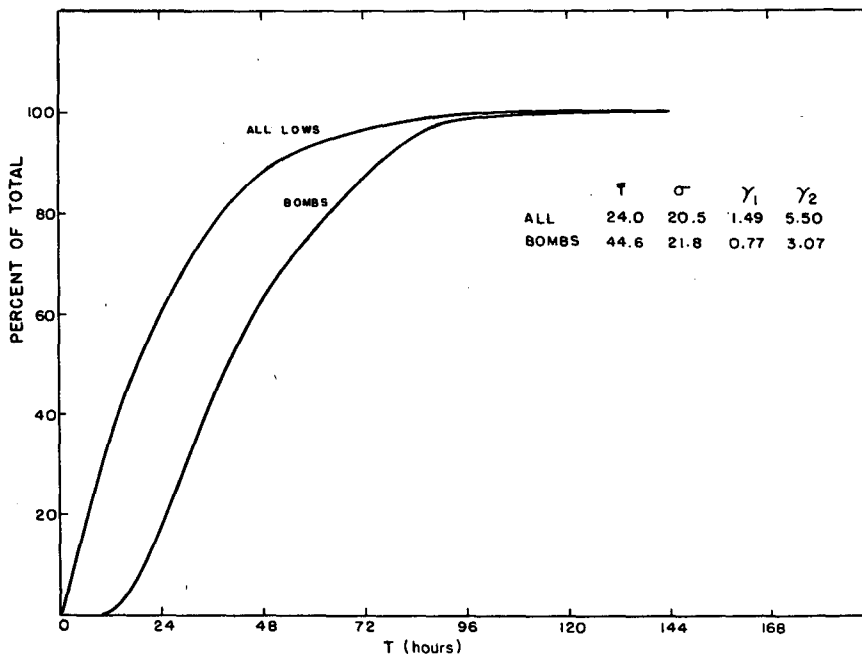


FIG. 4. Cumulative distributions of deepening periods for all storms in the one-year sample and for explosive cyclones. The statistics of the distributions are also given:  $\bar{T}$  is the mean deepening period;  $\sigma$  is the standard deviation; and  $\gamma_1$  and  $\gamma_2$  are the coefficients of skewness and kurtosis, respectively. All times are in hours.

