

Synoptic-Scale Features Common to Heavy Snowstorms in the Southeast United States

THOMAS L. MOTE, DOUGLAS W. GAMBLE, S. JEFFREY UNDERWOOD, AND MACE L. BENTLEY

Climatology Research Laboratory, Department of Geography, University of Georgia, Athens, Georgia

(Manuscript received 15 May 1996, in final form 29 October 1996)

ABSTRACT

Eighteen heavy snowstorms in the Southeast are examined to determine the synoptic-scale features common to these storms. Storm-relative composites in the temporal domain are created by assigning a “zero hour” to each storm based on the time of initial snowfall at Asheville, North Carolina. The composites indicate the importance of warm air advection (isentropic upglide) in producing upward motion within these storms. Of secondary importance in producing upward motion are the right entrance region of an upper-level jet streak, diabatic processes, and cyclogenetic lift. The composites also indicate that moisture is drawn off the Gulf of Mexico to feed these storms, while Atlantic moisture pools at low levels and may inhibit snowfall in the Piedmont region by limiting evaporative cooling. The surface cyclones, which deepen over the Atlantic near the Carolina coast, appear to play a small role in the development of Southeast snowstorms but often lead to heavy snowfall in the Northeast.

1. Introduction

The southeast United States is an enigma in terms of winter precipitation research. The meteorological literature is voluminous concerning snowfall and frozen precipitation, but the Southeast is generally neglected. Notable exceptions are Maglaras et al. (1995), Gurka et al. (1995), and Keeter et al. (1995), who published companion works that described winter forecasting problems in the eastern United States, including the Southeast. The set of climatological elements one encounters in the Southeast and the relative rarity of heavy snowfall events in that region explain the slight treatment the region has received in winter precipitation research. The meteorological complexities introduced by the Appalachian Mountains, the Gulf of Mexico, the Gulf Stream, and the region's latitude presented a daunting task for meteorologists concerned with snowfall events in the Southeast (Maglaras et al. 1995). More importantly, the Northeast and Midwest have attracted the majority of snowfall research due to the much more frequent snowstorms and higher snowfall totals in those regions.

Numerous dynamic elements at the synoptic scale have been examined in their relation to heavy snowfall over the Midwest and East Coast. For example, 500-hPa vorticity advection (Beckman 1987) and vorticity maximum digging and lifting (Younkin 1968) have been incorporated into forecasting research for the western

and central United States. Cook (1980) incorporated both 200- and 700-hPa warm air advection in the forecast of vertical motion fields associated with areas of heavy snowfall across the United States. Vertical motion resulting in heavy snowfall was also discussed in relation to the low-level jet (LLJ) beneath an exit region of an upper-tropospheric jet streak by Uccellini and Kocin (1987) and Kocin and Uccellini (1990). Kocin et al. (1995) analyzed the role of upper-level jets in the “superstorm” of March 1993. The transverse flow between regions of ascent associated with adjacent jet streaks was termed the signature of heavy snowfall producing systems along the East Coast (Uccellini and Kocin 1987). Snowfall research specific to the Southeast typically has been related to the effect of topography on precipitation type. The topographic influence of the Appalachian Mountains and Appalachian cold air damming (Richwein 1980; Forbes et al. 1987; Bell and Bosart 1988) add to the exceptionally complex nature of forecasting frozen precipitation in the mid-Atlantic and Southeast (e.g., Keeter and Cline 1991).

Research methodologies concerning synoptic-scale features associated with heavy snowfall have typically focused on one of two broad contexts. The first emphasizes a synoptic climatological approach encompassing one or two meteorological data fields for numerous snowstorms. The second, a case study approach, examines numerous meteorological phenomena that are associated with specific storms. The former approach is very useful in determining generalized antecedent conditions for a large population of snowfall events over a region. The latter approach is a diagnostic and prognostic tool, as specific features are critically examined as to their role in particular snowstorms.

Corresponding author address: Thomas L. Mote, Department of Geography, University of Georgia, Room 204, GGS Building, Athens, GA 30602-2502.
E-mail: tlote@uga.cc.uga.edu.

A synoptic climatological methodology often employs discrete composite analysis, in which the meteorological data fields for a number of storms are aligned in either the spatial or temporal domain. Aligning the data fields in the spatial domain is accomplished by means of a moving grid in which the origin follows some meteorological feature, such as a vorticity maximum or pressure minimum. Some studies of heavy snowfall that employ storm-relative composites in the spatial domain include the examination of surface low pressure centers and 500-hPa vorticity maxima (Fawcett and Saylor 1965; Goree and Younkin 1966; Younkin 1968) and the 850-hPa geopotential height minima (Browne and Younkin 1970) in relation to areas of heavy snowfall. An alternate approach is to align the storms in the temporal domain, which involves assigning a "zero hour" based on when snow begins (e.g., Brandes and Spar 1971). The latter approach offers a distinct advantage in locations where topography plays a significant role in the development of snowstorms because it does not utilize a moving grid.

In this study we borrow from both the synoptic climatological and case study approaches. This study is framed as a synoptic climatology of Southeast snowstorms, utilizing discrete composite analysis in the temporal domain. However, we have incorporated a number of meteorological data fields that traditionally have not been used in synoptic climatology. The result should be of value as a diagnostic tool to forecasters in the Southeast and may assist meteorologists in forecasting of heavy snowfall for the region.

