

Extratropical Cyclones with Multiple Baroclinic Zones and their Relationship to Severe
Weather

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ABSTRACT

Cyclones from the central United States and south-central Canada were examined from 1982 and 1989 to determine how often they contained more than one baroclinic zone. A baroclinic zone was defined if a gradient of 8°F (4.4°C) per 220 km was found and a length of 440 km was achieved. Forty-three percent of cyclones were found to have multiple baroclinic zones. The greatest frequency of cyclones with multiple baroclinic zones occurred during the transition months of April, May, August, and September. In addition, the baroclinic zones appeared to follow a seasonal progression. Ninety-four percent of all baroclinic zones were coincident with a moisture gradient that was apparent through isodrosotherm analysis every 4°F (2.2°C), and 73% contained a veering wind shift across them of at least 20°. Of cyclones with multiple baroclinic zones, severe weather was found to occur along 57% of southern baroclinic zones, significant severe weather along 41%, tornadoes along 35%, and significant tornadoes along 24%. During the spring and summer, severe weather occurred along 83% of southern baroclinic zones, significant severe weather along 65%, tornadoes along 57%, and significant tornadoes along 39%. The occurrence of severe weather, significant severe weather, tornadoes, and significant tornadoes was relatively consistent along the southern baroclinic zones between 1982 and 1989. Finally, the formation of multiple baroclinic zones was examined and two main forms were found. A second baroclinic zone can be the result of an interaction with a historical cold/stationary front, or can result through the attachment of a baroclinic zone from the north.

I. Introduction

Over 80 years ago, the Norwegian cyclone model was developed to describe the evolution and structure of midlatitude cyclones (Bjerknes 1919; Bjerknes and Solberg 1922). Even though the Norwegian cyclone model was based on maritime cyclones approaching northwestern Europe, the model is still the principal choice for map analysis across the United States and the world. Cyclones in Europe have access to different air masses traversing different topography than cyclones impacting the United States, and therefore, the cyclones that influence the United States may differ from the Norwegian cyclone model. Even though operational forecasters in the United States and elsewhere continue to employ the Norwegian cyclone model, oftentimes there is little justification to do so (e.g., Mass 1991).

The Norwegian cyclone model can be an oversimplification of the true nature of a cyclone, as the structure of a cyclone is often more complex than the model allows. Features that differ from the basic structure of the conceptual model have often been poorly documented, if at all. For example, warm-sector precipitation is not accounted for in the model (e.g., Harrold 1973; Browning and Monk 1982). As a result, a new model has been developed that describes cyclones that form in the lee of the Rockies and in the central United States that takes into account features such as lee troughs, drylines, and cold fronts aloft (Hobbs et al. 1990, 1996).

Although the model of Hobbs et al. (1990, 1996) may be a more accurate representation of some central United States cyclones than the Norwegian cyclone model, the Hobbs et al. (1990, 1996) model fails to capture other potentially significant weather-producing features. Hobbs et al. (1996) display a sea level pressure chart (Fig. 1) from Rossby and Weightman (1926) (RW26). The goal of RW26 was to determine to what

extent the Norwegian cyclone model could be applied to studies of American weather. In RW26, C_2 was referred to as a secondary cold front (Fig.1). The part of C_2 to the east of the low center D_1 appears to act as a warm front as observations show warm-air advection associated with this portion of the front. The feature W_1 was referred to in RW26 as the warm front. As a result, the RW26 analysis actually included two warm fronts. Each one of the features in the RW26 cyclone was related to and compared to a similar feature in the Hobbs et al. (1996) model except for one: W_1 . The front was not analyzed by Hobbs et al. (1996) because, in this particular case, the temperature gradient was not coincident with a pressure trough or a wind shift. No further discussion occurred in Hobbs et al. (1996) on what this warm-sector feature was and why RW26 decided to analyze the warm front in the position they did. Disregarding this feature follows a historical misrepresentation in which the warm sector is often considered barotropic (e.g., Petterssen 1956, p. 225).

Features resembling the RW26 analysis have been observed for years at the National Oceanic and Atmospheric Administration's (NOAA) Storm Prediction Center. Forecasters have often noticed multiple surface boundaries (of which many may be baroclinic zones) extending downstream from a cyclone (R. Johns 2003, personal communication). Further, the forecasters have observed that when these multiple boundaries are present, they sometimes serve as a focal point for severe weather development.

