Extratropical Cyclones with Multiple Warm-Front-Like Baroclinic Zones and Their Relationship to Severe Convective Storms

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ABSTRACT

Extratropical cyclones over the central United States and southern Canada from the years 1982 and 1989 were examined for the presence of two or more (multiple) warm-front-like baroclinic zones, hereafter called MWFL baroclinic zones. Of the 108 cyclones identified during this period, 42% were found to have MWFL baroclinic zones, where a baroclinic zone was defined as a magnitude of the surface temperature gradient of 8°F (4.4°C) 220 km^{-1} over a length of at least 440 km. The largest frequency of cyclones with MWFL baroclinic zones occurred during April, May, August, and September. Ninety-four percent of all baroclinic zones were coincident with a magnitude of the dewpoint temperature gradient of at least 4°F (2.2°C) 220 km^{-1}, and 81% of all baroclinic zones possessed a wind shift of at least 20°, suggesting that these baroclinic zones were significant airmass and airstream boundaries. Although cyclones with MWFL baroclinic zones formed in a variety of ways, two synoptic patterns dominated. Thirty-eight percent of cyclones with MWFL baroclinic zones formed as a cold or stationary front from a previous cyclonic system was drawn into the circulation of a cyclone center, forming the southern baroclinic zone. Twenty-two percent of cyclones with MWFL baroclinic zones formed as a cold front to the north of the cyclone center was drawn into the circulation of the cyclone, forming the northern baroclinic zone. Other synoptic patterns included outflow boundaries (9%), chinook fronts (4%), return flow from the Gulf of Mexico (4%), and unclassified (22%). Although the frequency of severe weather in cyclones was roughly the same for cyclones with and without MWFL baroclinic zones, the presence of the southern baroclinic zone provided a mechanism to focus the location of severe weather, showing their utility for severe weather forecasting. Despite the potential for severe convective storms along these southern baroclinic zones, 51% were not identified on the National Meteorological Center (now known as the National Centers for Environmental Prediction) surface analyses, indicating the importance of performing real-time surface isotherm analysis.

1. Introduction

Over 80 years ago, Norwegian meteorologists formulated a conceptual model to describe the structure and evolution of extratropical cyclones (Bjerknes 1919; Bjerknes and Solberg 1922). Because of the simplicity of the Norwegian cyclone model and because it was derived from analyses of maritime cyclones approaching northwestern Europe, the application of the Norwegian cyclone model to cyclones in other parts of the world may have limitations. For example, cyclones in Europe have access to different air masses and traverse different topography than cyclones in the United States, implying that modifications to the Norwegian cyclone model for cyclones in the United States may be required (e.g., Mass 1991).

The Norwegian cyclone model did not achieve immediate acceptance by the U.S. meteorological com-

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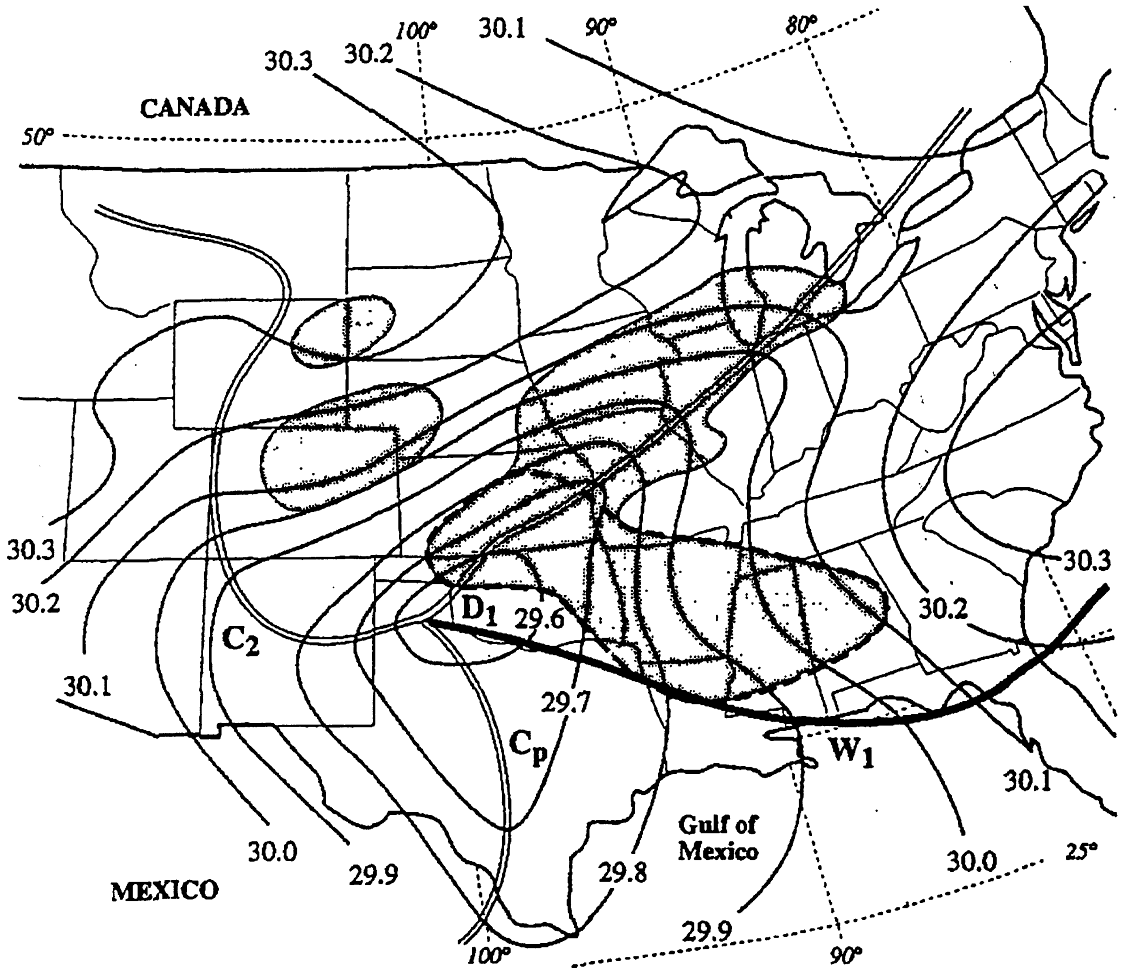

