A Survey of Extratropical Cyclone Characteristics during GALE

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ABSTRACT

For the population of cyclones that formed over North America and the adjacent Atlantic Ocean during the Genesis of Atlantic Lows Experiment (GALE; 13 January–16 March 1986), a variety of interrelationships between various cyclone characteristics are considered. Previous cyclone climatologies are extended by requiring no minimum cyclone amplitude. Particular attention is paid to the horizontal size distribution of the cyclones. It is found that 1) most cyclones are subsynoptic in scale, with only the deepest cyclones having a size consistent with classical baroclinic-instability theory; 2) almost all small-scale cyclones have a total life span of less than 48 h; 3) the pressure gradient within small-scale cyclones tends to be weaker than that within large-scale cyclones; 4) Atlantic cyclones deepen much more rapidly than cyclones over the continent, but for many cyclones, deepening rate is an unsuitable measure of intensification; and 5) the geographical distribution of cyclogenesis during GALE is broadly similar to that found in more comprehensive climatologies, but some significant differences are present that are attributable to the inclusion of weak cyclones and stationary, orographically forced cyclones.

1. Introduction

The climatological spatial and temporal distribution of synoptic-scale cyclones over North America is well known from the work of Petterssen (1956) and Klein (1957). Both authors presented maps of cyclone frequency and cyclogenesis locations for the Northern Hemisphere. Klein also constructed mean monthly storm tracks from cyclogenesis and cyclone frequency maps and from previous work by other investigators. Following similar methodologies, more recent studies have been concerned with the interannual variation of cyclogenesis (Reitan 1974, 1979; Zishka and Smith 1980; Hayden 1981) and with an updated hemispheric climatology (Whittaker and Horn 1984). Improved spatial resolution (1° – 2°) has been employed over the entire continent (Zishka and Smith 1980) and over smaller areas such as the eastern United States (Colucci 1976) and the lee of the Rocky Mountains (Chung et al. 1976).

Despite this body of work, little attention has been given to possible statistical or geographical relationships among various cyclone characteristics or to the cyclone characteristics themselves. Colucci (1976) investigated the geographical distribution of cyclone deepening characteristics. Zishka and Smith (1980) briefly compared the minimum pressure of cyclones forming in the lee of the Rockies and off the east coast of the United States. Explosively deepening cyclones were examined by Roebber (1984), and their locations of formation and deepening were compared to other cyclones. In a study of North Pacific cyclones, Gyakum et al. (1989) compared the temporal evolution of cyclones with maximum deepening rates, locations, and lifetimes.

The purpose of this study is to compile and compare such statistics as cyclogenesis location, deepening rate, size, intensity, and duration for the set of North American cyclones that formed during the Genesis of Atlantic Lows Experiment (GALE). Of particular interest is the size distribution of the analyzed cyclones. We are aware of no previous systematic investigation of the horizontal length scales of extratropical cyclones. Synoptic experience (and conventional baroclinic instability theory) would suggest a typical wavelength for a fully developed baroclinic cyclone of about 3000 km. However, the term *cyclone scale* has recently been associated with a wavelength of 1000 km by Moore and Peltier (1987) and Joly and Thorpe (1990). Both stud-

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ies present examples of 1000-km cyclones in an attempt to demonstrate their prevalence. One of our goals is to determine whether such a cyclone scale is readily discernible within a sample of extratropical cyclones in a comparatively data-rich region. We also wish to investigate whether different classes of cyclones (small versus large, stationary versus nonstationary) exhibit markedly different behavior.

2. Data and methods

The principal data sources for this study are the 3-h North American and 6-h North Atlantic and North Pacific surface analyses produced by the National Meteorological Center (Corfidi and Comba 1989) and distributed via DIFAX. The analyses are subjective but make use of a model initial-guess field over oceans. On rare occasions, a fully automated analysis was received from NMC. Because of the lack of a time-continuity constraint on these automated analyses, the maps were reanalyzed subjectively to determine cyclone parameters wherever data were available.