2. Data and methodology

The synoptic climatological analysis was completed in four steps: 1) identification and mapping of heavy snowfall events, 2) a determination of a zero hour (+00 hour) for each storm in order to produce time-relative composites, 3) construction of composites at 12-h intervals from 72 h prior to 48 h after the +00 hour, and 4) discussion of significant features represented in each composite. The study area was defined as the area including the physiographic regions of southern Appalachia and the associated Piedmont, the Atlantic Coastal Plain, and the Lower Mississippi Valley. Specifically, seven states were included in the study area: Virginia, North Carolina, South Carolina, Tennessee, Georgia, Alabama, and Mississippi. Florida was excluded from the analysis due to the rarity of snowfall across the state.

Identification of heavy snowfall events was facilitated through the construction of a database with 446 surface stations (first order and cooperative). Each of the surface stations included in the database had at least 90% data coverage for daily snowfall observations during the period of 1 January 1949–31 December 1992. The daily snowfall observations were taken from EarthInfo, Inc., Central and East 1993 Summary of the Day CD-ROMs (EarthInfo 1993). Identification of a heavy snowstorm

was loosely based upon the traditional definition as an event greater than 10 cm (4 in.) in 12 h over a minimum contiguous area of 6 square degrees of latitude (Younkin 1968). Specifically, for this study, a heavy snowstorm is defined as a daily snowfall total of at least 10 cm for at least 50 stations within the study area. If at least 1 day during a snowstorm meets that criterion, the entire storm is included in the analysis.

A total of 22 heavy snowstorms were defined for the period of study. Three of the storms occurred before 1960 (January 1949, January 1955, and February 1958) and could not be used in the analysis because of insufficient upper-air data. A fourth storm, in February 1973, was removed from the analysis due to a unique snowfall pattern along the Atlantic coast that was unrepresentative of a typical Southeast snowstorm. The February 1973 storm broke all records for much of Georgia and South Carolina (Suckling 1991).

A +00 hour for each storm was determined by the initial hour of continuous snowfall at Asheville, North Carolina. Asheville was chosen for selection of the +00 hour because it was the only station with hourly snowfall data that received snow during each of the storms included in the analysis. The hourly snowfall data used to determine each storm's +00 hour was taken from the Solar and Meteorological Surface Observation Network (SAMSON) 1961–1990 Version 1.0 CD-ROM from the National Climatic Data Center in Asheville (NCDC and NREL 1993). The +00 hour occurs early in each storm, because snowfall typically spreads from southwest to northeast. Asheville often received snowfall earlier in the storm than most stations in North Carolina and Virginia, where most of the snowfall occurred. The 0000 or 1200 UTC observation that occurred prior to the start of snowfall at Asheville was selected as the +00 hour observation, unless the initial snowfall occurred within 3 h of a radiosonde observation. The 0000 UTC observation was selected as the +00 hour for storms with snowfall beginning between 2100 and 0800 UTC; the 1200 UTC observation was selected for storms with initial snowfall between 0900 and 2000 UTC. Using the January 1988 storm as an example, snowfall began at Asheville at 0700 UTC 7 January (Fig. 1a). The previous radiosonde observation, 0000 UTC 7 January, was selected as the +00 for the storm, and the heaviest snowfall occurred between 1200 UTC 7 January and 0000 UTC 8 January (+12 to +24 h). At Huntsville, Alabama, snowfall began 4 h earlier, at 0300 UTC, but still after the +00 hour (Fig. 1b). Even at the western edge of the study area, Memphis, Tennessee, continuous snowfall did not begin until 1700 UTC 6 January (not shown). Meanwhile, continuous snowfall did not begin at Richmond, Virginia, until 2100 UTC 7 January, 21 h after the +00 hour for the storm, and the heaviest snowfall occurred between 2300 UTC 7 January and 0600 UTC 8 January (+23 to +30 h) (Fig. 1c). The period of maximum snowfall is expected to occur near +12 h in the composites.

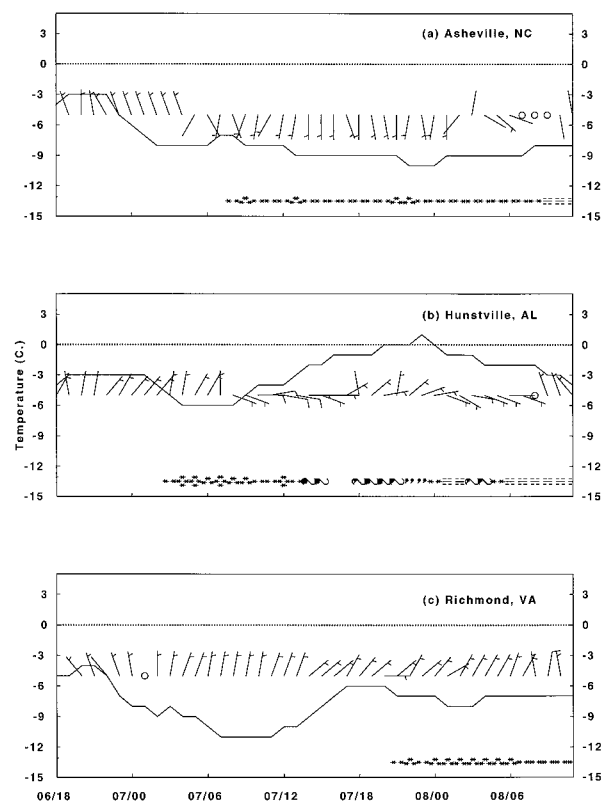


FIG. 1. Meteorograms of surface temperature, winds, and significant weather for 1800 UTC 6 January–1200 UTC 8 January 1988 at (a) Asheville, North Carolina; (b) Huntsville, Alabama; and (c) Richmond, Virginia.