FIG. 1. Reproduction of Rossby and Weightman's (1926) sea level pressure analysis (in in. of mercury) for 0100 UTC 18 Feb 1926: C_p was analyzed as a cold front, W_1 as a warm front, C_2 as a secondary cold front, and D_1 as the cyclone center. Areas of precipitation are shaded. Dashed line surrounding one precipitation area is discussed in the text. [From Hobbs et al. (1996).]

munity (e.g., Namias 1983; Newton and Rodebush Newton 1999). To encourage its acceptance, Rossby and Weightman (1926) showed how a central U.S. cyclone could be analyzed using the Norwegian methods (Fig. 1). On their analysis, the cyclone was labeled D_1, C_p was identified as the principal cold front, and C_2 was referred to as the secondary cold front (Fig. 1). The part of C_2 to the northeast of the low center appeared to act as a warm front, as indicated by warm-air advection on the original maps (not shown). Rossby and Weightman (1926) referred to W_1 as the warm front. Thus, this cyclone possessed two warm-front-like features and two cold-front-like features, distinctly non-Norwegian in structure (cf. Bjerknes 1919). This structure is similar to the Canadian three-front conceptual model in which two warm and cold fronts separate arctic, polar, and tropical air masses (e.g., Penner 1955; Anderson et al. 1955; Galloway 1958, 1960). In this paper, we focus only on the multiple warm-front-like structures. Henceforth, we refer to a cyclone with two or more (multiple) warm-front-like baroclinic zones as possessing *MWFL baroclinic zones.*[1] In Fig. 1, we refer to the part of baroclinic zone C_2 to the east of the low center as the *northern baroclinic zone* and W_1 as the *southern baroclinic zone.*

More recently, Hobbs et al. (1990, 1996) reexamined the structure of cyclones in the central United States and proposed a new conceptual model. Their conceptual model featured a warm-sector precipitation band (e.g., the area enclosed by the dashed line in Fig. 1) that was caused by frontogenesis at midlevels, a feature they

[1] We had considered the terms multiple baroclinic zones, multiple warm fronts, secondary warm fronts, and warm-sector baroclinic zones as possible alternatives to MWFL baroclinic zones, but those terms possessed their own ambiguities or limitations. Therefore, we feel that MWFL baroclinic zones is the least problematic term we could propose for these non-Norwegian cyclone structures.

termed a cold front aloft. In presenting this conceptual model, Hobbs et al. (1996) reanalyzed the cyclone discussed by Rossby and Weightman (1926). Each of the features in the Rossby and Weightman (1926) cyclone was related to and compared to a similar feature in the Hobbs et al. (1996) model except for W_1, which Hobbs et al. (1996) did not consider a significant feature.

Forecasters at the Storm Prediction Center (SPC) have long observed baroclinic zones similar to W_1 associated with low pressure systems advancing through the central and eastern United States. These baroclinic zones can serve as a focal point for the development of severe convective storms. For example, Miller's (1972) type C tornado-producing synoptic pattern features an east–west warm-front-like boundary along which tornadic storms develop. Yet, research on these baroclinic zones has not been performed. The purpose of this paper is to perform an exploratory study to raise awareness of cyclones with MWFL baroclinic zones—specifically, to determine the frequency of occurrence and seasonality of cyclones with MWFL baroclinic zones, the characteristics of these features, the synoptic patterns that favor their occurrence, and their association with severe convective storms.

The remainder of this paper is as follows. Section 2 describes the methodology employed in constructing the dataset of cyclones analyzed in this study. Each of these cyclones is examined for the occurrence of MWFL baroclinic zones. Section 3 presents the analysis of this dataset, demonstrating that cyclones in the central United States and southern Canada are frequently associated with MWFL baroclinic zones. In addition, the characteristics of these MWFL baroclinic zones are described, including their attendant magnitudes of the gradients of temperature, dewpoint, and wind direction. The synoptic patterns by which cyclones with MWFL baroclinic zones develop are contained in section 4. In section 5, the occurrence of severe convective storms in relation to the baroclinic zones is explored. Section 6 concludes this study.

2. Methodology

To calculate the percentage of cyclones with MWFL baroclinic zones, a dataset was constructed containing all cyclones over the central United States and southern Canada for the years 1982 and 1989. These years were chosen for two reasons. First, the years were selected to maximize the number of National Meteorological Center [NMC, now known as the National Centers for Environmental Prediction (NCEP)] manually analyzed 3-h surface maps archived on microfilm at the SPC. This step avoided the perceived degradation in the quality of the surface analyses in more recent years from the switch to automated isobar analysis (e.g., Bosart 1989). Second, we wanted to compare cyclones in a year with an above average number of tornadoes and significant (F2 intensity or greater) tornadoes (1982) to cyclones in a year with a below average number of tornadoes and significant tornadoes (1989). The selection of these years was based on the operational experience of SPC forecasters and was supported by the SPC severe weather database having twice as many significant tornadoes in 1982 (248) compared to 1989 (123).

