A Climatology of the Structure, Evolution, and Propagation of Midlatitude Cyclones in the Southeast United States

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ABSTRACT

The seasonal and interannual variability of the structure, evolution, and propagation of midlatitude cyclones in the southeast United States are studied using a composite analysis. In the upper levels, the composites show that the axis of the wintertime upper-level trough remains north–south oriented and propagates eastward along 40°N, while the summertime upper-level trough has a much slower propagation at a farther north latitude and an axis that is tilted in the northeast–southwest direction. Upper-level circulation changes are consistent with a shift from wintertime ''cyclonic behavior'' to summertime ''anticyclonic behavior'' midlatitude cyclones. Significant changes in the low-level structure and precipitation patterns of midlatitude cyclones ensue from these upper-level changes. While the winter composite is characterized by eastward-propagating midlatitude cyclones that extend deep into the subtropics, the summer composite is characterized by semistationary midlatitude troughs that only briefly skirt the subtropics. Wintertime precipitation occurs only in and ahead of the surface low pressure center, whereas summertime precipitation occurs in all days of the composite. As a result, over 70% (30%) of wintertime (summertime) precipitation in the Carolinas occurs on days when midlatitude cyclones are present. The wintertime composites also show that midlatitude cyclones produce more precipitation on the windward side of the Appalachians than over the Carolinas, suggesting a rain shadow effect of the mountains.

The ENSO-related variability of the structure, evolution, and propagation of midlatitude cyclones shows the presence of a more intense and southward-displaced upper-level jet, stronger midlatitude cyclones, and more intense precipitation over a larger area during El Niño than La Niña or normal years.

1. Introduction

As population increases (U.S. Census Bureau 2013) and climate changes (Solomon et al. 2007), water management and sustainability policymaking in the southeast (SE) United States will be increasingly dependent upon an improved understanding of the spatial and temporal distribution of regional precipitating systems (Robinson 2006). Each year the southeastern United States receives precipitation from a variety of weather systems such as midlatitude cyclones (Curtis 2006) and tropical cyclones (e.g., Larson et al. 2005; Shepherd et al. 2007), sea breeze circulation (Koch and Ray 1997), mesoscale convective systems that form in the mountains (Parker and Ahijevych 2007), and the diurnal cycle of convection during summertime (Winkler et al. 1988). Midlatitude cyclones are especially important because they bring significant amounts of precipitation to the southeast United States year-round.

This study uses a composite analysis to examine seasonal and interannual changes in the synoptic-scale structure, evolution, propagation, and precipitation of midlatitude cyclones in the southeast United States. Previous synoptic climatologies of midlatitude cyclones in the southeast United States have focused on the seasonal and interannual variability of storm numbers (Curtis 2006), preferred regions of origin and tracks (e.g., Reitan 1974; Colucci 1976; Zishka and Smith 1980; Whittaker and Horn 1984; Hirsch et al. 2001; Senkbeil et al. 2012), wintertime total precipitation and snowfall amounts (e.g., Frankoski and DeGaetano 2011; Senkbeil et al. 2012), extreme precipitation events (Wuensch and Curtis 2010; Konrad 1997), and storm impacts on the East Coast of the United States (e.g., Dolan et al. 1988; Mather et al. 1964). Synoptic climatologies of special types of midlatitude cyclones such as inverted troughs in the central United States (Weisman et al. 2002) and Canadian Alberta

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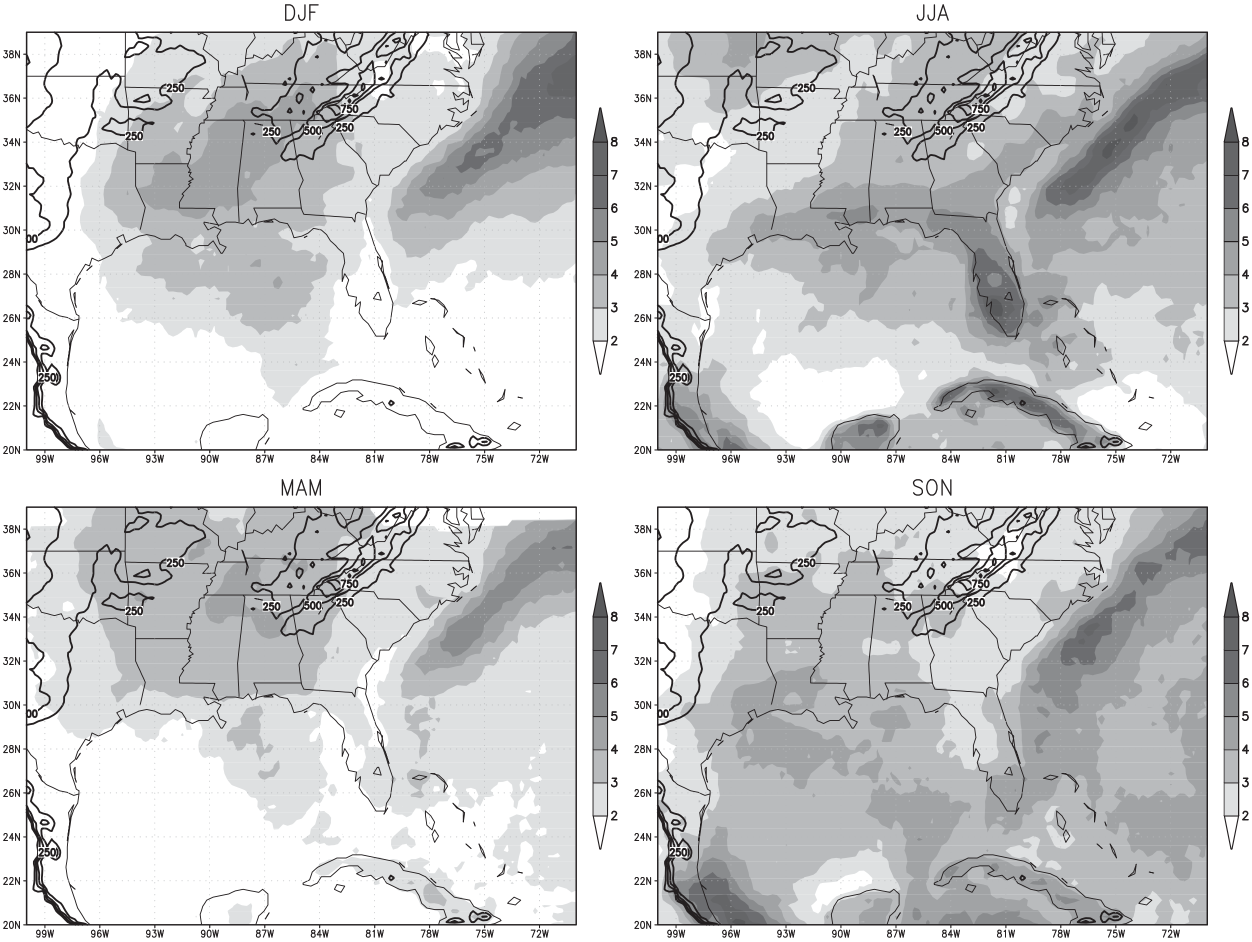


FIG. 1. Seasonal climatology of TRMM precipitation (shaded; mm day^{-1}). The location of the Appalachian Mountains is indicated by the elevation contours (solid lines; m).

clippers (Thomas and Martin 2007) are also available. However, no general synoptic climatology of the seasonal variability of midlatitude cyclone structure and evolution in the southeast United States has been published. This study aims to fill this gap by presenting composites of the daily sea level pressure (SLP), upper- and lower-level winds, geopotential, and precipitation signatures of midlatitude cyclones in the southeast United States and thus contributes to an improved understanding of the dynamics of their seasonal-to-interannual variability. This study forms the basis for a forthcoming radar-based study of the seasonal variability of the precipitation system organization in midlatitude cyclones that affect the southeast United States. This two-pronged approach can lead to improvements in our understanding of the role of midlatitude cyclones in the precipitation variability of the southeast United States and possibly also to improvements in precipitation prediction on climate time scales.