Two sets of time-relative composites were constructed for each snowstorm. The first set of composites was constructed from data on the NCDC Radiosonde Data of North America 1946–1993 Version 1.0 CD-ROMs (NCDC 1994a). Geopotential height, temperature, dew-point temperature, and u and v wind components at every 50 hPa from sea level to 300 hPa, and at 200 and 100 hPa, were interpolated onto a $2^\circ \times 2^\circ$ grid using the Barnes objective map analysis technique in GEMPAK 5.2. The Barnes objective map analysis is a Gaussian weighted-averaging technique that assigns a weight to a datum solely as a known function of distance between datum and grid point (Barnes 1973). As incorporated into GEMPAK 5.2, the Barnes technique adequately recovers details after only two passes through the data (Koch et al. 1983).

In addition to gridding the radiosonde data, GEMPAK 5.2 was also used for vertical interpolation onto isentropic coordinates from 270 to 340 K at 5-K intervals. The GEMPAK function GDOMEK was used to calculate the ω field at every 50 hPa from 950 to 350 hPa. GDOMEK computes kinematic vertical motions from gridded wind data using the variational correlation method of O'Brien (desJardins et al. 1994).

The second set of composites utilized the initialized

TABLE 1. Dates of storms included in the analysis and the radiosonde observation selected as +00 hour for each storm.

Storm dates	Hour
13–14 Feb 1960	0000 UTC 13 Feb
2–4 Mar 1960	1200 UTC 2 Mar
9–11 Mar 1960	0000 UTC 9 Mar
9–11 Jan 1962	1200 UTC 9 Jan
22–24 Dec 1963	1200 UTC 23 Dec
31 Dec 1963–1 Jan 1964	0000 UTC 31 Dec
25–27 Jan 1966	0000 UTC 26 Jan
29–30 Jan 1966	1200 UTC 29 Jan
29 Feb–1 Mar 1968	0000 UTC 29 Feb
15–17 Feb 1969	1200 UTC 15 Feb
25–27 Dec 1969	1200 UTC 25 Dec
25–27 Mar 1971	1200 UTC 25 Mar
7–9 Jan 1973	1200 UTC 7 Jan
6–8 Feb 1979	0000 UTC 7 Feb
17–19 Feb 1979	0000 UTC 18 Feb
1–3 Mar 1980	1200 UTC 1 Mar
22–23 Jan 1987	0000 UTC 22 Jan
6–8 Jan 1988	0000 UTC 7 Jan

fields available on Gridded NMC Analyses for the Northern Hemisphere, Version II, CD-ROM, available from the National Center for Atmospheric Research in Boulder, Colorado (NCAR and University of Washington 1990). The dataset includes 1977-point hemispheric grids of sea level pressure; geopotential height at 850, 700, 500, and 200 hPa; temperatures at 850 hPa, and u and v wind components at 850 and 250 hPa. Both upper-air datasets were mapped using GEMPAK 5.2.

3. Results

a. Snowfall patterns

The 18 storms included in the analysis are given in Table 1. A number of these storms were also considered major snowstorms for the Northeast. For example, of the 20 major snowstorms of the Northeast as given by Kocin and Uccellini (1990), 4 storms are also included in this analysis: 2–4 March 1960, 29–30 January 1966, 25–27 December 1969, and 17–19 February 1979 (the Presidents' Day storm). In addition, many of the remaining storms also produce snowfall over the Northeast, even though the heaviest snowfall may have occurred in the southeastern or mid-Atlantic states.

The pattern of snowfall from the storms was almost oriented in a southwest–northeast direction. In many cases, the majority of the snowfall occurred east of the border of Tennessee and North Carolina (Fig. 2). Five of the storms originated in the Mississippi Valley of Mississippi and eastern Tennessee. In most cases the snowfall from the Mississippi Valley snowstorms continued into the Appalachians. The one exception was the 29 February–1 March 1968 storm, in which nearly all of the snowfall occurred in northern Mississippi and eastern Tennessee. In most of the storms, the heaviest snowfall occurred in the higher elevations of northeast Georgia, the western Carolinas and Virginia, and eastern