For each of the two years, a dataset of cyclone dates was constructed by examining daily 1200 UTC surface maps in the weekly National Oceanic and Atmospheric Administration (NOAA) publication *Daily Weather Maps.* A cyclone was added to the dataset if it was associated with at least one closed isobar (contour interval = 4 mb) on at least two consecutive 1200 UTC surface maps, similar to the criteria of Zishka and Smith (1980). The cyclone also needed to be centered between 30° and 55°N, and between the front range of the Rockies and western slopes of the Appalachians. These domain boundaries generally allowed for an adequate amount of surface data to construct a reliable manual reanalysis for identifying baroclinic zones (described in the next paragraph), yet limited direct orographic effects due to the variations in surface temperature and dewpoint with elevation over short distances. Two separate cyclones appearing on the same day were both disregarded if the distance between them was less than about 1100 km (10° latitude). This criterion was added to ensure that each individual cyclone could be examined without being directly affected by another cyclone. If the separation between the two cyclones was greater than 1100 km, the cyclone with the lower central pressure was added to the dataset.

Next, NMC's 3-h surface maps were examined for each case. The process by which NMC constructed these maps and the notations on the maps are described in Corfidi and Comba (1989). Each previously identified cyclone was required to meet all of the above criteria for each of the nine surface maps from 1200 to 1200 UTC on successive days. If the criteria were met for multiple days, the day on which the cyclone had the lowest central pressure was chosen for analysis in order to limit the number of surface maps to analyze. This process resulted in 108 cyclone dates: 55 from 1982 and 53 from 1989.

The 1800 UTC NMC surface maps for each of the 108 cyclone dates were manually analyzed for temperature and dewpoint using a contour interval of 4°F (2.2°C). The time 1800 UTC was chosen to limit the occurrence of local minima in temperature due to nocturnal cooling and convective outflows. In order for a region of thermal gradient to be considered a baroclinic zone, a temperature difference of at least 8°F (4.4°C) over 2° latitude (220 km) was required (e.g., Fig. 2). Our criterion is roughly half that of Sanders (1999), who used 8°C 220 km^{-1} to identify what he called a moderate baroclinic zone. Here, we chose a weaker criterion than that of Sanders (1999) in order to examine a wider range of baroclinic zones. We analyzed the maps in degrees Fahrenheit since the data were plotted on the

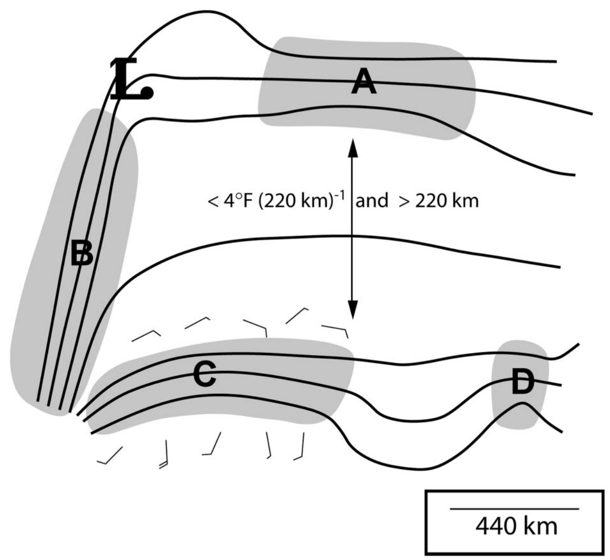

FIG. 2. Schematic illustrating some of the criteria used in identifying baroclinic zones (shaded), described in the text. Solid lines represent surface isotherms contoured every 4°F (2.2°C). A, B, C, and D label shaded regions of temperature gradient greater than 8°F (4.4°C) 220 km^{-1}. The wind barbs outside baroclinic zone C are from stations used to calculate the average wind direction on each side of the baroclinic zone.

NMC maps using that temperature scale. Two baroclinic zones were considered to be distinct if the area separating them possessed a magnitude of the temperature gradient of no more than 4°F (2.2°C) 220 km^{-1}, the area was at least 440 km long, and the spacing between the two baroclinic zones was at least 220 km (Fig. 2). Finally, each region of thermal gradient meeting the criteria for a baroclinic zone needed to be at least 440 km long (Fig. 2). The length was chosen to be consistent with the upper end of Fujita's (1981) mesoscale, 400 km. Thus, we were looking to identify baroclinic zones that were synoptic scale in length.

The process of identifying MWFL baroclinic zones involved performing the following: First, consider a north–south-oriented line segment extending north of the low center. The line segment was rotated anticyclonically (clockwise in the Northern Hemisphere) about the low center until a baroclinic zone meeting the criteria described above was encountered, which was termed the northern baroclinic zone and represented the northern edge of the warm sector. Next, consider a north–south-oriented line segment extending south of the low center. This line segment was rotated up to 180° anticyclonically until a baroclinic zone (not necessarily meeting the baroclinic zone criteria above) was encountered, which represented the western boundary of the warm sector. In some cases, the warm sector was unbounded to the west.

With the warm sector defined in this manner, baroclinic zones within the warm sector meeting the criteria described above were identified. If no baroclinic zones were identified in the warm sector, the cyclone was said to possess only a northern baroclinic zone and the cyclone was not considered to have MWFL baroclinic zones. If one baroclinic zone was identified within the warm sector, it was termed the southern baroclinic zone and the cyclone was considered to have MWFL baroclinic zones. If two baroclinic zones existed within the warm sector, the southernmost of the two was termed the southern baroclinic zone and the northernmost of the two was termed the *central baroclinic zone.*

An example of a hypothetical isotherm analysis is presented in Fig. 2 to illustrate the criteria described above. Regions A, B, and C in Fig. 2 meet the criteria and represent the northern baroclinic zone, western boundary of the warm sector, and southern baroclinic zone, respectively. If a third baroclinic zone was identified between A and C and was separated by at least 220 km from the northern and southern baroclinic zones, it would represent the central baroclinic zone. Region D does not meet the 440-km length criteria and, thus, would not be considered a baroclinic zone.