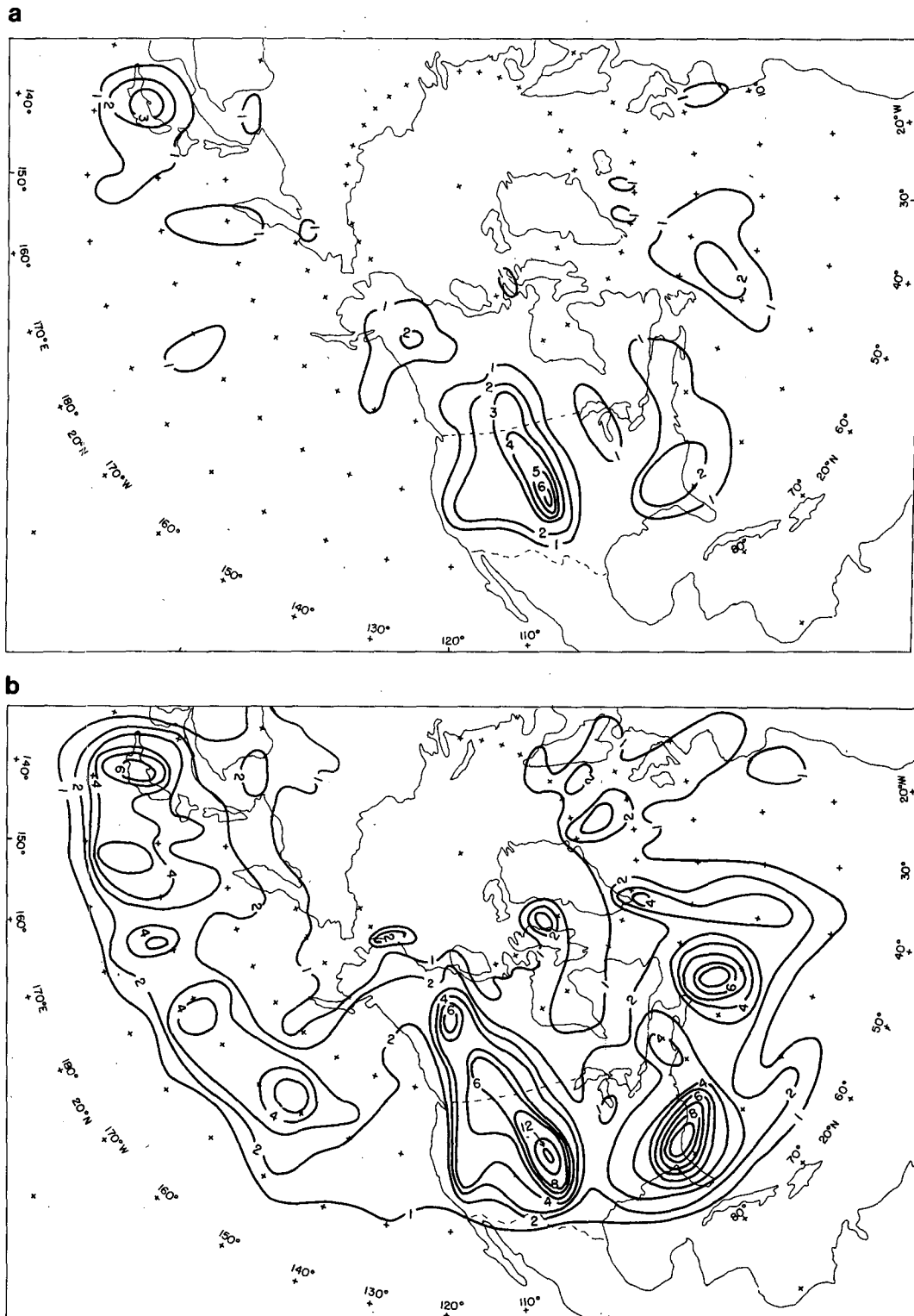


FIG. 5. Geographic distribution of formation positions, (a) warm season, (b) annual, (c) explosive cyclones. Frequencies are smoothed from the five degree latitude/longitude tessera grid of raw data, according to the formula of one-eighth of four times the central frequency plus each of the four adjacent frequencies.

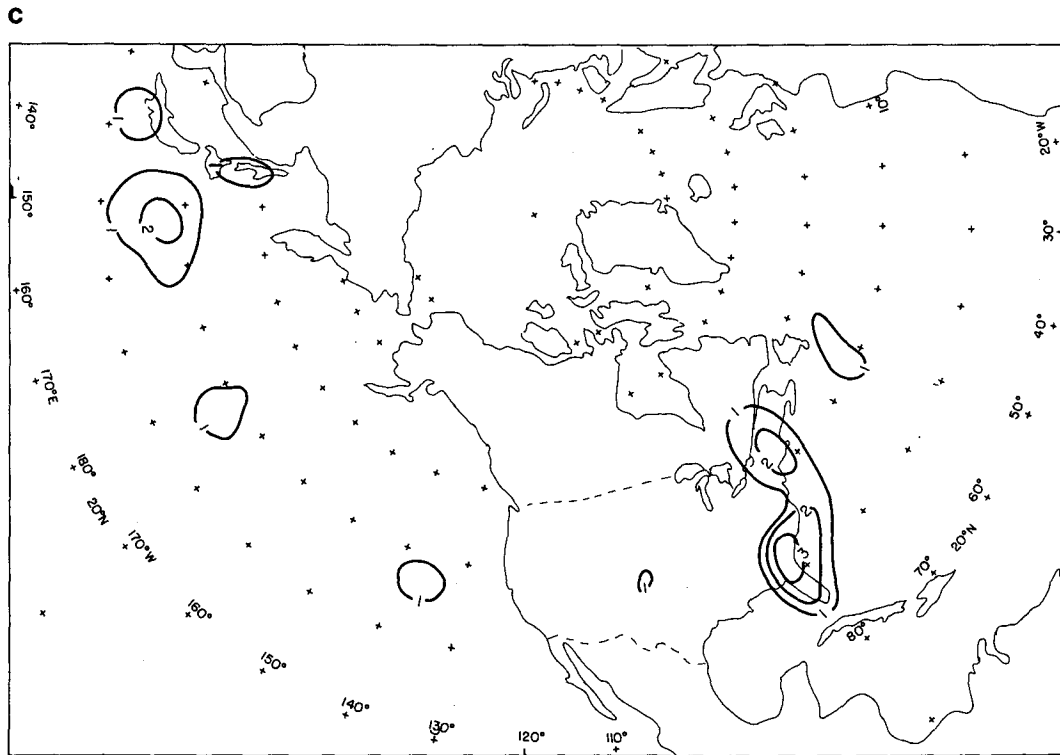


FIG. 5. (Continued)

storm at 0000 GMT, if the most rapid deepening occurred from 1200 GMT to 1200 GMT, and the position at 1200 GMT, if the most rapid deepening occurred from 0000 GMT to 0000 GMT.

The dissipation position was taken to be the last analyzed position of a storm before it lost its identity, either through absorption by another storm or complete decay, so that the low center was no longer analyzed on successive maps. The duration (in days) of each storm was also recorded. Any system that moved out of the range of coverage was not included in the compilation of dissipation positions or duration time, as these could not be determined from the data.

All pressure falls were adjusted geostrophically<sup>2</sup> to 42.5°N, the approximate latitude of maximum "bomb" occurrence. Thus, the lower limit of 24-hour adjusted pressure fall to be considered a "bomb" under the "Bergeron" definition is 19 mb. This is an arbitrary definition, presumably designed to include only the most rapid deepeners in the "bomb" class. The statistical analysis of deepening rates makes it possible

to examine the adequacy of this definition with respect to the observations of the one year data sample.

### 3. Statistical analysis

The basis of the analysis is the Central Limit Theorem which states that under certain conditions, statistical distributions can be approximated by a normal curve. If we let  $X_n$ ,  $n = 1, 2, \dots, N$  be a set of  $N$  stochastic variables (e.g., the stochastic variable  $X_1$  is the random outcome of process number one), and we let  $j$  denote the number of independent realizations of that process, then we can define a variable  $Y_j$  such that

$$Y_j = X_{1,j} + X_{2,j} + \dots + X_{N,j}.$$

Thus the summation is over processes, and the stochastic variables  $Y_j$  are the sums of additive effects. As  $N \rightarrow \infty$ , provided the random variables  $X_n, j$  are independent, the distribution of the  $Y_j$  can be represented as a normal distribution. In this analysis, one would expect the distribution of the deepening rates to be normal, provided the  $N$  underlying processes (e.g., orographic effects, warm advection, differential vorticity advection, etc.) have the same linear relationship to deepening rate in all cases (realizations). Thus we could represent the deepening rate  $Y_j$  as a linear combination of a fixed set of underlying processes

<sup>2</sup> Storms at different latitudes with identical pressure gradients do not produce the same maximum geostrophic wind. The pressure falls can be adjusted such that  $\Delta P(\text{adj}) = \Delta P \sin 42.5 / \sin \phi$ . Sanders and Gyakum (1980) have defined one Bergeron as a 24-hour pressure fall equivalent to 24 mb at 60°N.