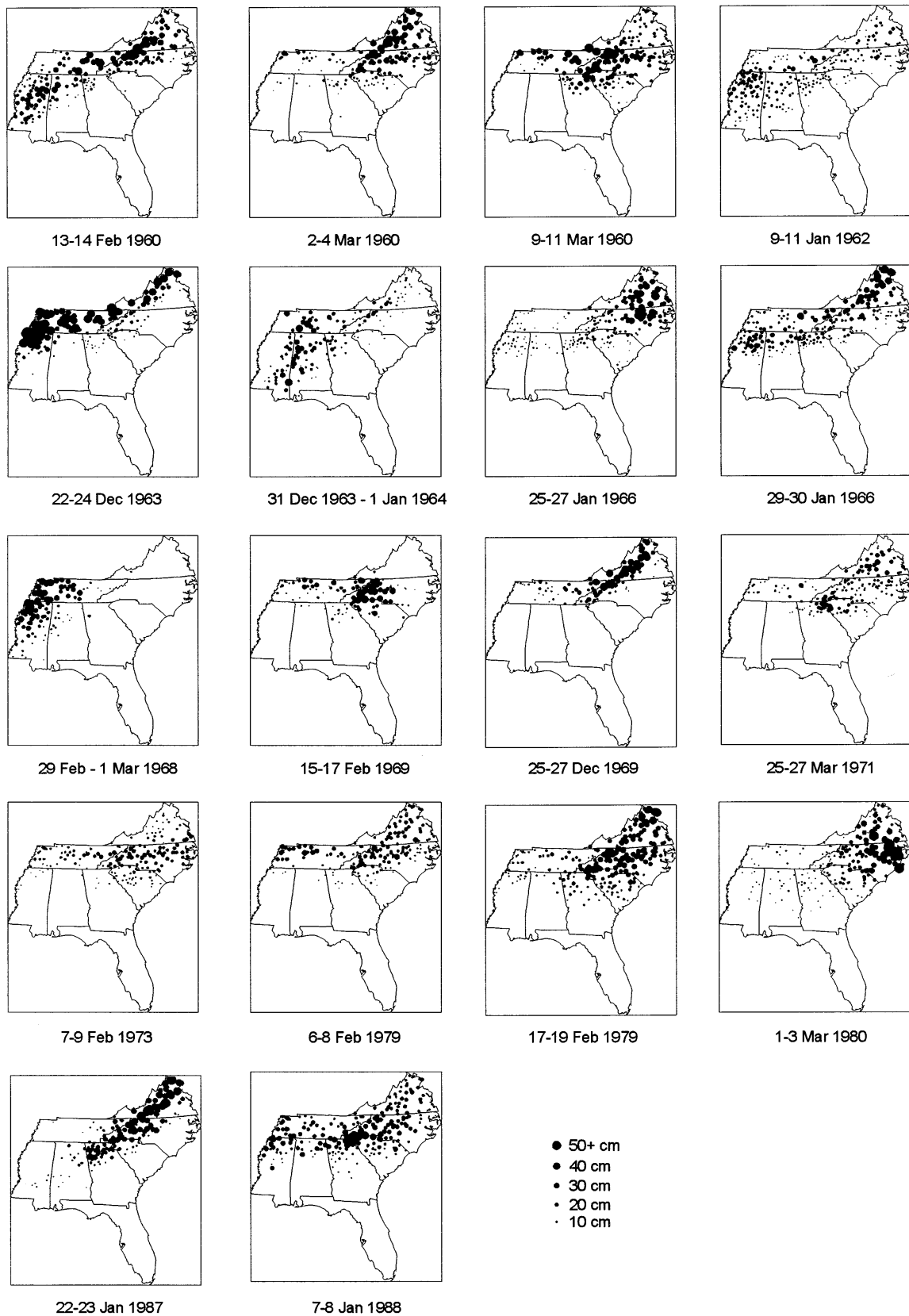


FIG. 2. Snowfall totals for the 18 storms included in this study.