Applying the procedure described above to the 108 cyclones resulted in 45 cyclones (42%) with MWFL baroclinic zones: 23 from 1982 and 22 from 1989. Only three (7%) of the 45 cyclones with MWFL baroclinic zones contained three baroclinic zones. This dataset yielded a total of 93 baroclinic zones for the cyclones with MWFL baroclinic zones (45 northern, 45 southern, and 3 central baroclinic zones). Of the remaining 63 cyclones without MWFL baroclinic zones, 58 had only one baroclinic zone and 5 had no baroclinic zones meeting the above criteria.

Since some baroclinic zones may represent fronts, we examined whether these MWFL baroclinic zones were associated with changes in wind direction. The following method was employed. The length of each baroclinic zone was bisected near its middle. At the point of bisection, a line perpendicular to the baroclinic zone was drawn to the cold and warm sides of the baroclinic zone until it extended outside the defined magnitude of the temperature gradient criteria above. The nearest surface observing station to the point of bisection was examined, in addition to the closest two surface observing stations on either side that were located immediately outside of the baroclinic zone (as defined previously). Up to five surface observing stations were examined in this manner. An average wind direction was calculated from five stations on each side of the baroclinic zone. Figure 2 shows an example of the 10 surface observing stations used on both the cold and warm sides of baroclinic zone C. The mean wind directions on either side of the baroclinic zone were compared to determine how the wind changed, if at all, across the baroclinic zone.

3. Description of cyclones with MWFL baroclinic zones

The annual cycle in the frequency of cyclones with MWFL baroclinic zones was examined. Of the 108 cy-

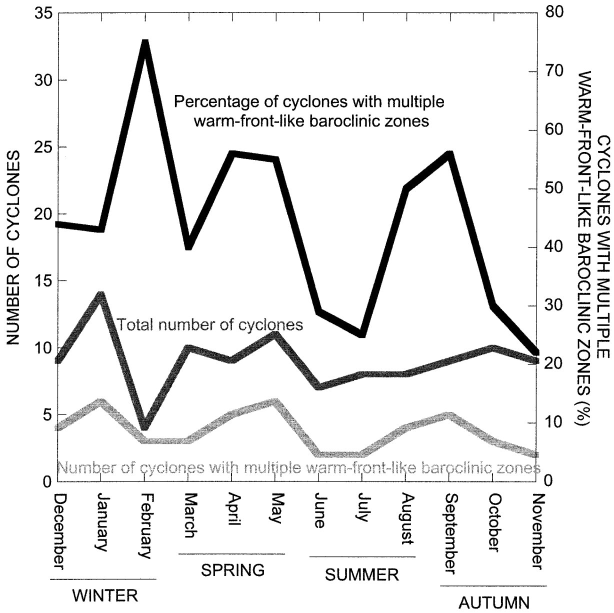

FIG. 3. Number of cyclones, number of cyclones with MWFL baroclinic zones, and percentage of cyclones with MWFL baroclinic zones, by month.

clones, 30 occurred in spring [March–April–May (MAM)], 28 in autumn [September–October–November (SON)], 27 in winter [December–January–February (DJF)], and 23 in summer [June–July–August (JJA)]. The observed annual cycle in the frequency of cyclones (Fig. 3) was consistent with previous work that demonstrated fewer cyclones occurred during the summer over the United States (e.g., Zishka and Smith 1980). The percentage of cyclones with MWFL baroclinic zones also varied annually; three maxima, each greater than 50%, occurred in February, April, and May, and again in August and September (Fig. 3). Because of February's small sample size, however, this month appeared to be an outlier, having only four cyclones (three less than in June, the month with the next fewest cyclones), but three of those four had MWFL baroclinic zones. (February 1982 and February 1989 tended to be dominated by anticyclones in the central United States and were below average in temperature in the central United States, perhaps explaining the relatively low number of cyclones.) Excluding February, 20 (44%) of all 45 cyclones with MWFL baroclinic zones occurred in these four months (April, May, August, and September). Throughout the rest of this section and the next (section 4), only these 45 cyclones with MWFL baroclinic zones will be discussed.

The positions of the northern and southern baroclinic zones appear to exhibit an annual cycle (Fig. 4). The northern baroclinic zones ranged farther west and south in winter than summer (cf. Figs. 4a,c). The southern baroclinic zones had an eastward progression from winter to spring as two distinct maxima formed: one over the upper midwest United States and the other over the southern plains and southeast United States (Figs. 4a,b). The southern baroclinic zones shifted west from spring to summer (Figs. 4b,c). The regions occupied by baroclinic zones covered a larger area in the winter than in the summer (cf. Figs. 4a,c). Additionally, the average length of the baroclinic zones was greater in the winter and spring (Figs. 4a,b) than in the summer and autumn (Figs. 4c,d). We speculate that the stronger mean baroclinicity over the United States in winter and spring resulted in a greater length of the baroclinic zone meeting the magnitude of the temperature gradient criterion described in section 2.

The maximum magnitudes of the temperature gradients within the northern and southern baroclinic zones were compared. The magnitude of the northern gradient was the largest in 28 (62%) of the 45 cyclones with MWFL baroclinic zones, whereas the magnitude of the southern gradient was the largest in 15 cyclones (33%). The magnitudes of the northern and southern temperature gradients were equal in the remaining two cyclones (4%).

The magnitudes of the dewpoint temperature gradients across the baroclinic zones were also analyzed and such gradients were found to be associated with nearly all of the baroclinic zones. Of the 93 baroclinic zones, 47 (51%) contained a magnitude of the dewpoint temperature gradient comparable to or stronger than the criteria for the magnitude of the temperature gradient [at least 8°F (4.4°C) 220 km^{-1} and at least 440 km in length within the boundaries of the baroclinic zone]. Another 40 (43%) of the baroclinic zones contained a magnitude of the dewpoint temperature gradient 4°–8°F (2.2°–4.4°C) 220 km^{-1}. The six remaining baroclinic zones (6%) had a magnitude of the dewpoint temperature gradient less than 4°F (2.2°C) 220 km^{-1}. Thus, 87 of 93 baroclinic zones (94%) were associated with a substantial magnitude of the moisture gradient, suggesting that these baroclinic zones may be substantial airmass boundaries.