For the purposes of this study, a simple objective measure of cyclone size is required that can be applied directly to surface analyses. Several different measures of cyclone size have been considered, including 1) the distance from the cyclone center to the nearest high pressure center, 2) the distance from the cyclone center to the nearest adjacent cyclone center, 3) the distance from the cyclone center to the nearest col (saddle point) of sea level pressure, or 4) the horizontal area encompassed by the largest closed isobar about the cyclone. Definition 1 proves to be unacceptable in the case of a family of cyclones growing along a front where the wavelength (or half-wavelength) of development is given by the distance to the adjacent cyclone (or to the nearest col). Definition 2 is unacceptable in the case of lee cyclogenesis produced by an isolated mountain: the distance to the nearest cyclone is irrelevant to the scale of the perturbation-pressure field. If the perturbation-pressure field is sufficiently intense, a pressure maximum will also be present, and definition 1 will be adequate. Otherwise, only definitions 3 and 4 will tend to give meaningful approximations to the true scale of development.

Based on a variety of real and imagined scenarios, definition 3 has been adopted for this study. The size measurement it produces (hereafter called the *radius* because it is a distance from the cyclone center to the outermost closed isobar) is equivalent to a half wavelength for the cyclone family example and tends to lie between one-third and one-half of the wavelength for more general wavelike geometries. In keeping with the half-wavelength analogy, it was found necessary to employ the distance to the nearest pressure maximum whenever it was less than the distance to the nearest col (about 5%–10% of the time).

Another complication is presented by the common situation of multiple low centers within a large-scale cyclonic circulation. Two cyclone scales are present, but the assignment of the larger scale to a particular low center is an arbitrary one. Furthermore, if one of the lows were to dissipate, the remaining low would suddenly not have a small scale. Thus far, an objective technique that completely circumvents these difficulties has not been developed. The method of using the distance to the nearest col assigns the smaller scale to all multiple lows. It turns out that no large-scale cyclones are missed by this method: all of the large-scale cyclones observed during GALE possessed a single low center for at least a part of their life cycle. However, apparent discontinuous changes of cyclone scale are not avoided. We shall, therefore, concentrate on the largest scale measured during a cyclone's lifetime, hereafter called *maximum cyclone radius*.

All cyclones passing through the survey area (Fig. 1) between 0000 UTC 13 January 1986 and 0000 UTC 17 March 1986 were tracked for the duration of their existence using these surface analyses. Each low pressure center was assigned an index number, and its associated characteristics were recorded at 3-h or 6-h intervals, depending on available map frequency (Fig. 1). Among the parameters recorded were: day and hour, position (to the nearest degree), cyclone radius (defined earlier in this section, to the nearest 50 km), central pressure, and the difference in pressure between the low center and the lowest adjacent col. This last parameter (to be termed *pressure deficit*) may be thought of as the number of closed isobars at 1-mb increments that can be drawn around a given low pressure center. A subset of these parameters, such as maximum pressure deficit and cyclogenesis location, was then entered into a computer for subsequent statistical analysis.

This study departs from most previous climatologies by not requiring a cyclone to attain a certain minimum pressure deficit (or minimum number of closed isobars). Instead, any analyzed low center that could be identified on two consecutive maps was included in the climatology. The purpose of this was to avoid establishing an a priori criterion for minimum intensity and to include in the sample smaller-scale lows, which tend to have fewer closed isobars. Climatologies can be quite sensitive to closed-isobar criteria imposed by the contour interval (Peyrefitte and Astling 1981; Zishka and Smith 1981).

During inspection of the surface maps, it became apparent that analysts often did not identify a developing surface low until it was 2 or 3 mb lower than its surroundings. Consequently, plotted data on the surface maps immediately preceding an analyzed cyclogenesis (and immediately following cyclolysis) were examined, and if a 1-mb-deep (or greater) surface low was deemed to be present, the lifetime of the low was extended accordingly. Particular attention was paid to

FIG. 1. Domain of cyclone survey area, showing availability of surface analyses. All cyclones passing through the survey area were tracked beyond the margins of the area from genesis to lysis.

attempting to enforce continuity in cases in which a low vanished in one analysis but reappeared a few hours later in another analysis. Continuity was sometimes difficult to establish offshore of the eastern United States. For some cases, it was necessary to construct independent analyses using ship and buoy data obtained from the GALE compact disk. Otherwise, no special GALE data was used, and it is doubtful that the GALE observations introduced an artificial enhancement of cyclone frequency.

A total of 213 cyclones were identified and tracked during the 61-day study period. The representativeness of this cyclone sample is discussed in section 6.