While it rains year-round in the southeastern United States, distinct seasonal regimes of precipitation occur over the Gulf and Atlantic coasts, as well as on the eastern and western sides of the Appalachian Mountains (Fig. 1). During boreal winter the highest precipitation amounts occur west of the Appalachian Mountains in a wide southwest–northeast-oriented band that extends from the Gulf of Mexico to near the Great Lakes. A relative minimum in precipitation stretches from Florida northeastward across the Atlantic states during the winter. During the boreal summer, the sea breeze circulation causes the precipitation maxima along the Gulf Coast and over the Florida peninsula as well as a weaker precipitation maximum that stretches northeastward along the southeast United States coast (Carbone and Tuttle 2008). Summer convection initiated in the Appalachian Mountains propagates eastward and can organize into mesoscale convective systems, enhancing precipitation in the coastal plains (Parker and Ahijevych 2007).

Precipitation is relatively scarce on the lee side of the Appalachian Mountains during boreal fall, winter, and spring. The highest precipitation amounts on the lee side of the Appalachians occur during boreal summer. In addition to these regional seasonal differences, precipitation in the southeastern United States also varies from year to year and extremes such as droughts and floods often occur. Remote influences such as the El Niño–Southern Oscillation (ENSO; e.g., Ropelewski and Halpert 1986; Eichler and Higgins 2006) and the North Atlantic Oscillation (NAO; e.g., Durkee et al. 2008) have also been shown to contribute to seasonal precipitation variability in the southeast United States.

Favored cyclogenesis locations and tracks of midlatitude cyclones over North America vary not only seasonally (e.g., Whittaker and Horn 1984; Eichler and Higgins 2006) but also on interannual time scales in association with ENSO (Curtis 2006; Eichler and Higgins 2006; Bengtsson et al. 2006). In general, there are four main cyclogenesis regions in North America (Whittaker and Horn 1984). Two of them are present year-round: one to the lee of the Rockies in Canada and another one over the Gulf Stream just off the East Coast of the United States. A third important region of cyclogenesis occurs to the lee of the United States Rockies during boreal winter, spring, and fall. A fourth weaker region of cyclogenesis occurs in the Gulf of Mexico off the coast of Texas during the winter. On average, the position of the tracks of midlatitude cyclones in North America oscillates between a southernmost wintertime average position at 40°–50°N and a northernmost position at 50°–60°N in the summer (Eichler and Higgins 2006). A synoptic climatology of the structure and propagation of midlatitude cyclones by cyclone type is presented in a companion study (submitted to the *International Journal of Climatology*).

On interannual time scales, the tracks of wintertime midlatitude cyclones are displaced southward of their average positions during El Niño years and northward of their average positions during La Niña years (e.g., Eichler and Higgins 2006; Bengtsson et al. 2006). This is due in part to an increase in cyclogenesis density in the Gulf of Mexico during El Niño years (Curtis 2006). In fact, Curtis (2006) noted that the total number of midlatitude cyclones observed in the southern United States, Gulf of Mexico, Caribbean, and the southern portion of the Gulf Stream (between about 15°–37°N and 97°–68°W) during El Niño years (33 yr^{-1}) is about double that of La Niña (14 yr^{-1}) or normal (18 yr^{-1}) years. These ENSO-related changes in storm tracks have a significant impact on the precipitation distribution over the southeastern United States. Eichler and Higgins (2006) show that during strong El Niño events when storm tracks are displaced southward of their average positions, the largest precipitation amounts associated with midlatitude cyclones extend from the Gulf Coast northeastward along the East Coast of the United States. In contrast, during strong La Niña years, midlatitude cyclone precipitation decreases in the eastern United States as a whole with the most dramatic precipitation deficits occurring along the coast. In essence, this means that during strong La Niña events the heaviest precipitation associated with midlatitude cyclones shifts westward of the Appalachians (Eichler and Higgins 2006).

Previous studies have shown dramatic changes in the behavior of midlatitude cyclones under varying background shear. Observed seasonal-to-interannual changes in upper-level jet width, strength, and latitude over North America have been shown to produce enough change in background shear to cause a shift in the behavior of midlatitude cyclones. Even modest changes in environmental shear can produce dramatically different midlatitude cyclone morphologies that affect not only the upper-level features of a midlatitude cyclone but also the strength, propagation, and length of surface warm and cold fronts (e.g., Hoskins and West 1979; Davies et al. 1991; Thorncroft et al. 1993). Midlatitude cyclones that are embedded in an environment with cyclonic shear, also known as "cyclonic behavior," tend to form upper-level "broadening troughs," weaker surface cold fronts, and strong warm fronts. On the other hand, midlatitude cyclones embedded in anticyclonic shear environments tend to evolve upper-level "thinning troughs" that become tilted in the northeast–southwest (NE–SW) direction as they advance into lower latitudes, sometimes producing nearly stationary cutoff cyclones. These so-called anticyclonic behavior midlatitude cyclones tend to produce strong elongated slower-moving surface cold fronts and little or no warm front signature. This paradigm has proven useful to explain differences in cyclone behavior associated with the opposite phases of ENSO (Shapiro et al. 2001; Martius et al. 2007) and of the NAO and Pacific–North American pattern (Martius et al. 2007). Observational evidence for a shift from cyclonic to anticyclonic behavior has also been found at the time of the abrupt onset of the monsoon rainfall in the South Atlantic convergence zone (Nieto Ferreira et al. 2011). Shifts in midlatitude cyclone behavior over seasonal time scales in the southeast United States will be addressed in this study.

There are two basic approaches to midlatitude cyclone composite analysis. The first and perhaps most frequently used can be thought of as a Lagrangian approach in that the composite is built using a cyclone-centered frame of reference that "follows" the cyclones (e.g., Weisman et al. 2002; Field and Wood 2007; Chang and Song 2006; Dacre et al. 2012). This approach produces an integrated picture of storm intensity and structure for an entire region. Field and Wood (2007) used this Lagrangian approach to produce composites of worldwide oceanic midlatitude cyclones. They found that for a given cyclone wind speed strength and atmospheric moisture content, midlatitude cyclones have similar structures in different geographical locations. Moreover they found that the rain rate and fraction of high-level clouds in the warm sector (southern and eastern flanks) of midlatitude cyclones increase with increasing cyclone strength. They attribute this relationship to the fact that a stronger cyclone has a stronger warm conveyor belt with stronger updrafts that tend to produce higher rain rates and larger high cloud fractions. Chang and Song (2006) used the Lagrangian approach to produce seasonal composites of midlatitude cyclones in the North Atlantic and Pacific storm-track regions. They found that North Atlantic midlatitude cyclones are deepest and have the strongest and most extensive precipitation in the winter, with minima during summer. North Pacific cyclones, however, while also deepest in the winter, produce the largest precipitation amounts in the fall, a fact that is in line with the well-known midwinter suppression of precipitation in that region (Nakamura 1992).

The second approach is Eulerian in the sense that it involves compositing cyclones that pass through a fixed location. This approach is well suited to study the evolution of midlatitude cyclones (e.g., Lau and Crane 1995; Thomas and Martin 2007; Garreaud 2000; Nieto Ferreira et al. 2011), especially downstream from preferred regions of cyclogenesis. Senkbeil et al. (2012) classified strong midlatitude cyclones that affect the SE United States into five types according to their formation region and calculated composite cumulative precipitation for each type to show that storms that form over the Gulf of Mexico tend to bring the largest precipitation amounts to the Carolinas. Thomas and Martin (2007) used an Eulerian composite approach to study the structure, propagation, and dynamical evolution of Alberta clippers that form to the lee of the Canadian Rockies. Nieto Ferreira et al. (2011) used the Eulerian approach to produce midlatitude cyclone composites in South America and show how abrupt changes in the structure of midlatitude cyclones can cause the observed abrupt onset of the monsoon season in the South Atlantic convergence zone. In general, composite studies find that the strongest precipitation amounts in a midlatitude cyclone occur in a comma-shaped region that extends eastward and equatorward from the center of the cyclone.