Sanders (1999) refers to baroclinic zones with significant wind shifts across them as fronts. In this study, we define a significant wind shift as a direction change of greater than 20°. Overall, the wind shifts ranged from −70° to +220° (Fig. 5). (A positive wind shift denotes a cyclonic shift wind across the front when moving from the warm to cold side, whereas a negative wind shift denotes an anticyclonic wind shift across the front.) Sixty-seven of the 93 baroclinic zones (72%) had a cyclonic wind shift of greater than or equal to +20° and eight baroclinic zones (9%) had an anticyclonic wind shift of less than −20°. The reason for the anticyclonic wind shift was not apparent, as there did not seem to be any common scenario for these events. Regardless, the vast majority of these baroclinic zones not only represented a strong magnitude of the temperature gradient, but also a substantial wind shift, suggesting that they likely qualified as fronts.

Since the majority of these baroclinic zones were as-

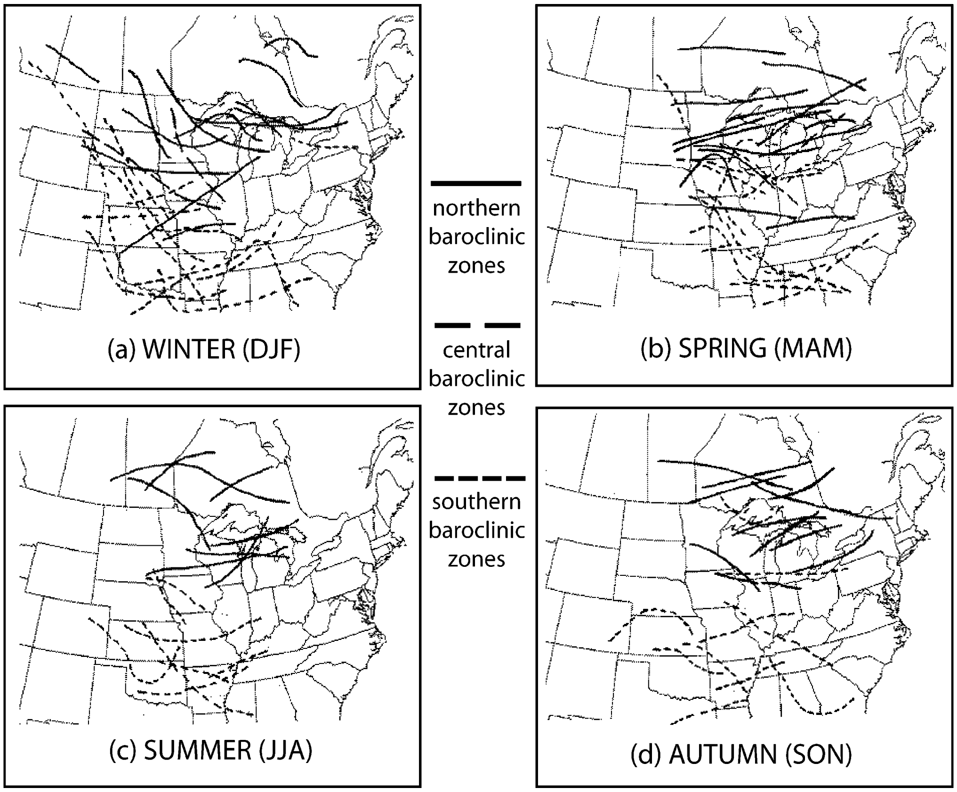

FIG. 4. Seasonal distribution of 1800 UTC northern (solid lines), central (long dashed lines), and southern (short dashed lines) baroclinic zones for cyclones with MWFL baroclinic zones: (a) winter, (b) spring, (c) summer, and (d) autumn.

sociated with large magnitudes of gradients of moisture and wind direction changes, the results from this section suggest that these baroclinic zones were indicative of significant airmass and airstream boundaries. In the next section, we explore the synoptic patterns by which cyclones develop such MWFL baroclinic zones.

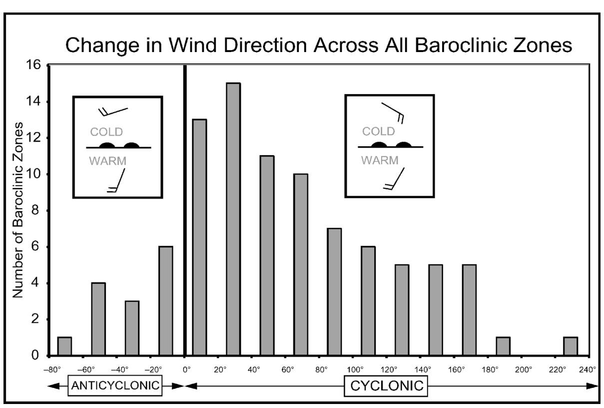

FIG. 5. Distribution of the change in wind direction (from the warm side to the cold side) across each identified baroclinic zone. Wind direction values were obtained as described in the text and shown in Fig. 2.

4. Synoptic patterns for the formation of cyclones with MWFL baroclinic zones

To understand the synoptic patterns that produce cyclones with MWFL baroclinic zones, a manual classification scheme was constructed by examining the 3-h NMC surface maps for each of the 45 cyclones with MWFL baroclinic zones. We identified five principal ways cyclones with MWFL baroclinic zones form, plus an unclassified category (Table 1).

Of the 45 cyclones with MWFL baroclinic zones, 17 (38%) resulted from a cold or stationary front from a previous cyclonic system being drawn into the circulation of a cyclone center, forming the southern baroclinic zone (Fig. 6). The previous baroclinic zone was

TABLE 1. Synoptic patterns for the 45 cyclones with MWFL baroclinic zones in this study.