3. The geographical distribution of cyclogenesis: Stationary versus traveling cyclones

The distribution of all cyclogenesis events during the study period is shown in Fig. 2. The overall pattern is roughly similar to previously published climatologies, such as Zishka and Smith (1980). Preferred areas of cyclogenesis are along the east coast of the United States and along the eastern slopes of the Rocky Mountains. The greatest cyclogenesis density is in the Carolinas, surprisingly far west and near the center of the inner GALE region. A second prominent maximum is located in southern Alberta, Canada. Other weaker maxima are found along the Gulf coast and in the intermountain region. Areas with little or no observed cyclogenesis activity include eastern Canada and the Atlantic south of 30°N.

From inspection of cyclone-track maps (not shown), it was noticed that many of the lows that formed along the Rocky Mountains or in the Carolinas were quasi-stationary, short-lived cyclones that appeared to be generated by the local orography. To separate such cyclones from the remainder of the sample, two classes of cyclones are defined. *Stationary cyclones* are defined as those cyclones whose cyclolysis positions were less than 400 km from their cyclogenesis positions. Conversely, *traveling cyclones* are those cyclones whose cyclolysis positions were 400 km or more from their cyclogenesis positions. A similar classification scheme has been used by Chung et al. (1976) for lows forming in the Canadian Rockies.

Although broadly similar, the cyclogenesis distributions for traveling (Fig. 3) and stationary (Fig. 4) cyclones differ substantially in their details. Figure 3, for instance, is a much closer fit to previous climatological distributions than either Fig. 2 or Fig. 4. The maximum of total cyclogenesis events in the Carolinas (Fig. 2) is found to be primarily due to stationary cyclones (Fig. 4), which inspection of synoptic maps reveals to be cyclones forming in the lee of the southern Appalachians. This cyclogenesis maximum is not an artifact of possible increased attention paid to the area by analysts; most cyclones forming there attained maximum pressure deficits of 2–3 mb, distinct enough on a surface map but too weak to satisfy most previous cyclone climatology criteria. Most of these cyclones formed along cold fronts deformed by the mountains, and disappeared when cold air filled the area from the north or west. The East Coast maximum for traveling

FIG. 2. Total number of cyclogenesis events per $3 \times 10^5 \text{ km}^2$ during GALE.

cyclones is offshore, just northeast of Cape Hatteras, North Carolina, and downstream of the inner GALE region, and coincides with the genesis location of many of the ERICA (Experiment on Rapidly Intensifying Cyclones over the Atlantic) cyclones.

Along the Rockies, stationary cyclones also tended to form a bit farther west than traveling cyclones. Traveling cyclones predominate in Colorado and Wyoming, to the lee of the Sierra Nevada, in southern Alberta, and in the vicinity of Great Slave Lake. Sta-

FIG. 3. Number of cyclogenesis events per $3 \times 10^5 \text{ km}^2$ during GALE, traveling cyclones only.

FIG. 4. Number of cyclogenesis events per $3 \times 10^5 \text{ km}^2$ during GALE, stationary cyclones only.

tionary cyclones have cyclogenesis maxima in eastern Washington, central Montana, New Mexico, and Texas. Examination of specific cases indicated that the stationary cyclone maximum over the Gulf of St. Lawrence was legitimate, while the maximum near Cape Cod, Massachusetts, may have been due to small-scale lows moving northward from the open ocean into data-rich areas. Elsewhere, the vast majority of cyclones forming in featureless areas, such as the open Atlantic Ocean and the Plains states, are traveling cyclones, suggesting that almost all stationary cyclones during this time period were orographically related.

The maximum for traveling cyclogenesis off Cape Hatteras is greater than the maximum in Alberta. This contrasts with the results of Zishka and Smith (1980), whose maximum cyclogenesis frequency is in Alberta. Although sampling variations may be responsible for some of this difference, it is also likely due in part to our considering all appearances of a new low pressure center as a separate cyclogenesis event. As a result of this difference in methodology, lows that "hop" the Appalachians and would have been counted as a single event by Zishka and Smith are counted as two cyclones in this study. Only one low pressure center during GALE successfully passed over the Appalachians and moved offshore, the rest having clearly redeveloped with both old and new low pressure centers present during redevelopment. Also, only two cyclones successfully crossed the coastal mountains of western North America from the Pacific.