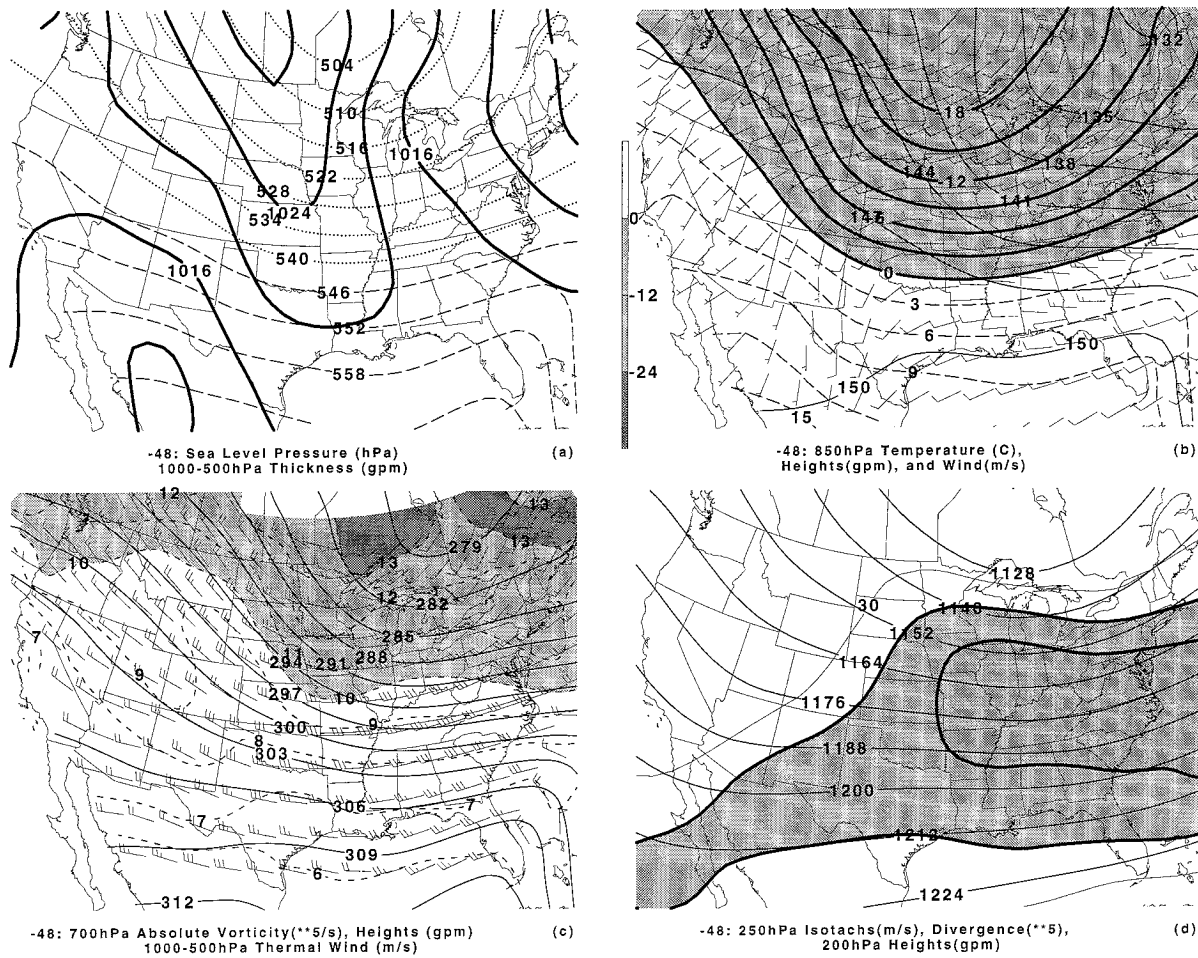


FIG. 3. The -48-h composite of (a) sea level pressure (hPa) and 1000–500-hPa thickness (gpm); (b) 850-hPa temperature ($^{\circ}\text{C}$), geopotential height (gpm), and wind (m s $^{-1}$); (c) 700-hPa absolute vorticity ($\times 10^{-5} \text{ s}^{-1}$), geopotential height (gpm), and 1000–500-hPa thermal wind (m s $^{-1}$); and (d) 250-hPa isotachs (m s $^{-1}$), divergence ($\times 10^{-5} \text{ s}^{-1}$), and 200-hPa heights (gpm).

Tennessee. Only one storm in this study did not have its heaviest snowfalls in the Appalachians or the Mississippi Valley. The 1–3 March 1980 storm had its heaviest snowfall in the Piedmont and coastal regions of North Carolina and Virginia. A detailed description of the spatial patterns of snowfall across the Southeast is provided by Suckling (1991).

b. Composite maps

In order to better understand the synoptic-scale features in common to these 18 snowstorms, discrete composite analysis was performed on all upper-air data fields extracted for each storm. Time-relative composites were created at 12-h intervals for -72 to +48 h, based on the +00 hour assigned to each storm. Only the time period of -48 to +24 h is discussed here; earlier and later composite periods were found to provide little additional diagnostic information about these storms.

1) THE -48-H COMPOSITE

Evidence of a cold air outbreak preceding the “composite storm” can be seen in the composite 48 h before the heaviest snowfall occurs at Asheville. An arctic air mass with a center of high pressure (1030 hPa) is located over northern Saskatchewan (Fig. 3a). A broad area of low pressure is also evident over northern Mexico northward toward the big bend region of Texas (in the NMC sea level pressure fields) (Fig. 3a). This surface low is found in the -48- to -24-h composites. An examination of individual storms shows that several were preceded by a weak low in the sea level pressure field near the big bend region of Texas. Temperatures at 850 hPa in the southern Appalachians are sufficient for snowfall at -48 h, with the 0°C isotherm extending southward to the northern fringe of Mississippi, Alabama, and Georgia (Fig. 3b). The -48-h composite also shows a weak lobe of positive vorticity migrating through the Great Lakes region (Fig. 3c). Immediately to the south