In this study, we choose to produce Eulerian midlatitude cyclone composites based on the passage of the low pressure center through eastern North Carolina (NC). Given its location halfway up the East Coast of the United States and downstream from the main North American cyclogenesis regions on the lee side of the Rockies (e.g., Whittaker and Horn 1984), centering our composites on North Carolina allows us to produce a synoptic climatology that focuses on the seasonal-to-interannual variability of the frequency, structure, propagation, and evolution of midlatitude cyclones in the southeastern United States. In particular, a synoptic climatology of the variability of cyclone structure in seasonal-to-interannual time scales is currently not available for the southeastern United States. The synoptic climatology presented here will shed light not only on preferred precipitation patterns in the region but also on mechanisms for seasonal-to-interannual precipitation variability. Section 2 discusses the datasets and methodology used to construct the midlatitude cyclone composites. Section 3 presents an analysis of the seasonal variability of the propagation, evolution, and structure of midlatitude cyclones that affect the southeastern United States. Section 4 investigates the interannual variability in the propagation, evolution, and structure of these storms. Conclusions are presented in section 5.

2. Datasets and methodology

The datasets used in this project are the high-resolution National Aeronautics and Space Administration (NASA)'s Tropical Rainfall Measuring Mission (TRMM) precipitation and the National Centers for Environmental Prediction (NCEP) reanalysis from 1998 to 2010. The TRMM-3B42 daily precipitation dataset provides homogeneous spatial and temporal precipitation coverage from 50°N to 50°S at 0.25° resolution (Huffman et al. 2007). The TRMM satellite samples precipitation directly using spaceborne radar and the ice scattering signature from deep convection, both of which work equally well over land and ocean. The TRMM-3B42 product combines direct TRMM measurements with geosynchronous satellite cloud-top data and adjusts the precipitation amounts using rain gauges. As such, TRMM-3B42 has become the standard for producing regional and global precipitation maps (Huffman et al. 2007). The NCEP reanalysis (Kalnay et al. 1996) is a global daily 2.5° horizontal resolution blend of observations and model. In this study, the NCEP reanalysis sea level pressure, winds and geopotential anomalies, and the TRMM daily precipitation are used to construct composites of the life cycle of midlatitude cyclones that affected the southeast United States between 1998 and 2010.

For the purposes of this study, a midlatitude cyclone passage is defined as the time when the NCEP reanalysis SLP at a basis region in eastern North Carolina at 35°N, 75°W experiences a 2-mb fall over a 24-h period, taking care to remove consecutive days of greater than 2-mb pressure drop. The choice of threshold is based on a subjective analysis of the NCEP reanalysis daily time series of SLP at the basis region and concurrent surface weather maps [available from the National Oceanic and Atmospheric Administration (NOAA) at http://www.hpc.ncep.noaa.gov/dailywxmap/], with the goal of capturing local pressure drops associated not only with direct cyclone passage over the base region but also midlatitude cyclones centered somewhere else in eastern North America. Note that this criterion does not allow us to determine what portion of a midlatitude cyclone (e.g., the cyclone center, warm, cold, stationary, or occluded front) passes through the region of interest. This means that the composites shown here include for example Hatteras lows that form offshore and low pressure centers such as the rare Alberta clipper that crosses the coast farther north in Canada (Thomas and Martin 2007). Sensitivity tests of the robustness of the composites for different SLP drop thresholds were carried out. The cyclone composites were calculated for thresholds of 2-, 4-, and 6-mb SLP drops. The higher the threshold for the pressure drop, the lower the number of storms in the composite. While the number of storms captured by each threshold was different, the evolution of the patterns of precipitation, winds, and SLP in the three composites was quite similar. The main difference was that the 6-mb threshold had slightly stronger precipitation and winds and slightly deeper average SLP values. Similar SLP-based definitions of midlatitude cyclone passages have been used in previous studies (Garreaud 2000; Nieto Ferreira et al. 2011).

Seasonal and interannual changes in the structure, propagation, and evolution of midlatitude cyclones that affect the southeastern United States are studied using 6-day Eulerian seasonal composites of the TRMM precipitation and NCEP reanalysis SLP and winds and geopotential fields. The SLP field shows the location of the surface cyclone center, while the upper-level winds and geopotential are used to indicate the presence of upper-level support for the growth and propagation of the surface cyclone. The seasonal composites are calculated for the day of the midlatitude cyclone passage over NC (day 0) as well as for the nth day prior to its passage (day $-n$) and the nth day after its passage (day $+n$).

3. Seasonal variability

The aforementioned criterion detected a total of 861 midlatitude cyclones that affected North Carolina from 1998 to 2010. Tropical cyclones were removed from the list manually based on an archive of historical hurricane tracks (NOAA 2011). The seasonal variability of the structure, evolution, and propagation of midlatitude cyclones in the southeastern United States is analyzed in this section. This analysis focuses on differences in cyclone circulation fields (given by sea level pressure, 850-mb winds, 200-mb geopotential anomalies, and 200-mb wind intensity) and their associated precipitation distribution and amounts. In agreement with previous studies, the seasonal distribution of the number of midlatitude cyclones that passed through NC between 1998 and 2010 has a distinct annual cycle with a maximum in boreal winter [279 cyclones in December–February (DJF)] and a minimum in boreal summer [162 cyclones in June–August (JJA)]. The number of midlatitude cyclones observed in the boreal fall (September–November) and spring (March–May) were 242 and 200, respectively.

a. Winter composite

The winter composite is characterized by the presence of an eastward-propagating midlatitude cyclone that extends deep into the subtropics (Fig. 2). A total of 279 winter cases are included in this composite. A low pressure center first appears along the eastern side of the Rockies on day -2 (Fig. 2) and propagates eastward as it deepens to maximum intensity, as indicated by the presence of a closed low pressure center with very strong rainfall over the Gulf Stream on day 0. Ahead of the low pressure center on day -2, southwesterly winds bring moist air from the Gulf of Mexico to fuel a large area of precipitation that appears over the lower Mississippi Valley. This southwesterly wind pattern extends over the entire southeast United States by day -1 and continues to move eastward with the low pressure center, finally crossing into the Atlantic Ocean on day 0. In this composite, land-based precipitation occurs only in the presence of the synoptic-scale forcing by the midlatitude cyclone during days -2 and -1. At all other composite times, the presence of strong high pressure centers ahead and behind the cyclone inhibit precipitation over the central and eastern United States. This composite also shows that midlatitude cyclones produce much more precipitation over the lower Mississippi Valley than over the Carolinas, something that is readily reflected on the climatological winter precipitation (Fig. 1) for the region and may in part be associated with a rain shadow effect of the Appalachian Mountains. Although there is precipitation offshore on every day of the composite, the strongest rainfall occurs on day 0 when the midlatitude cyclone passes over the warm waters of the Gulf Stream.

Precipitation only occurs over the Carolinas during days -1 and 0 of the midlatitude cyclone passage. Figure 2