Synoptic pattern	No. of events	Percentage
Attachment of the southern baroclinic zone	17	38
Attachment of the northern baroclinic zone	10	22
Outflow boundary	4	9
Chinook front	2	4
Return flow	2	4
Unclassified	10	22

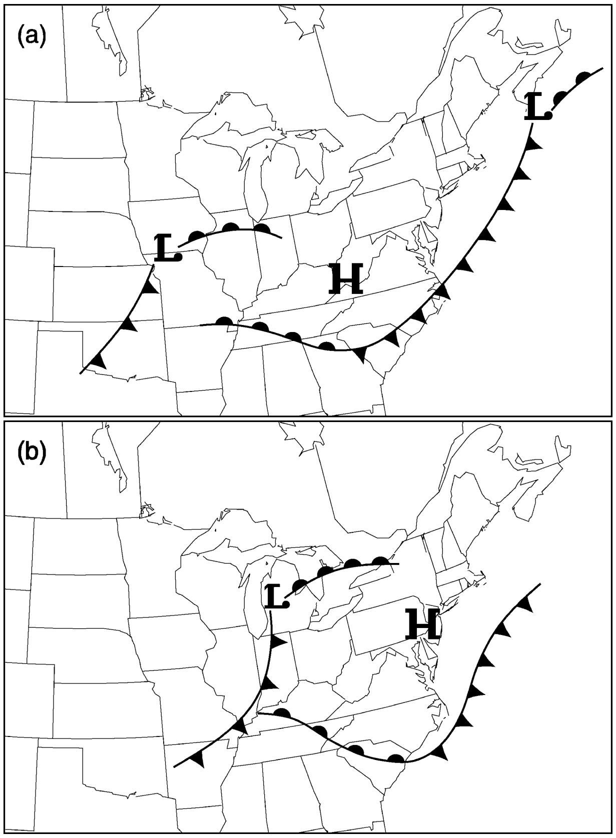

FIG. 6. Schematic illustration of the attachment of the southern baroclinic zone. The symbols H and L represent the positions of surface highs and lows, respectively. Frontal notation is standard. Panels (a) and (b) are separated by 6–18 h.

left behind by an earlier cyclone farther east (Fig. 6a), and was later attached to the frontal structure of a new cyclone emerging from the Rocky Mountains (Fig. 6b). When the previous baroclinic zone joined with the new cyclone, the new structure was composed of two distinct baroclinic zones. The most common way this occurred was for the cold front to catch up to the previous baroclinic zone. There were cases, however, in which the previous baroclinic zone attached directly into the center of the new cyclone. Attachment is similar to what happens in periodic baroclinic channel models: the anticyclone preceding the cyclone is associated with the movement of cold air equatorward, yet the developing warm front on the cyclone forms farther poleward (e.g., Fig. 5.10 in Hoskins 1990; Fig. 5 in Thorncroft et al. 1993), thus forming MWFL baroclinic zones.

Of the 45 cyclones with MWFL baroclinic zones, 10 (22%) resulted from a cold front to the north of the cyclone center being drawn into the circulation of the cyclone, forming the northern baroclinic zone (Fig. 7). In this synoptic pattern, a baroclinic zone (usually a cold front moved equatorward out of Canada (Fig. 7a). At the same time, an eastward-moving, open-wave cyclone emerged from the Rocky Mountains, merging with

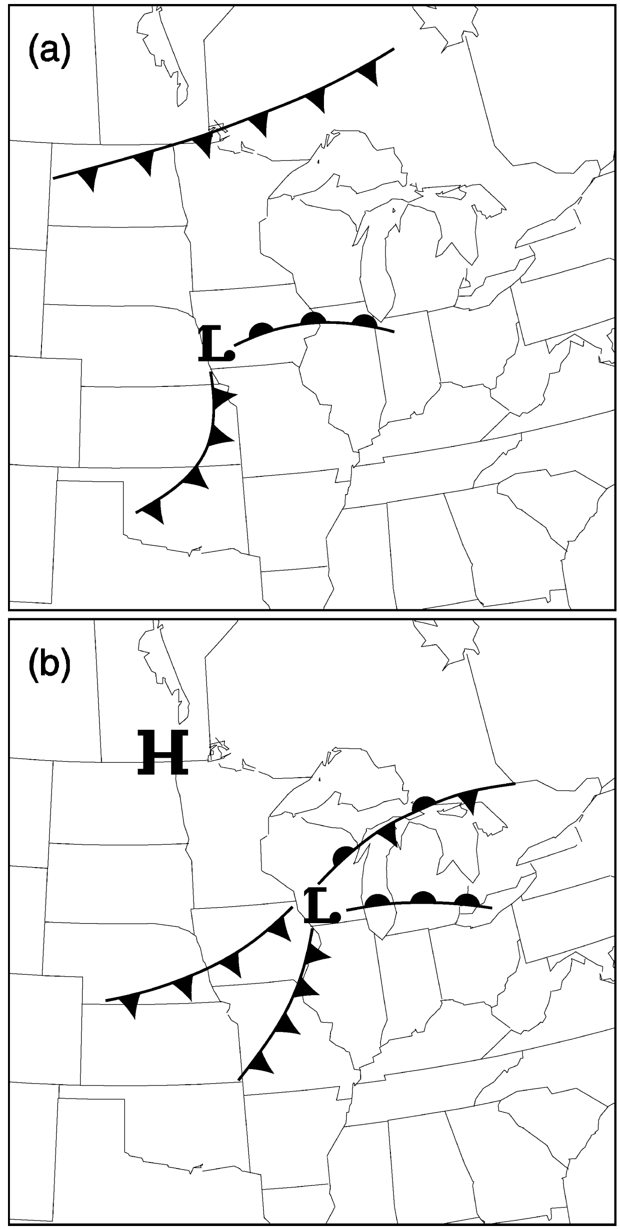

FIG. 7. Schematic illustration of the attachment of the northern baroclinic zone. The symbols H and L represent the positions of surface highs and lows, respectively. Frontal notation is standard. Panels (a) and (b) are separated by 6–18 h.

the equatorward-moving baroclinic zone (Fig. 7b). The cyclone then continued eastward with two distinct baroclinic zones. Such cases of attachment of an equatorward-moving cold front are similar to that discussed by Neiman et al. (1998, Fig. 5).