$(X_n, j)$  with a particular weight assigned to each of the component processes. This does not require that each of these processes be identically distributed, but only that the set of weights assigned to these processes be the same in all realizations. The restriction of independence should be approximately correct, although some storms in close proximity may interact; we can say little about the interactions between cyclones, and the effect of cyclones on the upper level flow and subsequent systems, but it seems reasonable to assume that such effects would be statistically negligible over a sufficiently long period, since there would be statistical independence of a majority of cases.

Figures 1 and 2 show the 12 and 24 hour deepening distributions of the full year data sample. Analyses of 12 and 24 hour deepening distributions for warm season (May–August), cold season (September–April), and annual data samples show statistically significant deviations from the normal curve, the largest deviations associated with the tail of the deepening curve. The analysis was accomplished using a chi-square goodness-of-fit test (Freund, 1971) at the 5% level of significance; thus, there is a 5% probability of erroneously concluding the distributions are not normal.

It is clear from these figures that the mean of the sample deepening rates is greater than the mode of the sample. In effect, the mean deepening of the sample has been pulled to the rapid deepening side by the tail of the distribution. Two normal curves of different means and standard deviations were fit to the deepening distributions (dashed lines in Fig. 3). The sum of the two normal curves provided a good fit to the data at the 5% level of significance. That is, there were no longer statistically significant deviations from the observed distributions. These curves were chosen through an iterative process. They represent only one set of a possible series of normal curves that, when summed, provide a good fit to the data. The statistics of the fitted normal curve associated with most rapid deepening, with mean  $-22.3$  mb and standard deviation of  $6.9$  mb, indicate that the Bergeron definition of a bomb was quite adequate; 68% of the explosive cases (as defined by the normal curve with mean  $-22.3$  mb) were included by this definition, while only 2% of the nonexplosive cases were included in this sample.

These results provide strong statistical evidence that rapid deepeners develop differently from less intense storms. If one makes the reasonable assumption that less rapid deepeners by and large result from ordinary baroclinic instability, the evidence suggests that explosive cyclogenesis is produced by a mechanism or mechanisms distinct in some meaningful way from the baroclinic process. That such an analysis, based on the often underestimated NMC surface pressure analyses over data sparse oceans, was able to demonstrate this feature further emphasizes this conclusion.

#### 4. Climatology of cyclones

A great deal of climatological information concerning the life cycle of cyclones can be obtained from the one year data sample; in the process, one can obtain some additional information about explosive cyclones.

One might expect a bias in the distribution of the time period of most rapid deepening, based on poor Pacific data coverage at 1200 GMT. The question of time bias in the deepening rates of the data sample was examined. No attempt was made to stratify the cases according to ocean basin, where the greatest potential of bias might have been expected. This was done in the study of Sanders and Gyakum (1980), and no bias was found in their sample of bombs. The results for this data sample, shown in Table 1, also indicate no statistically significant bias in the 12 and 24 hour samples; however, the 12-hour sample is suggestive.

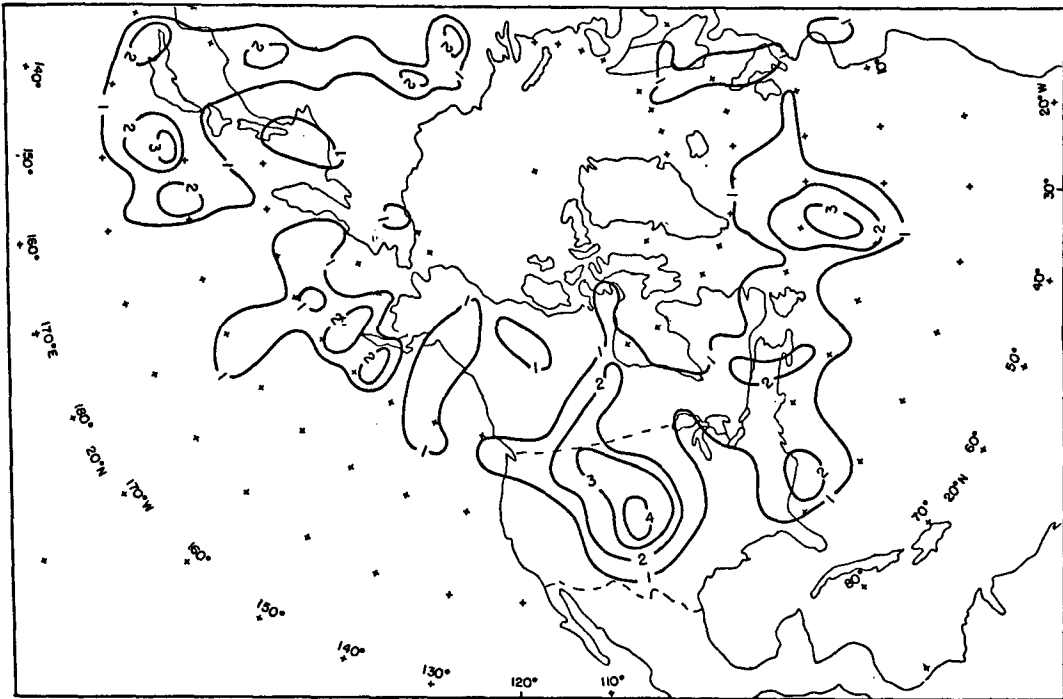
Within the limits of the 12-hour resolution of the data, the question of length of the deepening period was examined. The deepening period was taken to be the time interval over which successive 12-hour analyses indicate a continued fall in storm central pressure. The results are plotted in Fig. 4. By 36 hours more than 75% of all lows in the sample had ceased deepening, as compared to less than half of the explosive cyclones. The average deepening period of all lows was 24 hours, while that of explosive cyclones was about 45 hours. In interpreting these results, it should be remembered that the deepening rate for explosive cyclones exceeds the critical value (one Bergeron) for only a fraction of the total deepening period.