The geographical distribution of cyclolysis for trav-

eling cyclones (Fig. 5) is dominated by cyclones that die upon reaching the Appalachians. The maximum cyclolysis frequency is located in West Virginia, with a band of cyclolysis extending northeastward into Quebec, Canada. The maximum is located over the mountains rather than on the upslope side as other researchers have found, a distinction apparently due to our following low centers until they disappear completely. A lobe of frequent cyclolysis extends into the cyclogenetic region of Virginia and North Carolina. This lobe is apparently related to the presence of multiple low centers during East Coast cyclogenesis. During GALE, the easternmost East Coast low center tended to be the center that deepened most rapidly, absorbing any small-scale low centers located farther west. A second preferred region of cyclolysis was located near Labrador, Canada, and Baffin Island, Canada, the graveyard for cyclones passing northward over Newfoundland, Canada. Another band of cyclolysis is located 500–1000 km downstream of the Rockies and also appears to be related to the amalgamation of multiple low centers.

By definition, the cyclolysis distribution for stationary cyclones resembles the corresponding cyclogenesis distribution and is not shown.

4. Comparison of large-scale and small-scale cyclones

As discussed in section 2, the distance from a low pressure center to the nearest col is used as a measure

FIG. 5. Number of cyclolysis events per $3 \times 10^5 \text{ km}^2$ during GALE, traveling cyclones only.

of cyclone size. This radius should tend to be one-third to one-half the wavelength associated with the cyclone. For typical wavelengths associated with the maximum growth rate due to classical baroclinic instability (3000–4000 km), the expected range of cyclone radii would be 1000–2000 km.

The distribution of maximum cyclone radii during GALE (Fig. 6) is highly skewed, with the median radius being 500 km. Two-thirds of the cyclones have a maximum radius of 700 km or less in the mesoscale or subsynoptic-scale range. There is a local minimum in maximum cyclone radius near 750 km, and this radius will be adopted as the dividing point between what will be called small-scale and large-scale cyclones. As indicated in Fig. 6, about half of the small-scale cyclones are stationary cyclones, including most of the cyclones having a maximum radius of 300 km or less.

The traveling cyclones in Fig. 6 have a median maximum radius of 725 km and a mean maximum radius of 875 km. These sizes are still small compared to what one thinks of as a typical cyclone size. The “normal” cyclone size in Fig. 6 is recovered by selecting only those cyclones that attain at least a 12-mb pressure deficit relative to the lowest adjoining col, that is, those cyclones that would be surrounded by at least three closed isobars drawn at 4-mb intervals. These cyclones, which might be called prominent cyclones, are most noticeable on a weather map. The distribution of maximum radius of the prominent cyclones follows an approximate Gaussian curve, with the average radius of 1500 km implying a cyclone wavelength of about 3000

km, consistent with both synoptic experience and baroclinic-instability theory. But these characteristics apply to less than one-fifth of the cyclones that formed during the GALE period; most cyclones were of the small-scale variety.

Compared to large-scale cyclones, small-scale cyclones tend to be short-lived phenomena. Figure 7 is

FIG. 6. Distribution of maximum cyclone sizes during GALE. Also shown are the distribution of maximum radii for the subset of cyclones that traveled at least 400 km and for the subset of cyclones that attained at least a 12-mb pressure deficit.

FIG. 7. Total period of time that cyclones could be tracked on a weather map, as a function of the maximum radius attained by the cyclones.

a scatter diagram of maximum cyclone radius versus cyclone duration. Most of the small-scale cyclones have durations of 48 h or less, with the mean duration being 18.2 h. The large-scale cyclones are scattered about a wide range of lifetimes, with a mean duration of 83 h and a standard deviation of 56 h. Larger cyclones tend to last longer; the correlation between maximum radius and duration is .74. When the cyclone population is split into two groups by size, the correlation becomes .49 for the small-scale cyclones and .43 for the large-scale cyclones.

The maximum pressure deficit of cyclones is also correlated with maximum radius. However, maximum pressure deficit is a poor measure of cyclone intensity for the purposes of this study. Given two cyclones with

FIG. 8. Maximum cyclone intensity (maximum pressure deficit normalized by maximum cyclone radius), as a function of maximum cyclone radius.

equal pressure deficit but radii differing by a factor of 2, the smaller storm will tend to have twice the geostrophic wind speeds of the larger storm. Hence, intensity is estimated here by dividing the maximum pressure deficit by the maximum radius. Because maximum deficit and maximum radius do not necessarily occur simultaneously, this is only a lower bound on the largest mean radial pressure gradient attained by a cyclone.