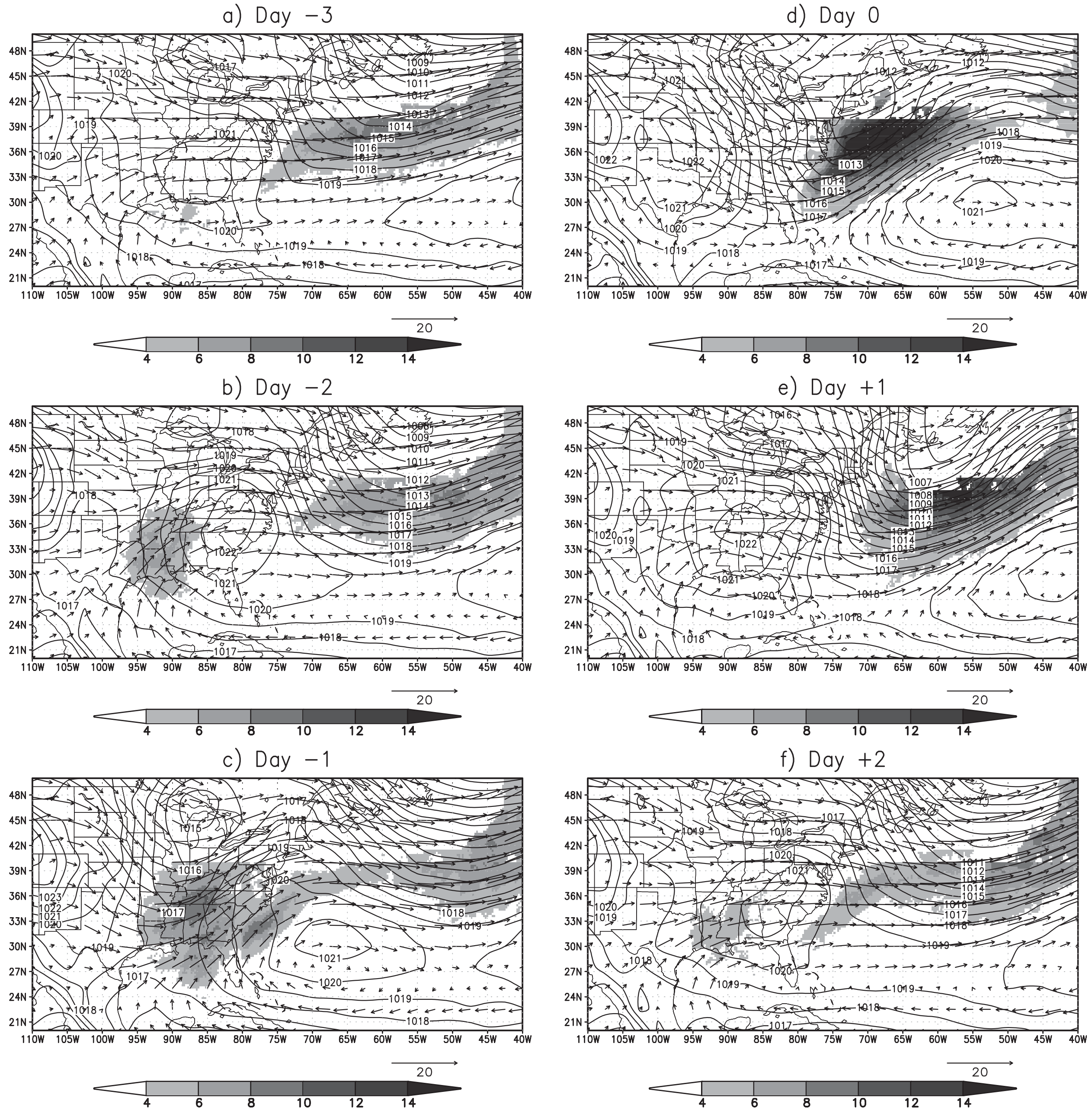


FIG. 2. Wintertime composites of TRMM rainfall (shaded; mm day^{-1}), NCEP reanalysis SLP (contours; mb), and 850-mb winds (vectors; m s^{-1}) for the period 1998–2010 (279 cases). The composites are shown for the day of (day 0), the *n*th day prior to (day −*n*), and the *n*th day after (day +*n*) the passage of a midlatitude cyclone over NC: day (a) −3, (b) −2, (c) −1, (d) 0, (e) +1, and (f) +2.

shows the percentage of the total wintertime precipitation that is contributed by the midlatitude cyclones on days −1 and 0 of the composite. More than 80% of the total wintertime precipitation in the eastern plains of the Carolinas is associated with the passage of midlatitude cyclones (Fig. 3). The Piedmont and mountainous regions of North Carolina also receive a large portion (over 70%) of their wintertime precipitation from midlatitude cyclones (Fig. 3).

In the upper levels, the core of the jet stream has winds in excess of 45 m s^{-1} at 200 mb and is centered over North Carolina on every day of the composite (Fig. 4). At 200 mb, a north–south-elongated center of negative geopotential anomalies first appears at the jet entrance region on the lee side of the Rockies on day −1. This center of negative geopotential anomalies indicates the location of the upper-level trough associated with the midlatitude cyclone. The center of negative geopotential

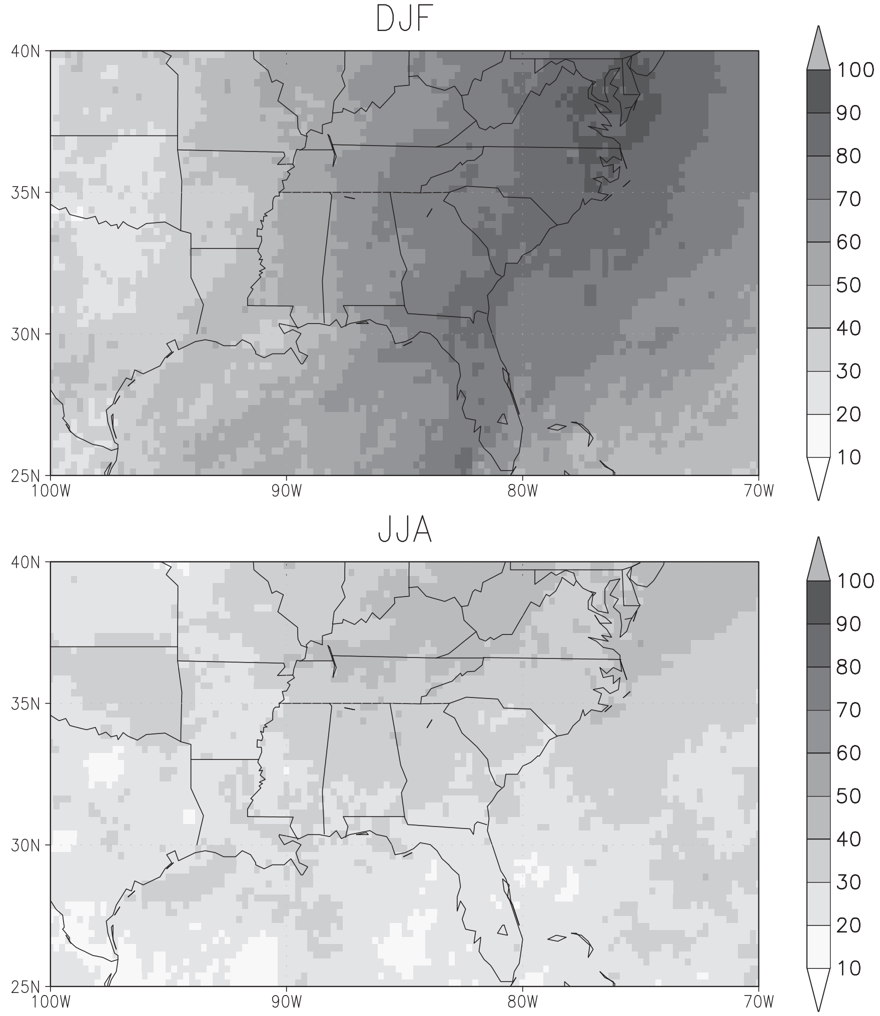


FIG. 3. Percent of total monthly rain that occurred during days −1 and 0 of a midlatitude cyclone passage in North Carolina for (top) winter (DJF) and (bottom) summer (JJA).

anomaly remains north–south oriented as it strengthens and propagates eastward along the jet stream reaching the exit region of the jet stream over the Atlantic on day +2. In agreement with the expected structure of a midlatitude cyclone, the surface low pressure center and precipitation (Fig. 2) remain ahead of the upper-level trough between days −2 and +3 (Fig. 4).

b. *Summer composite*

The summer composite is characterized by the presence of a low-level semistationary midlatitude trough that extends into the subtropics affecting the prevailing wind flow and precipitation patterns for a couple of days (Fig. 5). A total of 162 cases are included in the summer composite or a little over half the number of midlatitude cyclones in the winter midlatitude composite.

The effect of the midlatitude cyclone passage on precipitation is not nearly as dramatic in the summertime as it is in the wintertime. In the summertime, there is widespread precipitation over the southeastern United States on every day of the composite (Fig. 5). This daily widespread precipitation is in part modulated by the diurnal cycle of heating over the continent that plays a stronger role in the summer (Winkler et al. 1988). This is very different from the winter composite in which land-based precipitation only occurs during the passage of the midlatitude cyclone (Fig. 2). Consequently, only about 30%–40% of the total summertime precipitation in North Carolina (Fig. 3) occurs on days when a midlatitude cyclone is present, compared to over 70%–80% in the winter. In the summer, however, when widespread precipitation is present on most days, not all precipitation that occurs on a cyclone day can be attributed to synoptic-scale forcing. This means that the actual contribution of midlatitude cyclones to summertime precipitation is somewhat smaller than what is shown in Fig. 3.