A series of maps was prepared utilizing the data

TABLE 1. Distribution of times of most rapid deepening. The number and percentage of cases in the 1980–81 sample whose period of most rapid deepening began at 1200 GMT and at 0000 GMT.

Time of rapid deepening	N	1200 GMT	%	0000 GMT	%
12 h (1200–0000, 0000–1200 GMT)	1157	619	53.5	538	46.5
24 h (1200–1200, 0000–0000 GMT)	1178	579	49.2	599	50.8
Bombs (1200–1200, 0000–0000 GMT)	115	58	50.4	57	49.6

**a**



**b**

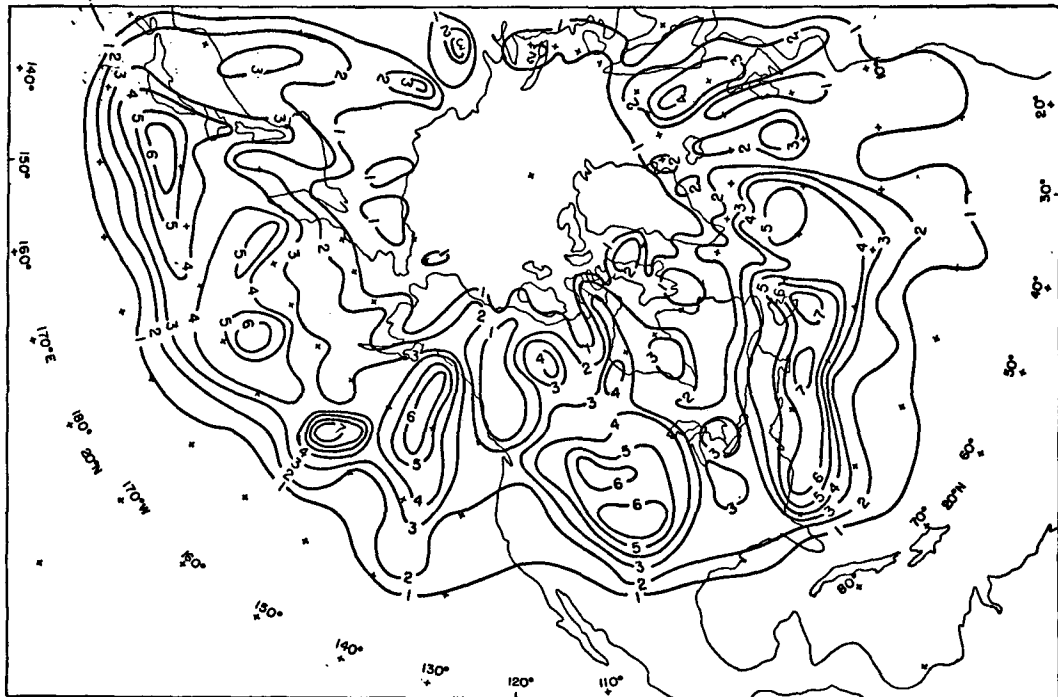


FIG. 6. Geographic distribution of maximum deepening positions, (a) warm season, (b) annual.