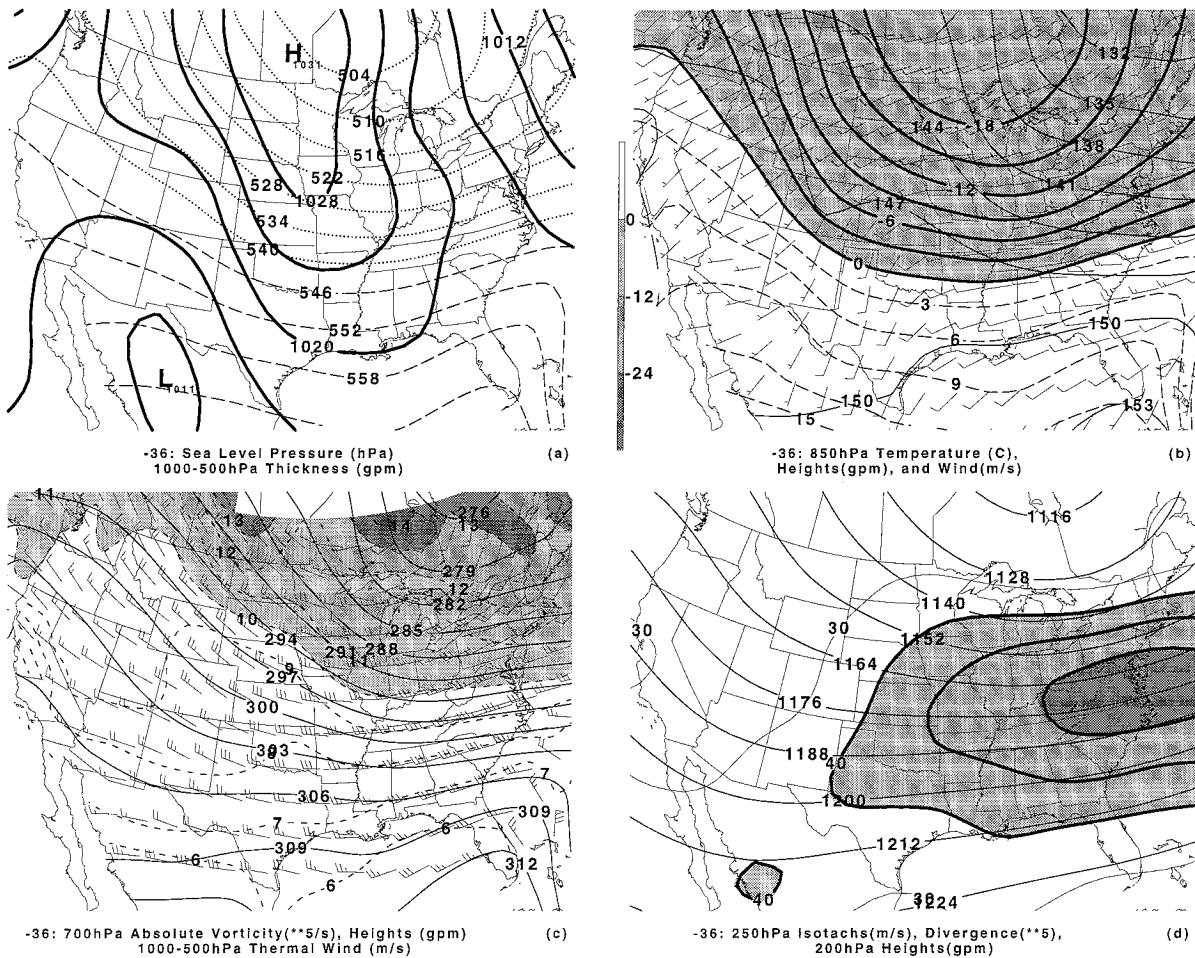


FIG. 4. Same as Fig. 3 except for the -36-h composite.

of the region of greatest vorticity advection at 700 hPa by the 1000–500-hPa thermal wind is evidence for a developing jet streak at -48 h, centered over southern Indiana (Fig. 3d).

2) THE -36-H COMPOSITE

By the -36-h analysis, the antecedent conditions to heavy snowfall in the Southeast have become much more evident. The Canadian anticyclone is centered almost over Winnipeg, Manitoba, with a central pressure of 1031 hPa. Sea level pressures of 1020 hPa extend to the Gulf Coast of the United States (Fig. 4a). Cold air advection (CAA) is evident throughout the Great Lakes but is particularly strong from Michigan to western New York state (Fig. 4a). The cold air advecting into the Southeast produces a low-level environment more conducive to snow and increases baroclinic instability near the Gulf of Mexico. A region of warm air advection (WAA), which subsequently advances across the Southeast, appears along the southwestern edge of the arctic outbreak (Fig. 4a). The southerly flow is ahead of a

weak low-level trough seen in eastern Colorado at 850 hPa (Fig. 4b). A second, stronger lobe of positive absolute vorticity at 700 hPa is present in the -36-h composite over Saskatchewan and Manitoba (Fig. 4c). A shortwave also seems evident in the 700- and 250-hPa geopotential height fields (Figs. 4c and 4d). The 250-hPa wind maximum over the eastern United States is better defined, with wind speeds in excess of 60 m s^{-1} from western Kentucky through Maryland, Virginia, and North Carolina (Fig. 4d).