These two synoptic patterns accounted for 60% of all the cyclones with MWFL baroclinic zones. Three other less frequent synoptic patterns also occurred. There were four cases (9%) containing an outflow boundary or gust front. Although analysis of 1800 UTC NMC surface maps was chosen in an attempt to limit the influence of convection, there were still cases in which convection inside the warm sector produced an outflow boundary as the southern baroclinic zone. The outflow boundaries formed as the result of cooler air from thunderstorm outflow and could be easily identified by the presence of thunderstorms at the surface stations. In two cases (4%), the southern baroclinic zone was a chinook front: a warm front due to warm downsloped air in the lee of the Rockies displacing the much colder continental air (e.g., Oard 1993). Return flow accounted for two cases (4%). Here, an anticyclone initially was associated with the advection of cold, dry air into the Gulf of Mexico. This air mass then moistened and warmed over the Gulf of Mexico, prior to being advected back into the southern and central United States due to the establishment of boundary layer return flow in association with the departing anticyclone (e.g., Crisp and Lewis 1992; Lewis and Crisp 1992; Thompson et al. 1994). Coastal frontogenesis may also have played a role in enhancing the magnitude of the temperature gradient across the return-flow boundary. This return-flow boundary then attached to a cyclone emerging from the lee of the Rocky Mountains, forming the southern baroclinic zone. Finally, there were 10 cases (22%) that were left unclassified, not fitting into any of the groups previously discussed. As Doswell (1991) has argued, such taxonomies with inexact morphological criteria should have an ''unclassified'' category, since the atmosphere is a continuum and, thus, not all cases fit neatly into specific, predefined categories. For example, some of these events may be due to differential diabatic heating due to horizontal variations in cloudiness or snow cover.

5. Relationship to severe convective storms

In this section, the relationship between cyclones with and without MWFL baroclinic zones and the occurrence of severe convective storms is explored. Severe weather is defined by the National Weather Service as hail 0.75 in. (1.9 cm) or greater in diameter, wind gusts of at least 50 kt (26 m s^{-1}), or tornadoes (e.g., Johns and Doswell 1992). Significant severe weather is defined as hail 2 in. or greater (5.1 cm), wind gusts of at least 65 kt (33 m s^{-1}), and F2 intensity or greater tornadoes (Hales 1988). A significant tornado is defined as an F2 intensity or greater tornado. Reports of severe weather for the cases in this study were obtained through the Severe Plot Version 2.0 software (Hart 1993). In this study, we considered severe weather to be associated with the baroclinic zone if reports occurred within 220 km in any direction from the 1800 UTC position of the baroclinic zone and within 6 h on either side of 1800 UTC (1200–0000 UTC) to encompass the time of maximum diurnal heating and likely convective initiation. The 220-km distance criterion was determined to account for the movement of the baroclinic zone and any offset of the severe weather reports from the baroclinic zone (e.g., due to possible elevated convection north of the baroclinic zone). The association between severe weather reports and the northern baroclinic zones was difficult to ascertain in some cases because some of the northern baroclinic zones occurred in southern Canada, where datasets of severe weather were not readily available. For this reason, we consider only the southern baroclinic zones in this section.

TABLE 2. (a) Number and percentage of cyclones with severe weather reports of various types (severe, tornado, significant severe, and significant tornado) in the warm sectors of cyclones without MWFL baroclinic zones. (b) Number and percentage of cyclones with severe weather reports of various types within 220 km and between 1200 and 0000 UTC in the vicinity of the southern baroclinic zones in cyclones with MWFL baroclinic zones.

	No. of events	Percentage
(a) 63 cyclones without MWFL baroclinic zones		
Severe	33	52
Tornado	19	30
Significant severe	17	27
Significant tornado	12	19
(b) 45 cyclones with MWFL baroclinic zones		
Severe	25	56
Tornado	14	31
Significant severe	13	29
Significant tornado	9	20

For cyclones without MWFL baroclinic zones, we considered severe weather reports associated with the cyclone if the reports fell within the warm sector, defined in the following manner. The western and northern boundaries were defined previously in section 2. The southernmost boundary was the continental United States, and the easternmost boundary was the easternmost limit of southerlies inside the warm sector (e.g., calm to northerly winds existed to the east of the easternmost boundary of the warm sector). This produced quite a large warm sector in some situations that may exaggerate the importance of severe weather in cyclones without MWFL baroclinic zones, a point we return to very shortly.