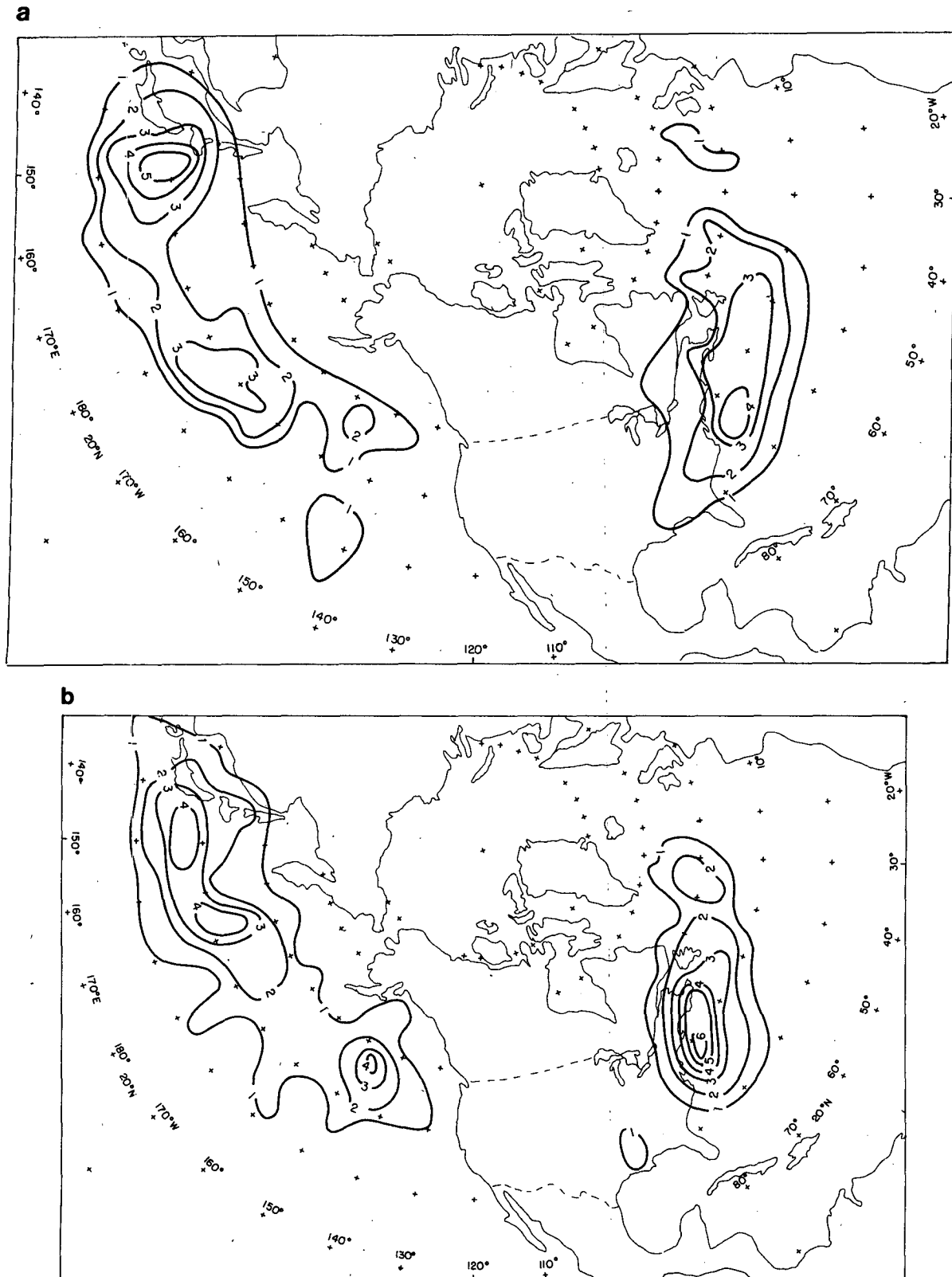


FIG. 7. Geographic distribution of maximum deepening positions, (a) 1976-79 1200 GMT-1200 GMT bombs, (b) 1979-82 1200 GMT-1200 GMT bombs, (c) 1976-82 1200 GMT-1200 GMT bombs.



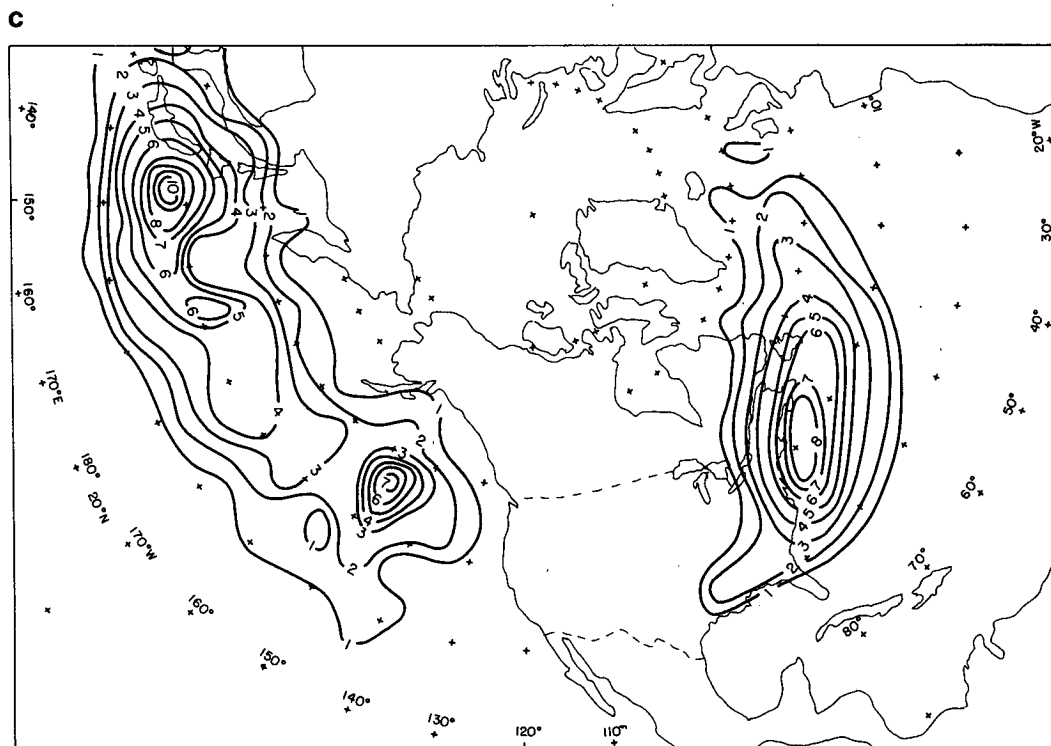


FIG. 7. (Continued)

concerning positions of formation, maximum deepening and dissipation. The raw frequency data were plotted on five degree latitude by five degree longitude tessera grids, and smoothed by taking one-eighth of four times the central value plus the four surrounding values.