The primary goal of this paper is to examine a collection of cyclones to provide evidence that a second baroclinic zone as identified by RW26 can exist and to determine its frequency of occurrence. Surface map analysis is performed to establish cases that contain multiple baroclinic zones in conjunction with a cyclone. A secondary goal is to

examine the moisture and wind along and across the baroclinic zones to determine the characteristics of the baroclinic zones when apparent. A tertiary goal is to determine the frequency of occurrence of severe weather associated with the each of the baroclinic zones to test the hypothesis set forth by forecasters at the Storm Prediction Center that multiple baroclinic zones occur many times throughout the year. A final goal is to examine the synoptic situations that lead to the development of multiple baroclinic zones.

Section 2 describes the methodology used in choosing the cyclones included in the study and identifying the subset from these cyclones that contain multiple baroclinic zones. Section 3 examines the frequency with which the baroclinic zones occur. Also, the nature of the baroclinic zones and the different temperature, moisture and wind properties that they are associated with are examined. In section 4, the occurrence of severe weather in relation to the baroclinic zones is explored. Section 5 discusses some of the observed synoptic patterns in which the baroclinic zones develop. Section 6 concludes this study.

II. Methodology

In order to examine cyclones with multiple baroclinic zones, a study of cyclones in the central United States, stretching into southern Canada, was established for 1982 and 1989. Years were chosen from the 1980s because during this time, the National Meteorological Center (NMC), now the National Centers for Environmental Prediction (NCEP), still hand-analyzed most 3-h surface maps. In addition, 1982 was chosen because it was a year that contained some large tornado outbreaks while 1989 did not (R. Johns 2003, personal communication). Overall, there were 6973 severe weather reports in 1982 and 10 344 reports in 1989. Some of the increase in severe weather reports over the seven-year period, however, may have been due to a general increasing trend in

reports (e.g., McCarthy et al. 1998; H. Brooks 2003, personal communication). Conversely, during the same period, the number of significant severe, tornado, and significant tornado reports did not show the same increasing trend. There were 696 reports of significant severe weather in 1982 and 770 reports in 1989. On the other hand, there were 1043 tornadoes in 1982 and 855 tornadoes in 1989. Finally, there were 248 reports of significant tornadoes in 1982 and 123 in 1989. Significant severe weather, tornadoes, and significant tornadoes can be compared for 1982 and 1989 to cyclones with multiple baroclinic zones, since these three measures do not show an increasing trend. For completeness, the comparison is also made for severe weather to show how the amount of severe weather relates to cyclones with multiple baroclinic zones.

The cyclones were first identified from the *Daily Weather Maps*. A cyclone was identified if it was associated with at least one closed isobar (contour interval = 4 mb) on at least two consecutive 12 UTC surface maps. The cyclones also needed to be located between the latitudes 30°N and 55°N, and between the front range of the Rockies and western slopes of the Appalachians. These boundaries generally allow for an adequate amount of surface data for reliable manual analysis. Since temperature and dewpoint are affected by elevation, this criterion is an attempt to limit cyclones containing boundaries due to orographic effects.

Lows considered part of the same complex were allowed in the study, and a complex consisted of either being surrounded by a common isobar or linked by a cold front. Two separate cyclones appearing on the same day were disregarded if the distance between them was less than 10° latitude. This criterion was to ensure that each individual cyclone or complex could be examined without being directly affected by another cyclone. If the separation between the two cyclones was greater than 10°

latitude, the deeper of the two lows was added to the dataset. Next, each of the cases was observed more closely by using the NMC's 3-h surface maps on microfilm. The processes of constructing these maps and their notations are described in Corfidi and Combra (1989). Each previously identified cyclone was now required to meet all of the above criteria for each of the nine surface maps between and including 12 UTC on successive days. If the criteria were met for multiple days, the day on which the cyclone was the deepest was chosen for analysis. This process resulted in a total of 108 cyclones, 55 from 1982 and 53 from 1989.