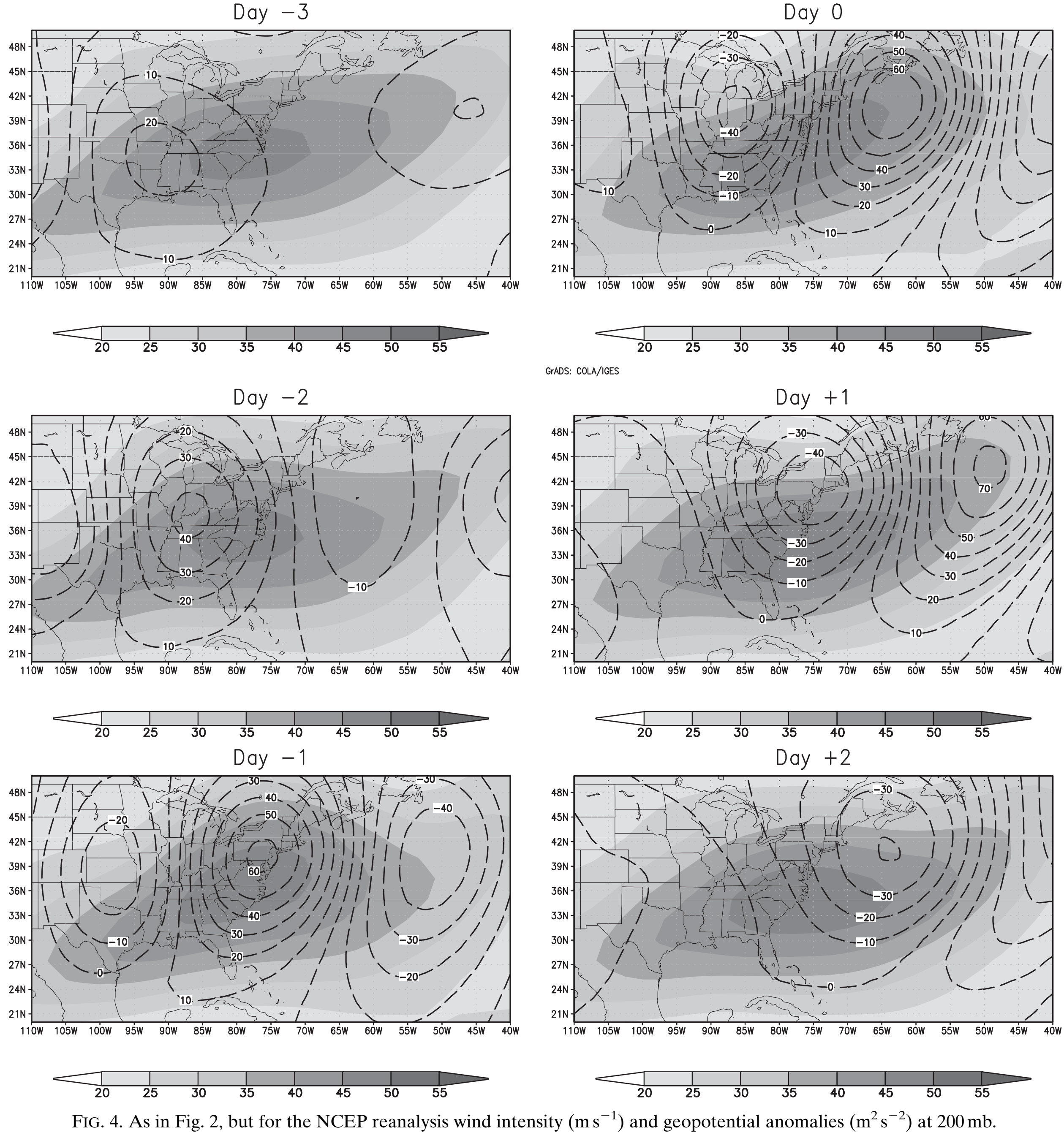
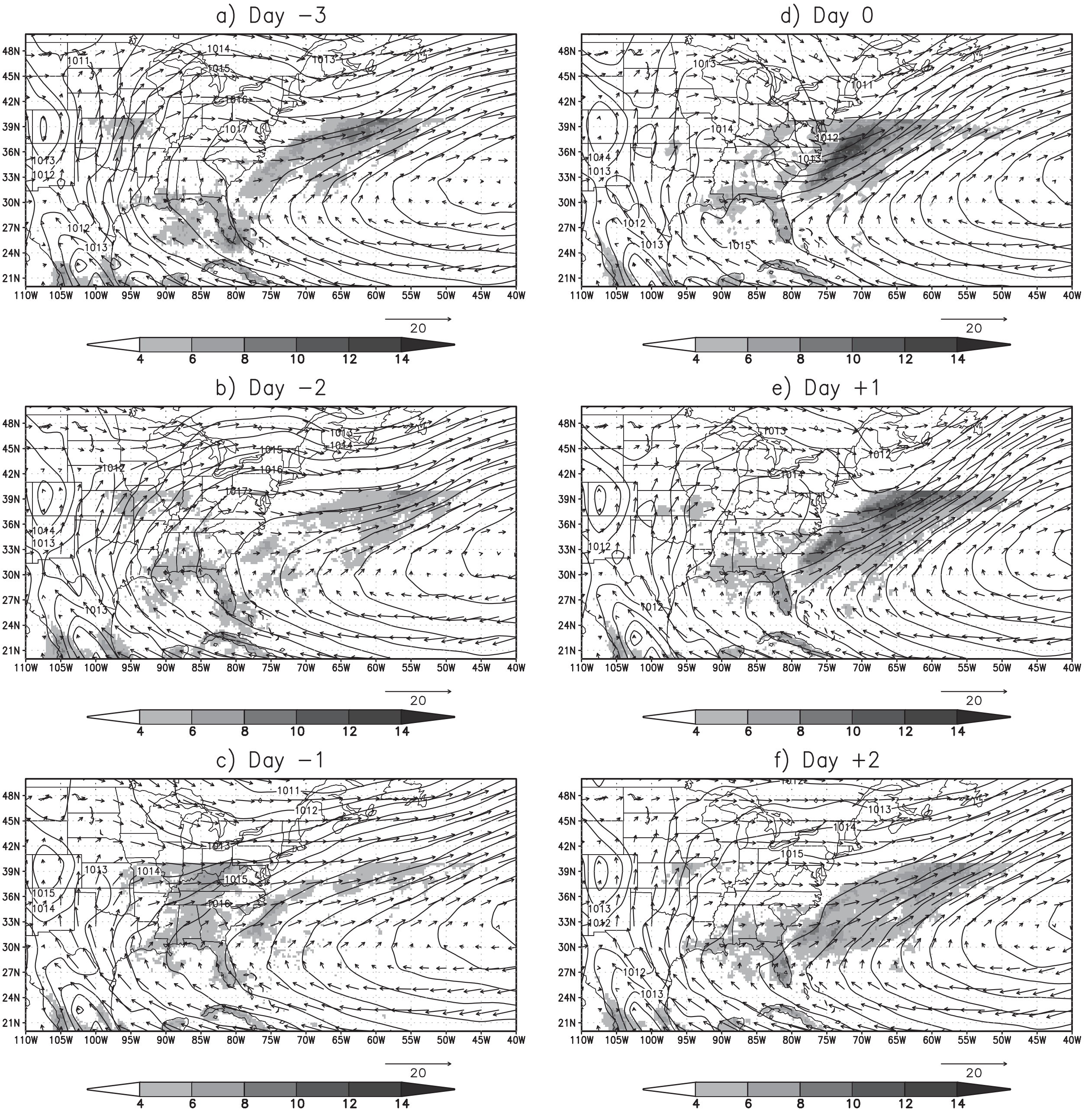


FIG. 4. As in Fig. 2, but for the NCEP reanalysis wind intensity (m s^{-1}) and geopotential anomalies ($m^2 s^{-2}$) at 200 mb.