Comparison of Fig. 5a with 5b shows a noticeable formation position maximum in the eastern Pacific Ocean around 42°N, 155°W, not apparent in the warm season climatology, which becomes established in the winter months. Figure 5c shows the formation positions of explosive cyclones in the one-year sample. Though the data sample is small, it is nevertheless quite evident that the positions of explosive cyclone formation are predominantly associated with the warm ocean currents off the eastern seaboard of the United States and off the coast of Japan.

Most of the positions of maximum deepening (Fig. 6) are well correlated with, and slightly downstream from, corresponding positions of initial cyclogenesis. However, the Pacific Ocean region between 150°W and 160°W, where the maximum in formation position was found, also displays a maximum in deepening. This maximum is not downstream of the initial formation position, and the magnitude is greater, suggesting that other cyclones moving through the area are intensifying. This region has no warm ocean cur-

rents akin to the Kuroshio or the Gulf Stream, but it can still be quite baroclinic, owing to outbreaks of Arctic air moving through the Bering Straits and across warmer ocean water. The speculative suggestion is that storms that do form in this area are redevelopments of existing storms that subsequently move into the Gulf of Alaska and decay. Storms moving through the area deepen in response to the enhanced baroclinicity.

The maximum deepening positions of all of the 24-hour bombs (1200 GMT–1200 GMT) for the periods 1976–79 (from Sanders and Gyakum, 1980), 1979–82, and 1976–82 are plotted in Fig. 7. The distributions of the maxima are well correlated with the positions of the warm ocean currents, primarily the Kuroshio and the Gulf Stream. A comparison between Fig. 6 and Fig. 7 reveals the concentrated localization of bomb events in these areas, an observation that conforms with the climatology of Sanders and Gyakum (1980).

There are some small but non-negligible differences in the two three-year samples of explosive cyclones. Most notable in terms of the impact on weather in the United States was the maximum off the east coast of the United States which was greater and closer to land in the later period. A cursory examination of the relationship between mean seasonal upper level flow fields and the distribution of explosive events along