3) THE -24-H COMPOSITE

The surface anticyclone continues to advance to the southeast in the -24-h composite, with a central sea level pressure of 1030 hPa over northern Minnesota (Fig. 5a). The anticyclone appears to move both to the south, across the Great Plains, and to the east-southeast, toward the mid-Atlantic. Initially, this was thought to be an artifact of the compositing, representing two preferred tracks to the surface anticyclones. An examination of the anticyclone paths for individual storms in-

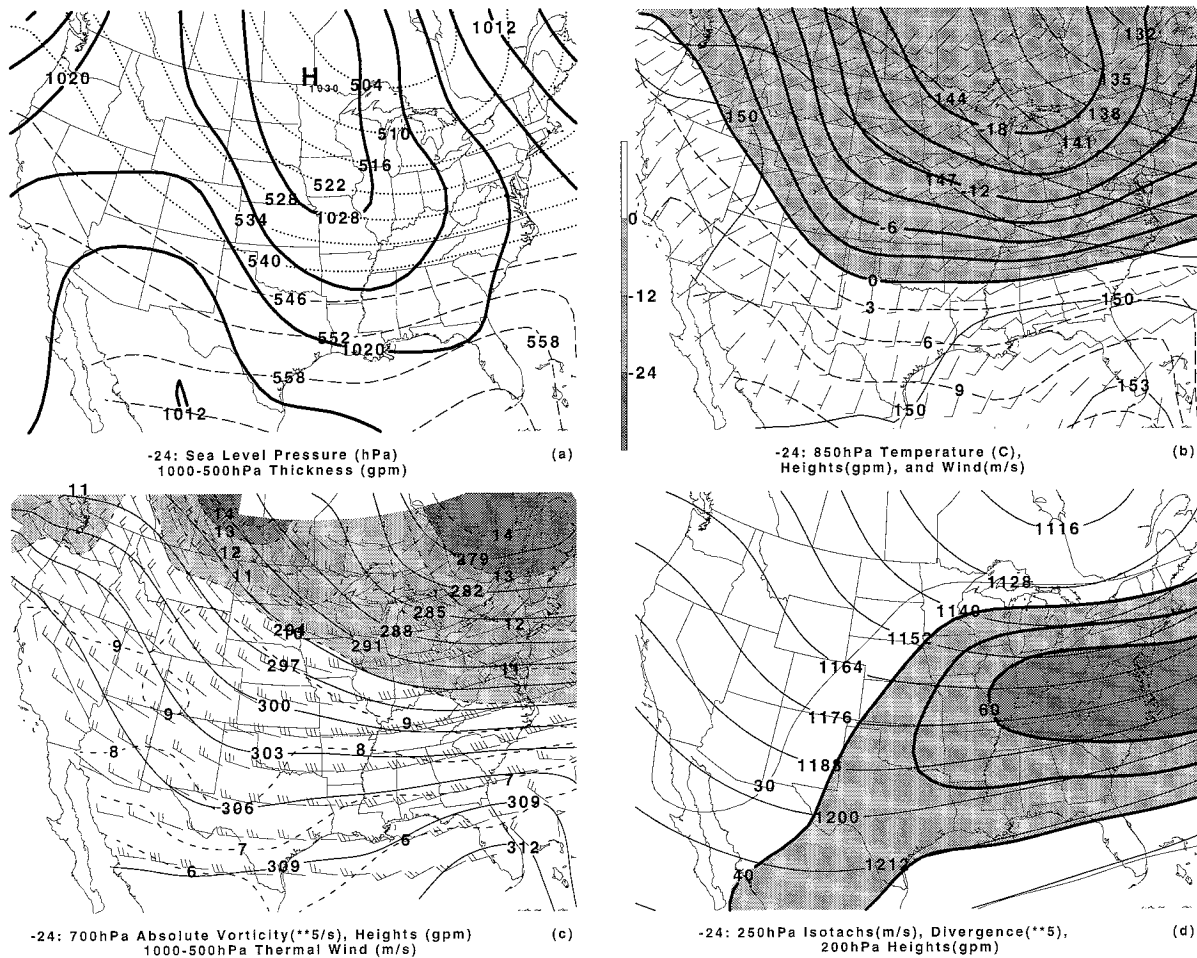


FIG. 5. Same as in Fig. 3 except for the -24-h composite.

indicates that high pressure is usually in place both over the Great Plains and the Northeast. Strong southerly flow advanced eastward since -36 h and covers most of Texas at -24 h (Fig. 5b). This southerly flow and WAA, once oriented over the Gulf of Mexico, will be associated with upward motion. A broad trough at 700 hPa is evident in the -24-h composite with a weak lobe of positive absolute vorticity located over western Colorado (Fig. 5c). A separate lobe of positive vorticity in excess of $15 \times 10^{-5} s^{-1}$ at 700 hPa has formed over Saskatchewan (Fig. 5c). The region of 250-hPa wind speeds in excess of $60 m s^{-1}$ remains anchored in nearly the same location as at -36 h but has expanded westward as far as St. Louis (Fig. 5d). This is likely in response to the strengthening low-level baroclinic zone in the southwest portion of the arctic outbreak.

4) THE -12-H COMPOSITE

The center of the surface anticyclone has moved little from -24 to -12 h, but the edge of the arctic air mass

has extended into the Southeast, with the 1020-hPa sea level isobar as far south as the Gulf Coast (Fig. 6a). The $0^{\circ}C$ isotherm at 850 hPa has moved farther south and extends from north Texas through South Carolina in the -12-h composite (Fig. 6b). A strong temperature gradient at 850 hPa is evident in the Gulf Coast states and over the northern Gulf of Mexico, with temperatures at $-3^{\circ}C$ in the Texas panhandle to $12^{\circ}C$ near Brownsville, Texas (Fig. 6b). Strong WAA is evident to the south of the $0^{\circ}C$ isotherm, in advance of the trough, from southeast Texas through central Mississippi. The region of strongest WAA, with values near $12 \times 10^{-5} K s^{-1}$, are located near Dallas, Texas (Fig. 7a).