Another distinct feature of the summertime composite is the presence of precipitation along the Gulf Coast from Louisiana to Florida and the entire Florida peninsula on every day of the composite (Fig. 5). Precipitation over the Gulf Stream is actually much weaker during the summer than winter composite. This is again reflected in the summertime climatological precipitation shown in Fig. 1. As summertime midlatitude cyclones cross into the Atlantic Ocean on days 0 and +1, they enhance precipitation over the Gulf Stream but not nearly as much as their wintertime counterparts, likely due to the weaker thermal contrast between air and sea in the summer. One similarity between summer and winter composites is that summertime midlatitude cyclones also produce more precipitation before crossing the Appalachian Mountains than on their lee side over the coastal plains of the Carolinas and Virginia, again suggesting a rain shadow effect of the mountains.



a) Day −3

b) Day −2

c) Day −1

d) Day 0

e) Day +1

f) Day +2

FIG. 5. As in Fig. 2, but for the summertime (162 cases).

The low-level trough associated with this cyclone begins intruding southward into the eastern United States on day −2, becoming elongated in the NE–SW direction along the East Coast on day 0 and later retreating northward with little eastward propagation (Fig. 5). A very significant feature of the summer composite that is absent in any of the other seasonal composites is the presence of two tropospheric ''rivers'' (Zhu and Newell 1998) that carry moist tropical air northeastward into the subtropics and midlatitudes. These tropospheric rivers are located along the Gulf Stream and along the Sierra Madre and Rocky Mountains and are present in every day of the summer composite. The passage of the midlatitude cyclone modulates the strength and direction of flow of the tropospheric rivers. Although southwesterly winds prevail over the Gulf Stream throughout the composite, the strongest southwesterly winds in this region occur on days −1 and 0, when the midlatitude trough reaches deepest into the tropics along the East Coast of the United States. This is also the time when the SLP gradients along the coast are strongest. The second tropospheric river is associated with the North American monsoon system. Southerly winds carry moist tropical air from the western Gulf of Mexico along the eastern side of the Sierra Madres and Rocky Mountains into the central United States.

The upper-level jet stream is located farther north (45°N), and it is weaker ($25\ \mathrm{m\,s^{-1}}$) in the summer (Fig. 6) than in the winter (Fig. 3), a set up that has been shown to favor anticyclonic behavior in midlatitude cyclone life cycles (Esler and Haynes 1999). During the summer, the southwestern tail end of a negative geopotential anomaly center first appears on day -1 (Fig. 6c) just west of the Great Lakes and propagates southeastward very slowly over the next few days. In the summertime composite, the axis of the upper-level trough is initially elongated in the northeast–southwest direction (day -1) and appears to rotate anticyclonically as it moves slowly southeastward from days 0 to $+2$. The summertime upper-level trough propagates eastward so slowly that its axis is still over the continent on day $+2$ (Fig. 6e). The summertime upper-level trough therefore has a different shape, much slower speed, and is centered farther north than its wintertime counterpart. An analysis of the monthly upper-level composites of midlatitude cyclones that cross North Carolina (not shown) indicates that as winter gives way to spring, upper-level troughs slow down, retreat northward, and become increasingly more tilted in the northeast–southwest direction, finally leading to a nearly stationary east–west-oriented midlatitude trough in the summer. The reverse occurs in the fall. This change in midlatitude cyclone behavior from wintertime north–south-oriented fast eastward-propagating upper-level troughs to summertime northeast–southeast-tilted nearly stationary upper-level troughs indicates a shift from cyclonic behavior storms in the winter to anticyclonic behavior storms in the summer. During the summertime when the southeastern United States is located on the anticyclonic shear side of the northward-displaced upper-level jet, midlatitude cyclones tend to display a more anticyclonic or thinning trough behavior with northeast–southwest-tilted upper-level troughs that are slow moving or nearly stationary. During the wintertime when the jet stream becomes centered over North Carolina, the cyclonic or ‘‘broadening trough’’ behavior prevails in the southeast United States. In good agreement with our finding of cyclonic behavior for the composite wintertime cyclones, Martius et al. (2007) found that twice as many cyclonic as anticyclonic behavior cyclones are observed during the wintertime in the North American sector.

c. *Fall and spring composites*

Figure 7 shows the day -2 through day 0 composites of SLP, 850-mb winds, and TRMM precipitation for the spring and fall seasons. The spring and fall composites have transitional characteristics that can be placed somewhere between the summer and winter composites. Spring midlatitude cyclones (Figs. 7a–c) are more similar to winter cyclones (Figs. 2b–d) in that they are characterized by the presence of a well-defined northeastward-traveling surface low pressure center that is accompanied by precipitation on its east-southeast flank. Like in winter, springtime land-based precipitation is limited to the days when the cyclone is present. The spring composite low pressure center propagates farther south than its winter counterpart. Oceanic precipitation in the spring is much weaker than during the other seasons, even over the Gulf Stream. Fall storms (Figs. 7d–f) on the other hand behave more like summer storms (Figs. 5b–d) in the sense that they are characterized by the presence of a trough that is propagating eastward farther north along the United States–Canada border. During fall, this trough is better able to organize precipitation in the SE United States than its summer counterpart (Figs. 5b–d). The fall composites are the only composites that have significant precipitation in the Gulf of Mexico.

4. Interannual variability

The interannual variability of wintertime midlatitude cyclone structure from 1998 to 2010 is studied by recalculating the seasonal composites segregated according to the phase of the El Niño–Southern Oscillation. The oceanic Niño index (ONI; from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) was used to classify each season as an El Niño, neutral, or La Niña period as shown in Table 1. A similar frequency of wintertime midlatitude cyclones is observed to occur in El Niño ($20\ \mathrm{yr^{-1}}$), La Niña ($21\ \mathrm{yr^{-1}}$), and normal years ($22\ \mathrm{yr^{-1}}$). This result stands in contrast to the Curtis (2006) finding that wintertime midlatitude cyclone counts in the southeastern region of the United States were twice as large in Niño years than those in either Niña or normal years. This discrepancy is likely due to differences in the domain of interest, which in Curtis (2006) includes storms over the ocean, as well as differences in storm counting techniques and time periods used in the two studies.

The composites show significant differences in the structure and propagation of wintertime midlatitude cyclones during Niña and Niño years. Figure 8 shows composites of the low-level structure of midlatitude cyclones that occurred during Niña (Figs. 8a–c; 107 events) and Niño (Figs. 8d–f; 98 events) years. The differences between the Niño and Niña midlatitude cyclone composites are also shown (Figs. 8g–i). Only results that