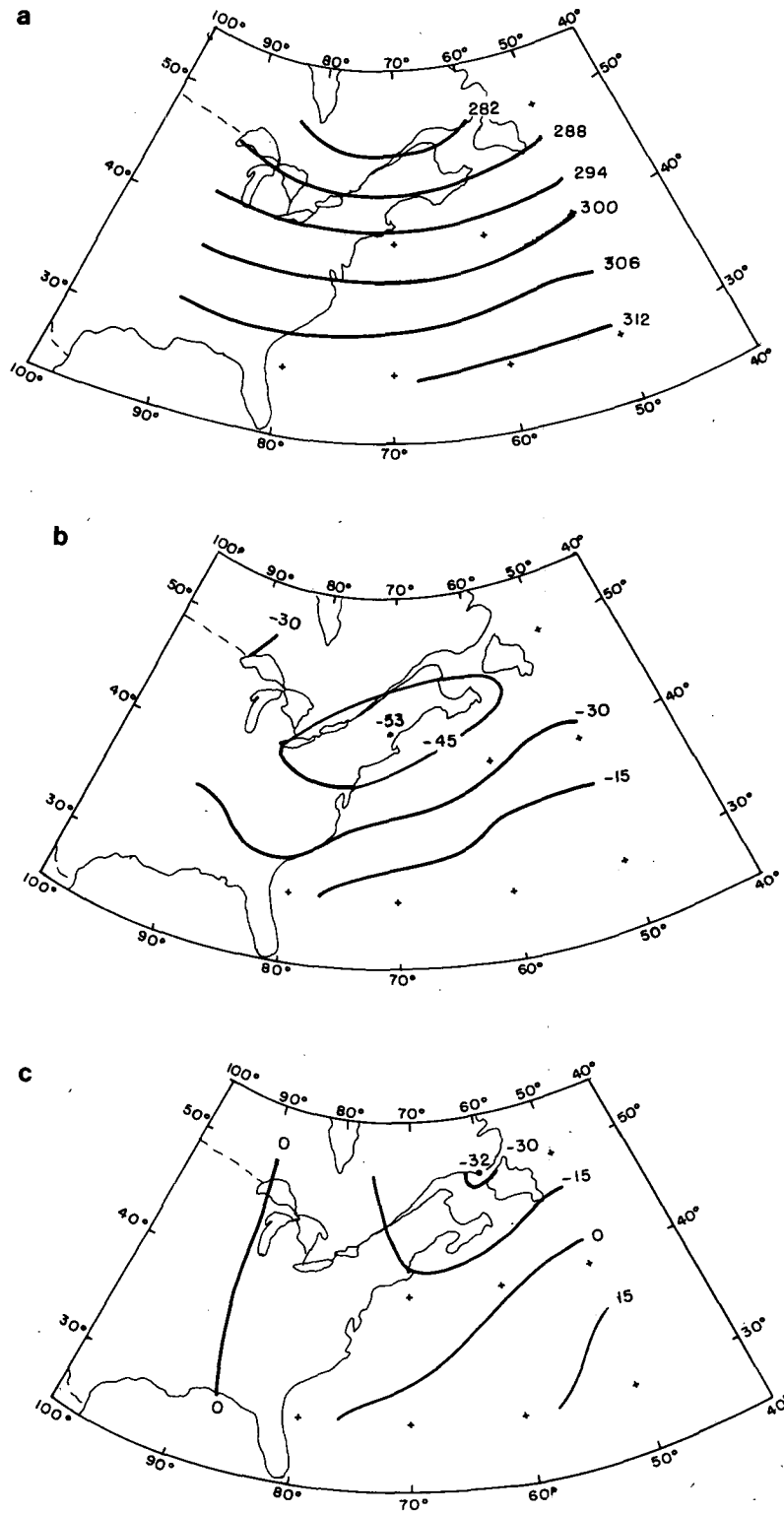


FIG. 8. Mean wintertime (Dec-Feb) 700 mb height fields for, (a) 22-year normal (1948-70) in dm, (b) 1976-79 height anomaly in meters and (c) 1979-82 height anomaly in meters.

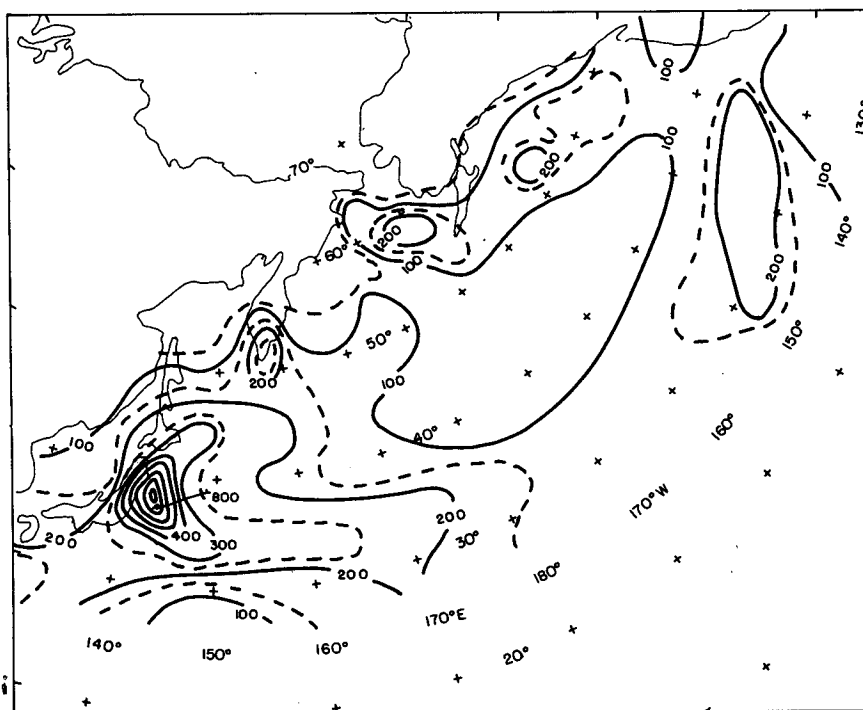


FIG. 9. Number of ship observations in January, 15-year average (1965–79), in five degree latitude by five degree longitude tesserars.

the eastern seaboard in the two three-year periods was made. Figure 8 shows the mean wintertime 700 mb flow fields, obtained from the 1976–82 almanac issues of *Weatherwise*. Figure 8a, the 22-year normal 700 mb height field, shows that the flow is, on average, nearly zonal in this area. Figure 8b, the mean 700 mb height anomaly for the 1976–79 winter seasons, reveals a fairly significant west-southwesterly anomaly in the flow. In comparison, the mean height anomaly for the 1979–82 winter seasons (Fig. 8c) is quite weak, with only a very slight west-southwesterly anomaly in the flow. These patterns suggest only a weak correlation at best with the distribution of explosive cyclogenesis in this area.

A better method of judging the relationship between the upper level and intense surface features would be to perform an analysis as in Sanders and Gyakum (1980), where each explosive case was examined individually with respect to the 500 mb flow. In that study, the authors found the relationship between the explosive cyclones and the upper trough to be qualitatively typical of deepening baroclinic lows, with most of the storms intensifying within or just poleward of the region of maximum 500 mb wind and baroclinicity. These findings were also consistent with the result of Frederiksen's (1979) linear stability analysis, in which the region of preferred development was located just downstream from the planetary wave trough.

The six-year pattern of bomb distribution (Fig. 7c) clearly shows an eastern Pacific maximum. This feature is of almost the same magnitude as the maxima associated with the Kuroshio current and the Gulf Stream. The possibility that this observation is due to an increase in available data in that region was examined. Figure 9 displays the distribution of the average number of ship observations in the month of January for the 15-year period ending in 1979. A broad swath of minimal data coverage appears to extend across the region from 170°E to 140°W. While this evidence is not conclusive, it does suggest the possibility that the maximum is simply an artifact of data coverage. At the time of the bomb event, the cyclone is moving from a region of "poor" data coverage to one of "good" coverage. Thus, it is possible that the already well developed cyclone is merely being discovered as it moves through the region.