The 18 UTC surface maps for each of the 108 cases were manually analyzed for temperature and dewpoint using a contour interval of 4°F (2.2°C). Eighteen UTC was chosen in an attempt to limit the occurrence of surface temperature inversions due to nocturnal cooling and convection. Gradients were then identified using the isotherms and isodrosotherms. In order for a gradient to be considered a baroclinic zone a temperature difference of at least 8°F (4.4°C) over 2° latitude (220 km) was necessary. The strength of the gradient parallels Sanders (1999) who used 8°C over 220 km to identify a moderate baroclinic zone. In this instance, Celsius was not used because the station models on the surface charts were expressed in Fahrenheit. Two baroclinic zones could be identified if an area with a temperature gradient of no more than 4°F (2.2°C) over at least 220 km was identified between them. In addition, each gradient meeting the criterion above needed to be at least 440 km long, and the spacing between the gradients needed to be at least 440 km long as well. This distance is consistent with the upper end of Fujita's (1981) mesoscale, which encompasses 4 km to 400 km.

To identify warm-sector baroclinic zones, the following procedure was performed. Consider a north to south oriented line segment north of the low center. The

line segment is rotated anticyclonically until a baroclinic zone meeting the criteria described above is encountered, which was termed the *northern baroclinic zone* and represents the northern edge of the warm sector. Next, consider a north to south oriented line segment south of the low center. This line segment is rotated up to 180 degrees anticyclonically until a baroclinic zone (not necessarily meeting the criteria above) is encountered, which was termed the cold front and represents the western edge of the warm sector. In some cases, a cold front is not encountered using this technique and the warm sector is unbounded to the west. With the northern and western edges of the warm sector defined in this manner, baroclinic zones within the warm sector meeting the criteria described above were identified, if any. If no such warm-sector baroclinic zones existed, the cyclone was said to only have one baroclinic zone. If one such warm-sector baroclinic zone existed, it was termed the *southern baroclinic zone*. If two such warm-sector baroclinic zones existed, the southernmost of the two was termed the southern baroclinic zone and the northernmost of the two was termed the *central baroclinic zone*.

To illustrate an example, a hypothetical isotherm analysis is presented in Figure 2. Gradient A fits the criteria laid out and would be the northern baroclinic zone. Gradient B would be considered the cold front and would be excluded from the analysis. Gradient C also meets all of the criteria set forth and would be the southern baroclinic zone. Gradient D is too short and would be excluded. If a third baroclinic zone was identified between A and C, it would be termed the central baroclinic zone. Applying the procedure, as illustrated in the schematic, to the 108 cyclones resulted in 46 (43%) with multiple baroclinic zones, 24 from 1982 and 22 from 1989. Three (7%) of the 46 contained a third baroclinic zone.

Each of these 46 cyclones with multiple baroclinic zones was examined for wind changes across them. The length of each baroclinic zone was bisected. The bisection was followed to the cold and warm sides of the baroclinic zone, until outside of the baroclinic zone as defined by the criteria. The nearest surface station to the bisection was examined in addition to the closest two on each side, which were also on the immediate outside of the baroclinic zone. If five stations were not available, as many as possible were used. An average wind speed and direction were calculated from the five stations. Temperature gradient C shows an example of the five stations used on both the cold and warm sides of the baroclinic zone (Fig. 2). A comparison was made from the cold to the warm side of baroclinic zone to the other to determine how the wind changed, if at all, across the gradient. Using the same method, the average dewpoint could also be calculated on each side of every baroclinic zone.

Finally, the severe weather was examined in relation to each of these baroclinic zones. Severe weather reports were obtained through the Severe Plot Version 2.0 software. One severe weather day is considered to extend between 12 UTC on consecutive days. Severe weather was considered to be associated with the baroclinic zone if reports occurred within 220 km on any side of the baroclinic zone. This distance helps to account for the movement of the gradient throughout the day.

While a large number of subjective criteria were used in the construction of this dataset, similarly derived methodologies by other reasonable researchers would likely yield datasets similar to the one produced in this study.

III. Description of cyclones with multiple baroclinic zones

Of the 108 cyclones examined, 30 occurred in spring, 28 in the autumn, 27 in the winter, and 23 in the summer. The frequency of cyclones agrees with previous work that

has shown cyclones are often fewer in number during the summer (e.g., Zishka and Smith 1980). The same general pattern occurs in both the percentage of cases with multiple baroclinic zones and in the number, which show a maximum of multiple baroclinic zone cyclones during the transition months of April, May, August and September. February is excluded because only four total cyclones were identified, three of which contained multiple baroclinic zones. Twenty cases (47%) have multiple baroclinic zones from these four months, and of the total amount of cyclones identified, each of these four months contains at least 50% with multiple baroclinic zones (Fig. 3).