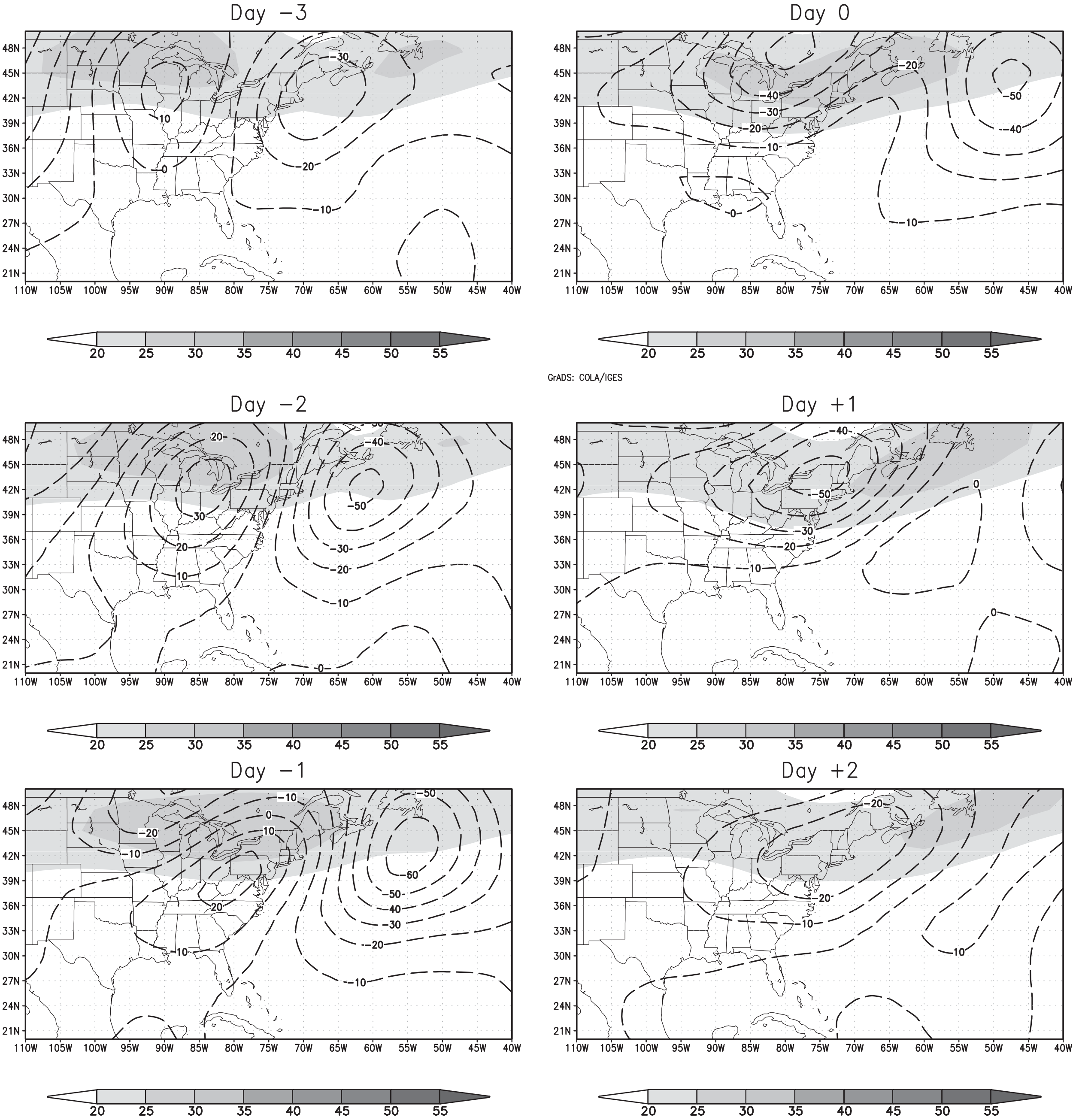


FIG. 6. As in Fig. 4, but for the summertime.

are statistically significant to the 95% level according to a Student's *t* test are shown in Figs. 8g–i.

The Niño and Niña composites differ in terms of precipitation amounts and distribution and in terms of the strength and latitudinal band along which the midlatitude cyclone propagates. Day −2 precipitation is stronger and more extensive in the Niño (Fig. 8d) than in the Niña (Fig. 8a) composite. By day −1, the Niño composite precipitation (Fig. 8e) extends over the entire southeast United States, including precipitation in the Carolinas, Virginia, and Florida, something that is absent in the Niña composite (Fig. 8b). This is in good agreement with the results of Eichler and Higgins (2006) that show an eastward extension of precipitation during El Niño years. On days −1 and 0, Niño midlatitude cyclones bring much more precipitation to the Gulf Stream than Niña midlatitude cyclones. The increase in wintertime midlatitude cyclone precipitation amounts in the

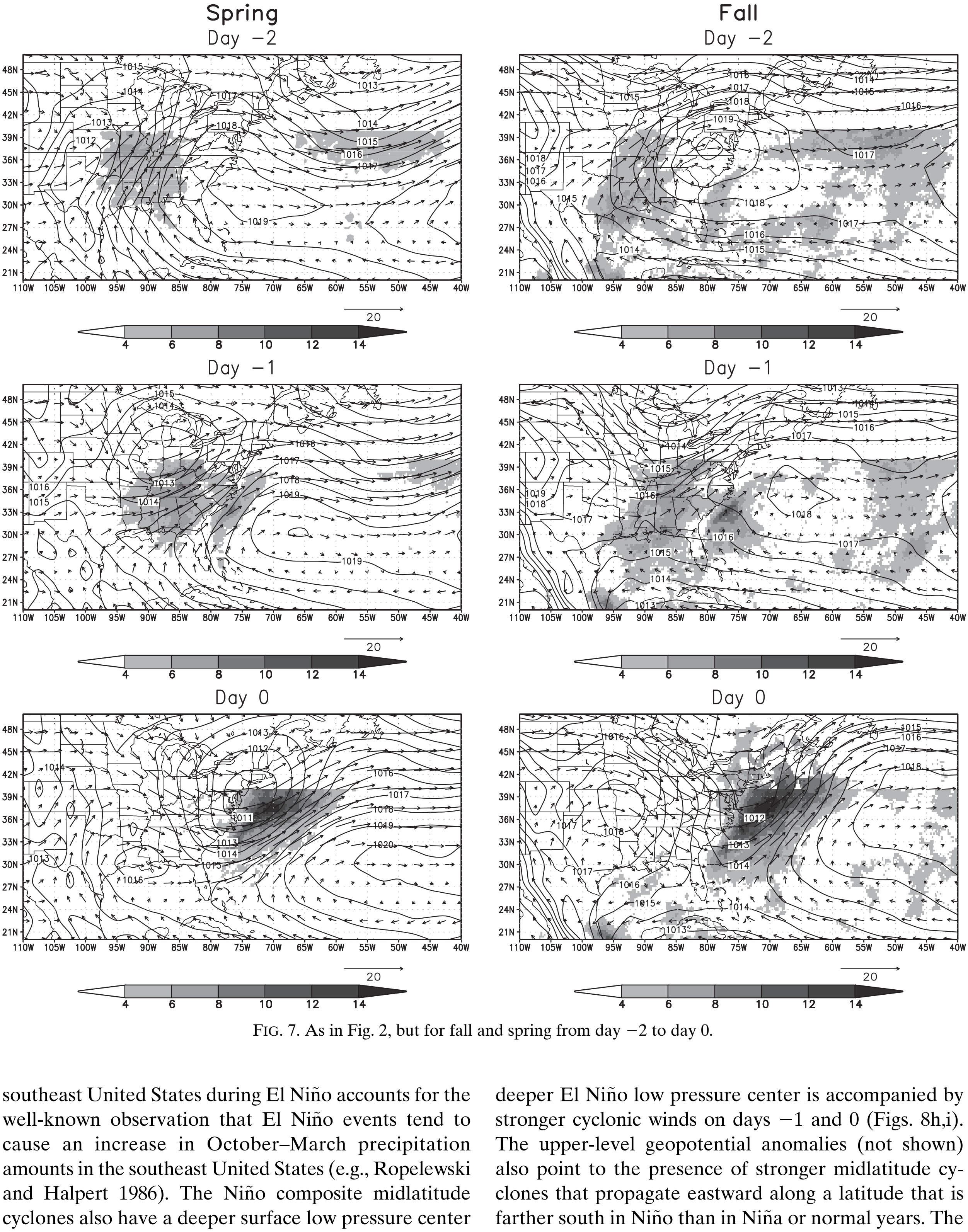


FIG. 7. As in Fig. 2, but for fall and spring from day −2 to day 0.

southeast United States during El Niño accounts for the well-known observation that El Niño events tend to cause an increase in October–March precipitation amounts in the southeast United States (e.g., Ropelewski and Halpert 1986). The Niño composite midlatitude cyclones also have a deeper surface low pressure center that propagates eastward along a latitude farther south than the midlatitude cyclones that occur during Niña years (in agreement with Bengtsson et al. 2006). This deeper El Niño low pressure center is accompanied by stronger cyclonic winds on days −1 and 0 (Figs. 8h,i). The upper-level geopotential anomalies (not shown) also point to the presence of stronger midlatitude cyclones that propagate eastward along a latitude that is farther south in Niño than in Niña or normal years. The reason for the increased strength and farther south location of the track of midlatitude cyclones during Niño winters is the presence of a stronger upper-level midlatitude

TABLE 1. List of El Niño, normal, and La Niña years used in making the DJF ENSO midlatitude cyclone composites. Years in which the absolute value of the ONI > 1.5 are indicated in boldface.

	El Niño	Normal	La Niña
Years	**1997/98**, 2002/03, 2004/05, 2006/07, and **2009/10**	2001/02, 2003/04, and 2008/09	**1998/99**, **1999/00**, 2000/01, 2005/06, and 2007/08

jet that is centered farther south during those winters (not shown). A comparison between the two strongest Niño and Niña events of the study period (not shown) yields similar results.