Specifically, 33 of the 63 (52%) cyclones without MWFL baroclinic zones were associated with severe weather reports (Table 2a), whereas 25 of the 45 (56%) cyclones with MWFL baroclinic zones were associated with severe weather reports in the region along the southern baroclinic zone, as defined above (Table 2b). In addition, 5 of the remaining 20 cyclones (25%) with MWFL baroclinic zones had severe weather reports outside the region along the southern baroclinic zone. Although it would appear that the presence of southern baroclinic zones in a cyclone with MWFL baroclinic zones does not substantially change the *likelihood* of severe weather by the criteria in this study, the presence of southern baroclinic zones strongly indicates a favored *location* for the occurrence of severe weather, especially when compared to the potentially large warm-sector

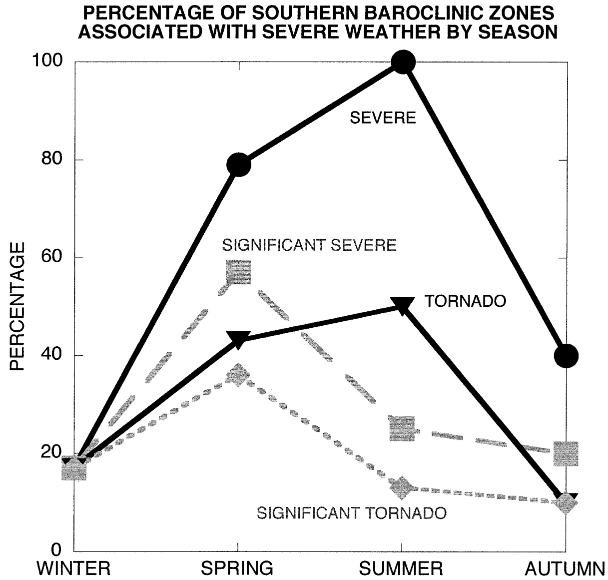

FIG. 8. The percentage of southern baroclinic zones associated with severe weather, significant severe weather, tornado, and significant tornado reports for each season (winter, DJF; spring, MAM; summer, JJA; and autumn, SON). Note that every southern baroclinic zone in the winter that was associated with severe weather reports was also associated with at least one report of a significant tornado.

area for cyclones without MWFL baroclinic zones. Thus, we argue that the southern baroclinic zone provides a region for forecasters to focus on for the potential occurrence of severe weather.

In addition, the southern baroclinic zones were quite likely to be associated with severe convective storms. For example, 56% of all southern baroclinic zones were associated with severe weather reports, with as many as 20% associated with significant tornadoes (Table 2b). Finally, the percentage of southern baroclinic zones with reports of severe weather varied by season, with spring and summer having the highest percentages and winter and autumn having the lowest percentages (Fig. 8).

In 1982, 57% (30%) of the southern baroclinic zones were associated with reports of severe weather (significant severe weather), compared to 55% (32%) in 1989. The percentages of southern baroclinic zones associated with tornado reports were 26% and 32% in 1982 and 1989, respectively. The percentages of southern baroclinic zones associated with significant tornado reports were 22% and 18% in 1982 and 1989, respectively. Thus, there do not appear to be substantial differences in the rates of occurrence of severe convective storms along southern baroclinic zones between these two years (section 2).

Finally, we examined the NMC 1800 UTC surface maps to see if these southern baroclinic zones were analyzed. Of the 45 cyclones with MWFL baroclinic zones, 23 cyclones (51%) did not have the southern baroclinic zones analyzed as any type of boundary on the NMC 1800 UTC surface maps. Of the unanalyzed baroclinic zones, 39% were associated with severe convective storms. Thus, the potential significance of these baroclinic zones for forecasting severe convective storms cannot be overemphasized. Real-time surface isotherm analysis is one way to help identify these baroclinic zones in an operational setting, as previously argued by Sanders and Doswell (1995).

6. Conclusion

One hundred and eight cyclones were identified in the central United States and southern Canada for the two years 1982 and 1989. These cases were then examined to find the number and characteristics of cyclones with MWFL baroclinic zones—defined here as the presence of two or more (multiple) warm-front-like baroclinic zones. Forty-five of the 108 cyclones (42%) contained MWFL baroclinic zones.

The greatest frequency of cyclones with MWFL baroclinic zones occurred during April, May, August, and September. These four months contained almost half (44%) of all the cyclones with MWFL baroclinic zones. In nearly two-thirds of the cyclones with MWFL baroclinic zones examined, the northern baroclinic zone had a larger magnitude of the temperature gradient. MWFL baroclinic zones were often significant boundaries between air masses or airstreams, indicating that they were fronts. For example, 94% of all the baroclinic zones were coincident with a magnitude of the dewpoint temperature gradient and 81% possessed a wind shift of greater than 20°.

Although cyclones with MWFL baroclinic zones formed in a variety of ways, two synoptic patterns dominated. Thirty-eight percent of cyclones with MWFL baroclinic zones formed as a cold or stationary front from a previous cyclonic system was drawn into the circulation of a cyclone center, forming the southern baroclinic zone. Twenty-two percent of cyclones with MWFL baroclinic zones formed as a cold front to the north of the cyclone center was drawn into the circulation of the cyclone, forming the northern baroclinic zone. Other cyclones formed MWFL baroclinic zones from outflow boundaries, chinook fronts, return-flow boundaries, or were unclassified.

Severe convective storms are an important forecasting problem with these cyclones. The occurrence of severe weather appears to be enhanced along the southern baroclinic zones in cyclones with MWFL baroclinic zones. Given the high percentage of cyclones that produced severe convective storms, recognizing these baroclinic zones is important for operational forecasters. Nevertheless, half (51%) of the southern baroclinic zones were unanalyzed on the 1800 UTC NMC surface charts.

The results of this study yield two important implications. First, a single conceptual model of cyclone structure and evolution, like the Norwegian cyclone model or that of Hobbs et al. (1996), is inadequate to explain completely the observed variety of cyclones in the central United States. This result echoes that of Locatelli et al. (2002), who found that 31% of cyclones east of the Rockies could not be classified as either Norwegian or Hobbs et al. (1996) type cyclones. This evidence indicates forecasters and research scientists must be alert to the potential for weather systems that differ from previously published research. Perhaps, a more systematic approach to understanding the variability of cyclone structure will one day be developed. Second, the importance of performing manual analyses of the surface data in real time and recognizing these baroclinic zones cannot be overstated, given their association with severe convective storms. Previously, Sanders and Doswell (1995) have argued for an increased emphasis on manual analysis of surface isotherms, an admonition supported by the results of this research.

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