The strength of the temperature gradients across the baroclinic zones varies from case to case. In 63% of the multiple baroclinic zone cases, the northern gradient is the strongest. In 32% of the multiple baroclinic zone cases, the southern gradient is the strongest. In 4% of the cases, the strengths of the north and south temperature gradients are equal. The relative strengths of the baroclinic zones may be related to the manner in which they form. More will be discussed on the types of multiple baroclinic zone structure in section 5.

The positions of the northern and southern baroclinic zones appear to show a relationship to the season within which they occur. Beginning in the winter, the northern baroclinic zones show a general north and east progression with each season (Figs. 4a-d). In the winter, the highest concentration of northern baroclinic zones is located from Minnesota to the upper peninsula of Michigan (Fig. 4a). In the autumn, the concentration of baroclinic zones is highest in south-central and southeast Ontario (Fig. 4d). The southern baroclinic zones show an eastward movement from winter to spring as two distinct maxima form (Figs. 4a,b). Moving into the summer and autumn, the maximum concentration shifts somewhat westward (Figs. 4c,d). The two baroclinic zones do not

always progress in the same direction between seasons. In the transition from spring to summer, the northern baroclinic zones remain relatively stationary, whereas the southern baroclinic zones shift westward (Fig. 4b,c).

A moisture gradient is associated with the baroclinic zones on most occasions. Of the 95 baroclinic zones identified, 48 (51%) contain a moisture gradient of at least 8°F (4.4°C) per 220 km, that is at least 440 km long within the boundaries of the baroclinic zone. Another 41 (43%) of the baroclinic zones contained a weaker moisture gradient than 8°F (4.4°C). The six remaining baroclinic zones (6%) had a dewpoint gradient that was not apparent through isodrosotherm analysis of every 4°F (2.2°C). In total, 89 of 95 baroclinic zones (94%) were coincident with a moisture gradient.

When baroclinic zones have significant wind shifts across them, Sanders (1999) refers to them as fronts. In this study, a significant wind shift was defined as greater than or equal to 20°. Overall, the wind shifts range from -70° to 220° (Fig. 5). Sixty-nine of the 95 baroclinic zones (73%) have a positive wind shift of greater or equal to 20° across them. A positive wind shift denotes veering wind across the front from the cold to warm side, whereas a negative wind shift denotes backing wind across the front from the cold to warm side. Most of the baroclinic zones exist in conjunction with veering winds, but backing of greater than 20° occurs across eight baroclinic zones (8%). The reason for the backing is not apparent, as there does not seem to be any common scenario in which backing winds occur. Regardless, the vast majority of these baroclinic zones not only represent a discontinuity in the temperature, but also in the wind field, suggesting that they are likely fronts.

IV. Multiple baroclinic zones and severe weather

Severe weather is defined as hail of 0.75 inches (1.9 cm) or greater, wind gusts of at least 50 knots, and tornadoes. The association between severe weather and the northern baroclinic zones can be difficult to ascertain in some cases because many of the northern baroclinic zones lie in southern Canada, where datasets of severe weather were not readily available. For this reason, only the southern baroclinic zones will be examined closely. Of the 46 cases with multiple baroclinic zones, 26 (57%) had severe weather associated with the southern baroclinic zone. During the height of the severe-weather season (spring and summer), there were 23 instances of multiple baroclinic zones, 19 (83%) of which were associated with severe weather (Fig. 6). Further, 16 (35%) of the southern baroclinic zones were associated with only tornadoes. In the spring and summer, the percentage of southern baroclinic zones associated with tornadoes jumped to 57%.

Significant severe weather is defined as hail 2 inches or greater (5.1 cm), wind gusts of at least 65 knots, and F2 or greater tornadoes (Hales 1988). Of the 46 cases with a southern baroclinic zone, 20 (41%) were associated with significant severe weather. The 41% is only 16% less than overall severe weather occurrences. In the spring and summer, nearly 65% of all the southern baroclinic zones were associated with significant severe weather (Fig. 6). The percentage is only 18% less than the overall severe weather occurrences in these months. Further, 11 (24%) of the southern baroclinic zones were associated with only significant tornadoes, of F2 or greater. In the spring and summer, the percentage of southern baroclinic zones associated with significant tornadoes jumped to 39%. The southern baroclinic zones are not only associated with severe weather, but are likely to produce significant severe weather.