The scatter diagram of cyclone intensity, as defined in the preceding paragraph, versus cyclone radius is shown in Fig. 8. Overall, a correlation of .53 is present, but points are widely scattered throughout most of the figure. The most intense storms are seen to have maximum radii between 1200 and 1800 km. The mean maximum intensity for the large-scale, traveling cyclones is $14 \text{ mb } (1000 \text{ km})^{-1}$. The small-scale cyclones tend to be weaker, with a mean of $8 \text{ mb } (1000 \text{ km})^{-1}$, but are still comparable in intensity to many larger cyclones. Rather than being overwhelmed by the larger cyclones, small-scale cyclones over their generally short lifetimes attain significant amplitudes.

A problem in comparing this figure to baroclinic instability theory is that the maximum cyclone radius is not necessarily the scale at which the most rapid intensification occurs. The radius of a typical cyclone changes considerably during its lifetime. Figure 9 is a scatter diagram of maximum cyclone radius versus the radius of cyclones 6 h after cyclogenesis. Aside from the tendency of cyclones (particularly short-lived cyclones, as would be expected) to cluster near the diagonal, little coherent pattern is evident. Of the 19 cyclones that attained a maximum radius of 1500 km or more, 14 would still be classified as small-scale cyclones (radius of less than 750 km) after 6 h, and 8 of those had a 6-h radius of less than 400 km.

Because of the definition of cyclone radius, a large portion of these apparent changes in scale are due to

FIG. 9. The radius of cyclones 6 h after formation, as a function of the maximum radius attained during the cyclones' lifetime.

FIG. 10. Maximum 24-h deepening (mb; positive numbers indicate filling), as a function of maximum pressure difference between the cyclone center and the lowest adjacent col.

large-scale cyclogenesis occurring when more than one small-scale cyclone is present. In a typical scenario, two small-scale cyclones are located along a front, separated from each other by 450 km and from other lows by 1250 km. If one of the small-scale cyclones intensifies rapidly, or if development takes place on the larger scale, eventually one of the low centers will be absorbed into the other. When that happens, the col distance of the developing cyclone increases from 225 km to near 800 km instantaneously. Thus, the individual points toward the right side of Fig. 9 may indicate either the sudden initiation of cyclogenesis on a large scale or the gradual increase in scale or intensity of a smaller cyclone.

5. Cyclone deepening rates

Cyclone intensification is commonly estimated by the change in central pressure (e.g., Sanders and Gyakum 1980). We have called this "deepening," and its usefulness as a measure of intensification depends in part on the assumption that the pressure of a cyclone's environment remains roughly constant. This assumption is often violated when, for example, a weak cyclone propagates toward a region of large-scale low pressure, such as is often present over the North Atlantic. Although the cyclone may remain weak, its central pressure will fall in response to the changing environmental pressure it experiences.

The validity of cyclone deepening as a measure of intensification may be investigated by comparing deepening with pressure deficit. Figure 10 is a scatter diagram of maximum 24-h deepening versus maximum pressure deficit for all traveling cyclones that formed within the study region during the study period. If the environmental pressure were constant along the path of a cyclone, the maximum pressure deficit at-

tained by a cyclone would be at least as large in magnitude as the maximum 24-h deepening it experienced. As can be seen, this assumption is violated by many cyclones. Eleven of the 33 cyclones that deepened at least 12 mb in 24 h failed to attain a pressure deficit as large as their maximum change in central pressure. An impressive outlier is the point nearest the upper-left corner of Fig. 10; the cyclone it represents deepened 24 mb in 24 h without attaining more than one closed isobar (drawn at a 4-mb increment).

While strong deepening does not necessarily imply a large pressure deficit, a large pressure deficit is a good indicator of prior rapid deepening. Of the eight cyclones that attained a maximum pressure deficit of at least 40 mb, all deepened at a maximum rate of at least 20 mb in 24 h. For this limited sample, rapid deepening was a prerequisite for attaining a large pressure deficit.

Unfortunately, in the context of the present study, deepening rate is the only available measure of intensification. The alternative, change in pressure deficit, often varies rapidly with the birth or death of adjacent cyclones and is, therefore, not useful as a general measure of cyclone intensification.