The distribution of dissipation positions are shown in Fig. 10. The warm season pattern is somewhat diffuse, although there is a suggestion of a preference for the Gulf of Alaska region, as well as the area between Newfoundland and Greenland, and to the south of Iceland. The maximum in the central United States likely indicates the sporadic analyses of thermal lows. The annual pattern greatly accentuates the Gulf of Alaska as a region of loss of storm identity. Orographic forcing and oceanic heating in this region maintain a

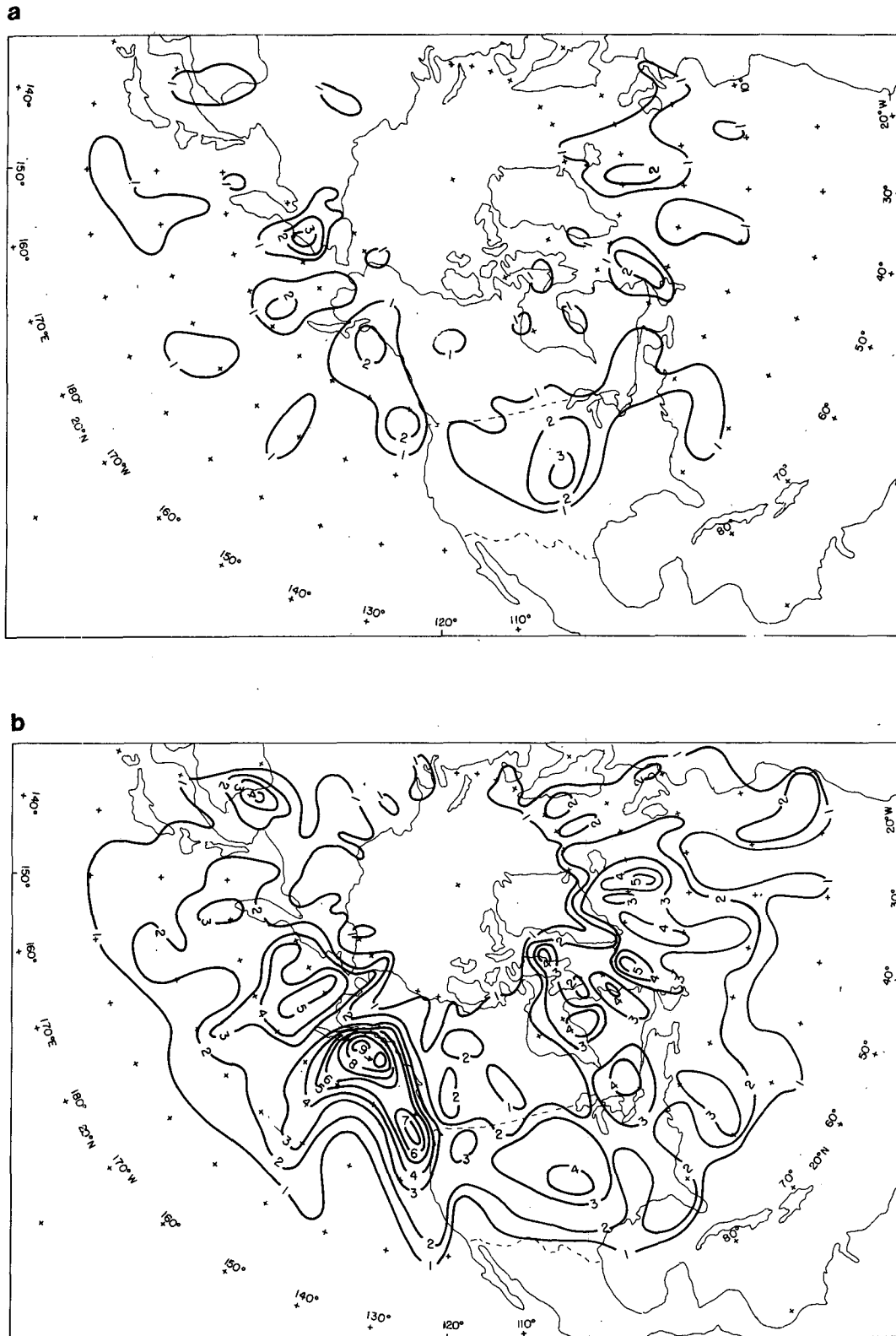


FIG. 10. Geographic distribution of dissipation positions for (a) warm season and (b) annual.

quasi-steady low, which absorbs mobile cyclones approaching from the southwest, terminating their separate identity.

## 5. Summary

The question of explosive cyclogenesis as a process or processes distinct from ordinary baroclinicity was examined, and statistical evidence was found that supported this hypothesis. The climatology of cyclones indicated that the preferred regions of explosive cyclogenesis are primarily baroclinic zones, areas which support the development and continued existence of ordinary low pressure systems. This finding is consistent with that of Sanders and Gyakum (1980)—that explosive cyclones exhibit a relationship to the upper level flow which is qualitatively similar to less intense storms. The evidence thus suggests that the mechanism operative in cases of explosive cyclogenesis is some combination of the baroclinic process with another mechanism(s). This is entirely consistent with the results of Gyakum (1983b) and Bosart (1981), who studied particular cases of explosive cyclogenesis in detail, and suggested that the bulk effects of cumulus convection in combination with the baroclinic process was the explosive forcing mechanism. A study designed

to further examine this mechanism will be detailed in a subsequent paper.

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