In 1982, 54% of the southern baroclinic zones were associated with severe weather, whereas in 1989, 59% of the southern baroclinic zones were associated with severe weather (Table 1). The percentage of southern baroclinic zones with associated significant severe weather was 42% and 41%, respectively. When tornadoes were considered, 38% of southern baroclinic zones were associated with tornadoes in 1982, and 32% of southern baroclinic zones were associated with tornadoes in 1989. The percentage of southern baroclinic zones with associated significant tornadoes was 29% and 18%, respectively. Thus, the southern baroclinic zones appear to show a similar relationship to severe weather for both years regardless of what type of severe weather is considered.

Every southern baroclinic zone that was associated with severe weather, except for one, had an average dewpoint on its warm side of 57°F (14°C) or greater (Fig. 7a). The one outlier had an average dewpoint of just over 49°F (9°C). On the other hand, only three of the southern baroclinic zones with average dewpoints on the warm side of above 57°F (14°C) did not have severe weather associated with them. Every other nonsevere case had an average dewpoint of less than 50°F (10°C) along the warm side of the southern baroclinic zone. This data suggests that the average dewpoint of the air on the warm side of the southern baroclinic zone may be an important factor in forecasting the occurrences of severe, but not significant severe weather (Miller 1972). In particular, some of the cases with the highest average dewpoints on the warm sides of the southern baroclinic zones are not associated with significant severe weather (Fig. 7b). Clearly, there are factors other than surface dewpoint on the warm side of the southern baroclinic zones that are responsible for severe weather. A more detailed study, however, is beyond the scope of this project.

The relationship between the southern baroclinic zones and severe weather is noteworthy; however, the baroclinic zones might not be immediately apparent to a forecaster. Of the 46 cyclones with multiple baroclinic zones, 25 of them (54%) did not have the southern baroclinic zones analyzed as boundaries of any type on the NMC 18 UTC surface maps. That the operational analysts at NMC did not analyze 54% of the southern baroclinic zones and that 36% of those were associated with severe weather provides support for the admonition by Sanders and Doswell (1995) of the importance of performing operational surface isotherm analysis as a possible indicator of baroclinic zones.

V. Synoptic regimes

Many different processes can lead to a cyclone having more than one baroclinic zone. The processes through which the cyclones and their baroclinic zones formed were examined. Some common modes through which the baroclinic zones formed were apparent. The two most common modes leading to multiple baroclinic zones were baroclinic zones left behind from previous cyclones, and baroclinic zones that attached to the cyclone from the north. Some cases also formed multiple baroclinic zones from outflow boundaries, Chinook fronts, and return-flow boundaries (Table 2).

Of the 46 cases with multiple baroclinic zones, 17 (37%) contained at least one baroclinic zone which was formed as the result of an interaction with historical baroclinic zones. A historical baroclinic zone was once a part of another cyclone, but as this initial cyclone weakened, a baroclinic zone was left behind (Fig. 8). A new cyclone followed behind, and eventually encountered the remaining baroclinic zone. When the historical baroclinic zone joined with the new cyclone, the new structure was made up of two distinct baroclinic zones. The most common way this occurred was for the historical

baroclinic zone to attach itself along the cold front of the new cyclone. There were cases, however, in which the historical baroclinic zone connected directly into the center of the new cyclone.

Ten of the 46 (22%) cyclones with multiple baroclinic zones contained a baroclinic zone that was formed through attachment of another baroclinic zone from the north. In this mode, a baroclinic zone moved equatorward out of Canada (Fig. 9). At the same time, a cyclone, with one baroclinic zone attached to it, progressed in a general easterly direction. The baroclinic zone from the north eventually merged with the cyclone at its center. The cyclone then continued eastward with two baroclinic zones.