The maximum 12-h deepening rates are shown in histogram form in Fig. 11 for stationary and traveling cyclones. The stationary cyclones are tightly clustered, and their average maximum deepening rate is actually a filling of 1.7 mb. The traveling cyclones approximate the deepening distribution found by Roebber (1984), but the two distributions are not strictly comparable because of differences in geographical area, map frequency, and season. The GALE sample has a greater proportion of cyclones that deepen more than 15 mb

FIG. 11. Maximum 12-h deepening (mb; positive numbers indicate filling) distributions for stationary and traveling cyclones.

FIG. 12. Maximum 12-h deepening (mb; positive numbers indicate filling) distributions for traveling cyclones forming west of the Appalachians (continental cyclones) and east of the Appalachians (Atlantic cyclones).

in 12 h, but this is to be expected because 6-h rather than 12-h maps were used, increasing the likelihood of the period of most rapid deepening being detected. The outlier, a traveling cyclone that filled 18 mb in 12 h (an "antibomb"), was the redevelopment over Alaska and the Yukon of a large-scale cyclone that was undergoing rapid cyclolysis as it passed over the Gulf of Alaska.

Roebber (1984, 1989) has suggested that oceanic cyclones possess different deepening-rate characteristics than continental cyclones. To determine whether this was true during GALE, the traveling cyclone sample was divided into Atlantic and continental cyclones based on whether they formed east or west of the line given by $^{\circ}\text{N} + ^{\circ}\text{W} = 120^{\circ}$, which lies approximately along the western slope of the Appalachians. Cyclones forming to the east of this line are presumed to have access to Atlantic moisture and to have the capacity to be influenced by sea surface temperature gradients during their lifetime. Recall that only one cyclone formed west of the Appalachians and successfully crossed them to reach the coast. Also, because of the lack of notable cyclogenesis in the vicinity of the Gulf of Mexico, the question of whether the Gulf should be considered part of the Atlantic for deepening-rate purposes was moot.

When the cyclones are thus segregated by formation position, marked differences are found. The two deepening distributions are shown in Fig. 12. All of the rapid deepeners (greater than 15 mb in 12 h) were Atlantic cyclones, consistent with the findings of Sanders and Gyakum (1980) and Roebber (1984) that ex-

plosive cyclogenesis is almost exclusively an oceanic phenomenon. A second cluster of Atlantic deepening is centered near -4 mb. The continental cyclones are distributed about a mean of -3.0 mb. This deepening rate is 28% of the mean Atlantic deepening rate of -10.8 mb, a difference significant at the 99% confidence level using the large sample Z test. The Z test assumes that the individual cyclones represent independent samples of deepening rate, an assumption that becomes poor if the study period is short. However, similar differences in continental versus oceanic deepening rates have been observed in other samples (Roebber 1989).

6. Representativeness of the GALE cyclone sample

The cyclogenesis maps (Figs. 2 and 4) are similar to previously published maps, but the extent to which other characteristics of the 61-day cyclone sample are representative of general wintertime cyclones cannot be determined with confidence without performing a much longer climatology. However, the extent to which both the time-mean flow and the level of synoptic-scale transient-eddy activity over the period resemble their corresponding climatological-mean values can be assessed.

The strength of the 500-mb mean GALE jet over the western Atlantic (not shown) was close to normal, although the jet was oriented more southwest-northeast than usual and displaced northward 4° . Over western North America, there was an enhanced time-mean ridge, resulting in weaker-than-normal flow over northern Mexico and a more-northerly-than-normal jet across the central United States. If jet strength is correlated with cyclogenesis, the height anomalies would imply enhanced activity in central Canada and near Newfoundland and reduced activity in the southern United States.

The observed anomalies in 1000-mb bandpass (2.5–6-day) height variations, expressed as a percentage of normal, are shown in Fig. 13. This statistic, which is called a "vstat anomaly," is interpreted as a measure of anomalous synoptic-scale eddy activity (Nealley 1990; Nealley and Dole 1991). Along the East Coast, eddy activity was generally within 10% of normal. The northward displacement of the jet over the Atlantic is associated with anomalously low eddy activity near 35°N , 45°W . Below-normal eddy activity is also found over the Gulf of Mexico and in the Great Basin region. Along the Rocky Mountains, eddy activity was stronger than normal to the north and weaker than normal to the south. Despite these variations, most of the study region had eddy activity within 20% of normal levels during GALE. We infer that the cyclone sample should be grossly representative of climatological conditions for the period but with below-normal cyclone activity in the southwestern United States, or originating in the Gulf of Mexico, and above-normal cyclone activity in

FIG. 13. Mean GALE 1000-mb vstat anomalies (thick lines, negative anomalies dashed), expressed as a percentage of normal. Also shown (thin lines) are climatological vstat values. Positive anomalies imply enhanced synoptic-scale eddy activity.