5. Conclusions

Previous synoptic climatologies of midlatitude cyclones in the southeast United States have focused on the seasonal and interannual variability of storm numbers, preferred regions of origin and tracks, wintertime total precipitation and snowfall amounts, and extreme precipitation. This study fills a gap in the literature by providing a general synoptic climatology of the seasonal-to-interannual variability of the structure and evolution of midlatitude cyclones in the southeast United States. Daily TRMM precipitation and NCEP reanalysis products were used to calculate 6-day-long composites of midlatitude cyclones that affected North Carolina between 1998 and 2010. The midlatitude cyclone composites in this study are based on a −2-mb 24-h pressure tendency in eastern North Carolina. This basis region is chosen because its location is halfway up the East Coast of the United States and downstream of the main North American cyclogenesis regions on the lee side of the Rockies (e.g., Whittaker and Horn 1984) makes it well positioned to capture cyclones that affect the eastern United States. This study finds that nearly twice as many midlatitude cyclones affected North Carolina during winter (279 events) as during summer (162 events). The number of midlatitude cyclones observed in the spring and fall were 242 and 200, respectively.

The composites show significant seasonal changes in the propagation and structure of midlatitude cyclones in the southeastern United States. In the low levels, the winter composite shows an eastward-propagating

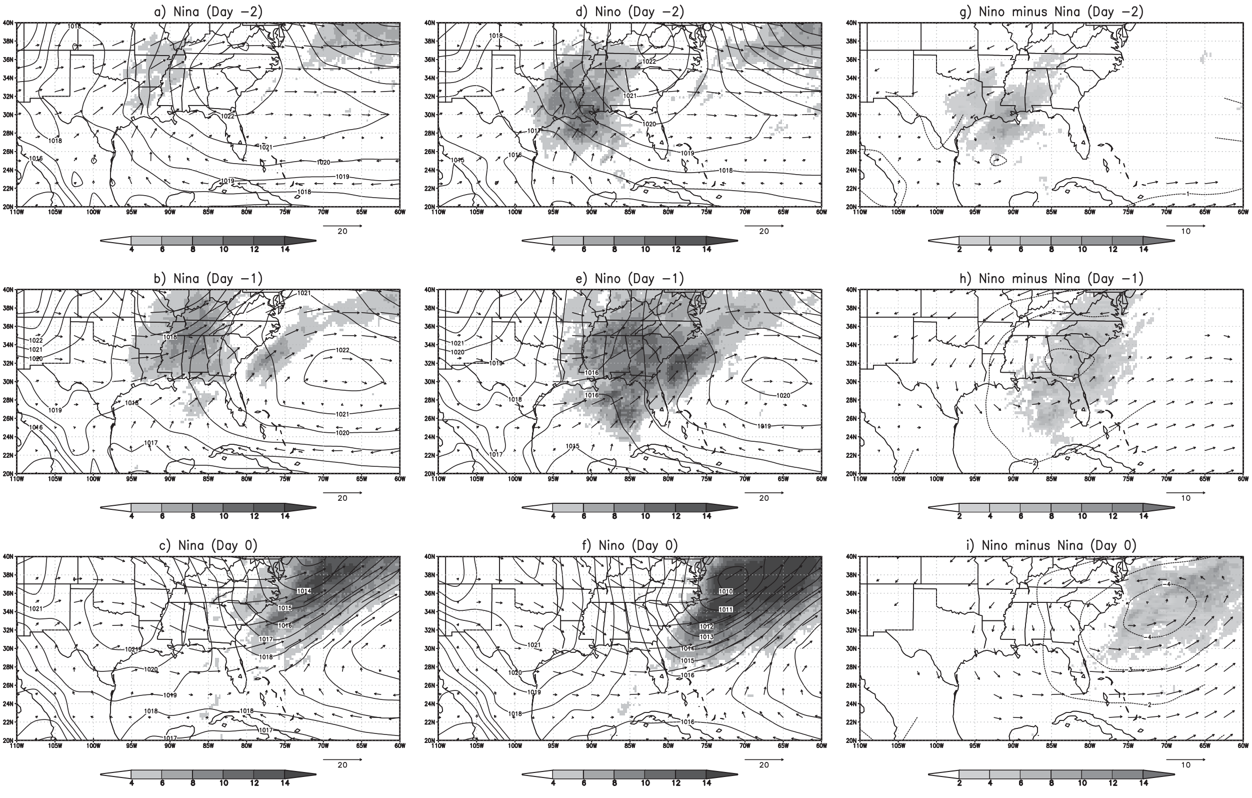


FIG. 8. As in Fig. 2, but for (left) La Niña (107 midlatitude cyclone events), (center) El Niño (98 midlatitude cyclone events), and (right) the difference between El Niño and La Niña: (top)–(bottom) from day −2 to day 0.

midlatitude cyclone that extends deep into the subtropics. Land-based wintertime precipitation occurs only on days −2 and −1 in and ahead of the low-level midlatitude cyclone low pressure center. More than 80% of the total wintertime precipitation in the eastern plains of the Carolinas is associated with the passage of midlatitude cyclones. The Piedmont and mountainous regions of North Carolina also receive a large portion (over 70%) of their wintertime precipitation from midlatitude cyclones. The composites also show that midlatitude cyclones produce more precipitation on the windward side of the Appalachians over the lower Mississippi Valley than over the Carolinas, something that may be associated with a rain shadow effect of the Appalachian Mountains. This is consistent with the presence of a climatological wintertime rain maximum to the west of the Appalachians. The spring composites (not shown) are similar to the winter composites when it comes to land-based precipitation distributions. The summer composite is characterized by the presence of a semistationary midlatitude trough that extends into the subtropics, affecting the prevailing wind flow and rainfall patterns for only 1–2 days. The low-level trough associated with this cyclone passage begins intruding southward into the eastern United States on day −2, becoming elongated in the NE–SW direction along the East Coast on day 0 and later retreating northward without much eastward propagation. The effect of the midlatitude cyclone passage upon precipitation is not nearly as dramatic in the summertime as it is in the wintertime. Only about 30%–40% of the total summertime precipitation in North Carolina occurs on days when a midlatitude cyclone is present, compared to over 70%–80% in the winter. This difference occurs in part because the summer is characterized by the presence of widespread precipitation over the southeastern United States on every day of the composite. As in the winter, summer midlatitude cyclones bring much more precipitation to the west of the Appalachians than to the Carolinas.

In the upper levels, the axis of the wintertime upper-level trough associated with the midlatitude cyclone remains north–south oriented and propagates eastward along 40°N. During the summer, however, the upper-level trough has slower propagation and an axis that is tilted in the northeast–southwest direction. Closer analysis of the annual cycle of the characteristics of the upper-level troughs indicates that as spring progresses upper-level troughs slow down, retreat northward, and become increasingly more tilted in the northeast–southwest direction, with the reverse occurring in the fall. As discussed above, these seasonal changes in upper-level circulation are associated with significant changes in the low-level structure and precipitation patterns of midlatitude cyclones that affect the SE United States. In sum, our composites suggest that the baroclinic life cycle behavior shift paradigm (Thorncroft et al. 1993) may be useful to explain the winter-to-summer shift in midlatitude cyclone behavior observed in the southeastern United States.

The ENSO-related variability of the structure and propagation of midlatitude cyclones is also studied. During the boreal winter the composites show the presence of a more intense and southward-displaced upper-level jet, stronger midlatitude cyclones, and more intense precipitation over a larger area during Niño than Niña years. Specifically, there is a stark contrast in precipitation in the cyclone warm sector over the coastal plains on the eastern side of the Appalachian Mountains from Georgia to North Carolina with heavy rain in the Niño and light rain in the Niña cyclone composites.

This study of the synoptic climatology of midlatitude cyclones in the southeastern United States provides the foundation for an ongoing companion study of the detailed climatology of radar-observed mesoscale precipitation organization within midlatitude cyclones in the southeastern United States. According to the U.S. Census Bureau, the southern United States has some of the fastest growing state populations in the United States and this trend is expected to continue (U.S. Census Bureau 2013; http://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf). This line of work is especially important because model simulations of future climate predict that by the end of this century anthropogenic climate change will cause midlatitude cyclone tracks to be displaced poleward of their current position (e.g., Bengtsson et al. 2006; Yin 2005), affecting not only the number of midlatitude cyclones that will reach the southeast United States but also likely affecting their strength and structure, as well as causing a potential decrease in precipitation amounts in a region of the United States that is highly populated and accustomed to plentiful water availability.

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