There were other modes in which cyclones occurred with multiple baroclinic zones that were far less frequent. There were four cases containing an outflow boundary. Although, the 18 UTC map was chosen in an attempt to limit the appearance of convection, there were still cases in which convection produced an outflow boundary (gust front) as the southern baroclinic zone. The outflow boundaries formed as the result of cooler air from thunderstorm outflow, which set up a temperature gradient with the warmer air that was unaffected by the thunderstorms (e.g., Humphries 1914; Fujita 1958; Barnes 1973). In three cases, there were multiple baroclinic zones lying along a Chinook front. This feature forms in the lee of the Rockies as a downsloping wind is carried out into the plains (Oard 1993). Return flow is another mechanism that led to the development of multiple baroclinic zones. In the two return-flow cases, an initial cyclone brings cold, dry air into the Gulf of Mexico region. The modified air over the Gulf of Mexico then begins to move back northward along the gulf coast (Crisp and Lewis 1991a,b). The two baroclinic zones form as this return flow feature interacts with an

approaching cyclone, already with a preexisting baroclinic zone. There were ten cases that were left unclassified, not fitting into any of the groups previously discussed.

VI. Conclusions

Cyclones were analyzed from 1982 and 1989 using NMC's 18 UTC surface maps to identify cyclones with multiple baroclinic zones. A baroclinic zone was defined if a temperature gradient was present of at least 8°F (4.4°C) per 220 km. In order for another baroclinic zone to be identified, an area with a gradient of no more than 4°F (2.2°C) per 220 km needed to occur between the first baroclinic zone identified and a second baroclinic zones that fit the 8°F (4.4°C) per 220 km criteria. Each baroclinic zone was required to be at least 440 km long. Forty-six cyclones (43%) were identified that contained at least two baroclinic zones.

The greatest frequency of cyclones with multiple baroclinic zones occurred in during the transition months of April, May, August, and September. The four months contained 47% of all the multiple baroclinic zones, and each month contained a baroclinic zone in at least 50% of the total cyclones identified in that month. In nearly two-thirds of the cyclones examined, the northern baroclinic zone was the stronger of the two. Both the southern and northern baroclinic zones appear to follow a seasonal progression from the winter to the autumn. The northern baroclinic zones show a slow progression north and east, whereas the southern baroclinic zones begin with an eastward movement before going towards the west in the summer and autumn. In addition, 94% of all the baroclinic zones were coincident with a moisture gradient, even if it was not as strong as 8°F (4.4°C) per 220 km as used for temperature. Seventy-three percent of the baroclinic zones show a positive wind shift of greater than 20° across them. Thus,

baroclinic zones represent a wind discontinuity, as well as a temperature discontinuity and therefore are often fronts.

Severe weather is a common occurrence along the southern baroclinic zone as severe weather occurred along 57% of the southern baroclinic zones (within 220 km of the 18 UTC baroclinic zone position). In the spring and summer, 83% of the southern baroclinic zones existed in conjunction with severe weather. Tornadoes occurred along the southern baroclinic zone 35% of the time throughout the year and 57% in the spring and summer. Forty-one percent of the time, there were significant severe weather reports associated with the southern baroclinic zone. In the spring and summer, 65% of the southern baroclinic zones were associated with significant severe weather. Significant tornadoes occurred along the southern baroclinic zone 24% of the time throughout the year and 39% of the time in the spring and summer. The percentages of severe, significant severe, tornadic, and significant tornadic weather along the southern baroclinic zone remained relatively constant between 1982 and 1989. All of the severe weather cases examined, except for one, had a dewpoint on the warm side of the southern baroclinic zone of at least 57°F (14°C). Very few non-severe cases were above this threshold. The significant severe cases did not show as strong of a relationship.

Multiple baroclinic zones about a cyclone can form in many different fashions. The two most common modes seen were the result of a historical baroclinic zone from a previous cyclone (37%), and the attachment of a baroclinic zone from the north (22%). In addition, outflow boundaries, Chinook fronts, and return flow also resulted in the creation of multiple baroclinic zones.

The completed study shows that just under half of all cyclones examined have more than one baroclinic zone associated with them. Over 50% of the time, the southern

baroclinic zone is associated with severe weather, even though 54% of the time the southern baroclinic zone is not analyzed on NMC 18 UTC surface charts. Cyclones with multiple baroclinic zones form in modes that are common in the atmosphere, and as a result, through careful observation, can be identified with relative ease.

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