Canada and a possibly enhanced number of Alberta clippers.

7. Discussion

Two stratifications have been found to be useful when considering the GALE cyclone sample: stationary versus traveling cyclones and small-scale versus large-scale cyclones.

Stationary cyclones were found to exist almost exclusively near the Rocky Mountains and in the lee of the southern Appalachians, suggesting that they are directly forced by orography. The striking maximum of stationary cyclones over the southeastern United States is a consequence of cold fronts impinging on the southern Appalachians from the northwest. The class of traveling cyclones includes cyclones that would have been the subject of earlier climatologies, such as Pettersen (1956), but also includes mobile smaller-scale cyclones.

By requiring that lows be merely a pressure minimum instead of possessing a minimum number of closed isobars, we have included in the survey many small-scale cyclones of possible dynamical importance that would otherwise have been missed. We have also found that the initial formation (dissipation) of low centers occurs farther west (east) than indicated by previously published cyclogenesis (cyclolysis) studies.

The class of cyclones that attains a maximum radius of 750 km or less includes most stationary cyclones

and many traveling cyclones. In contrast to large-scale cyclones, most small-scale cyclones vanish less than a day after they first appear. The pressure deficits of small-scale cyclones, when normalized by radius to obtain a measure of intensity, are comparable to most large-scale cyclones. Most large-scale cyclones appear initially as small-scale cyclones, and although this fact may be of dynamical significance, it prompts the question of how one could expect to distinguish between a future large-scale cyclone and a permanent small-scale one.

The existence and frequent occurrence of traveling small-scale cyclones was discussed by Willett and Sanders (1959), who noted their importance for rapid local weather variations and predicted that their geographical distribution should be similar to that of large-scale cyclones. The latter prediction may be checked by means of Fig. 14, which shows the cyclogenesis locations of traveling small-scale cyclones (a subset of the cyclogenesis events in Fig. 3). The overall pattern is indeed similar, but there are some suggestive differences. In particular, maxima are noted east of Georgia (south of the maximum in the lee of the southern Appalachians) and southeast of Texas. Both of these locations are south of the main bands of cyclone activity, and are positioned over the northwestern edges of warm bodies of water. This implies that the local maximum of sensible and latent heating, displaced from the track of primary cyclones, may be leading to small-scale cyclogenesis. The local geometry favors cyclogenesis, both

FIG. 14. Number of cyclogenesis events per $3 \times 10^5 \text{ km}^2$ during GALE, traveling small-scale cyclones only.

by ensuring a local negative Laplacian of surface heating (Petterssen 1956) and by causing those areas to be the first areas of low-level latent heating to be affected by eastward-traveling regions of large-scale forcing.

Aside from these maxima, and other maxima related to orographic features discussed earlier, sporadic small-scale cyclogenesis events occurred throughout the domain, indicating that many traveling small-scale cyclones are not triggered by variations in the topography. The differences between stationary and traveling small-scale cyclones and the existence of occasional small-scale cyclogenesis throughout the domain, with a few maxima apparently related to the topography, suggests a broad range of small-scale cyclogenetic mechanisms.

Beyond their effects on local weather, Fig. 9 shows that small-scale cyclones can also be precursors to larger-scale cyclone developments. From these statistics, it cannot be determined whether the small-scale cyclones play an important role in larger-scale cyclogenesis. A direct role, in which an isolated cyclone somehow grows in scale or a preexisting small-scale cyclone interacts with an approaching upper-level potential-vorticity anomaly, should not produce a cyclone much larger than the initial small-scale cyclone. An indirect role might involve the triggering of latent heat release, the enhancement of the surface baroclinic zone, and the development of localized surface vorticity that experiences rapid spinup as large-scale ascent begins. Alternatively, the presence of small-scale cyclones

might merely indicate the existence of a region favorable for large-scale baroclinic development.

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