The trough traveling across the southwest through the southerly branch of the upper-level flow has advanced and deepened during the previous 12 h (Fig. 6c). The trough is clearly evident at 700 hPa from Kansas through Texas, and at 200 hPa from Colorado through New Mexico (Fig. 6d). This trough will continue to back the low-level flow to a more southerly component enhancing WAA and associated upward motion.

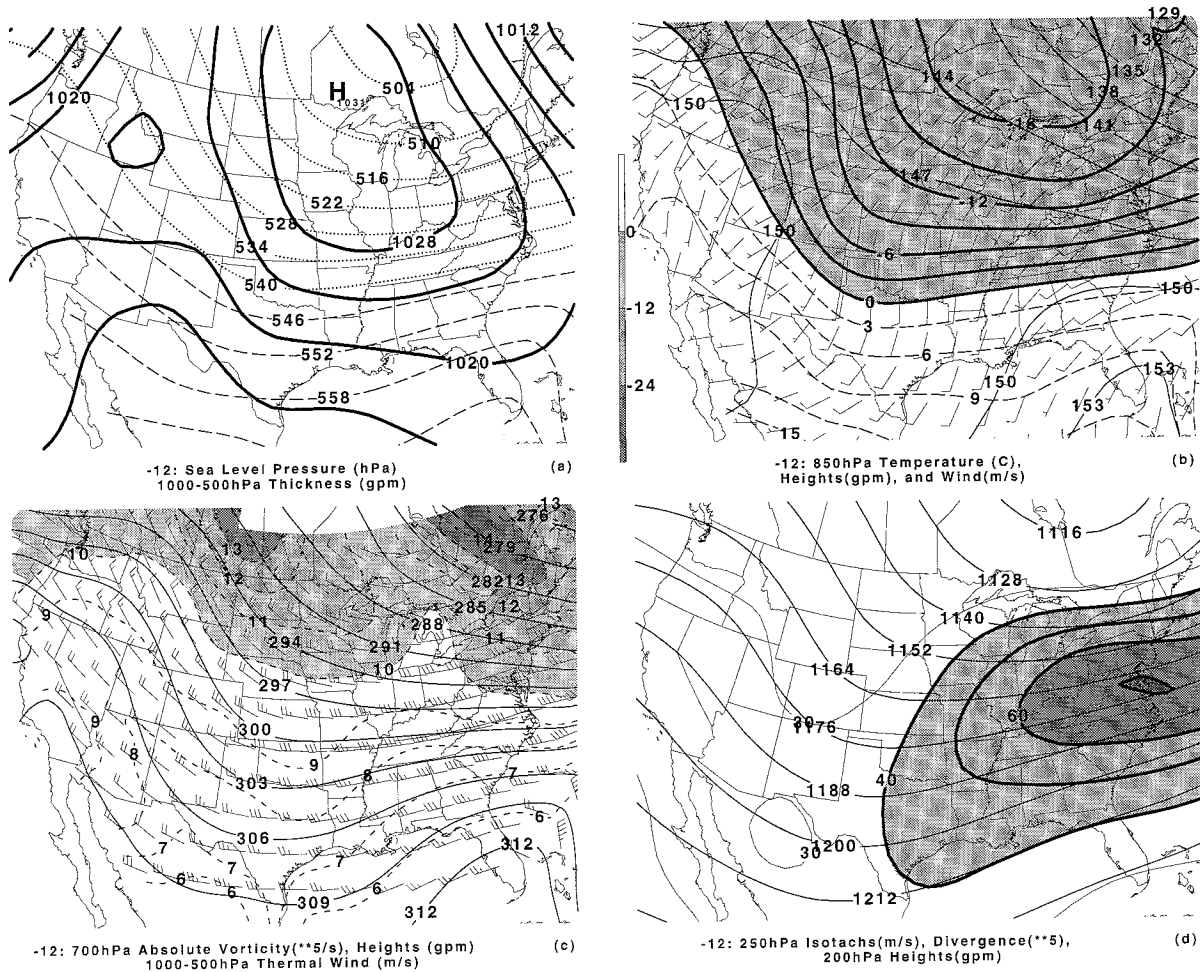


FIG. 6. Same as in Fig. 3 except for the -12-h composite.

5) THE +00-H COMPOSITE

At +00 h, the surface anticyclone is centered over western Wisconsin, with a central pressure at 1029 hPa, corrected to sea level, and an inverted trough is forming over the northern Gulf of Mexico (Fig. 8a). A weak sea level pressure minimum of 1015 hPa has formed off the Louisiana coastline by +00 h. The pressure center is too weak to be indicated by a closed isobar at +00 h but is evident by examining the individual grid points. The trough noted in the -36-h 850-hPa composite has almost cut off by +00 h (Fig. 8b). The trough axis is centered on the southern Mississippi Valley, with relatively strong WAA on the east side of the river through Mississippi, Alabama, and Georgia. An 850-hPa WAA advection maximum of $16 \times 10^{-5} \text{ K s}^{-1}$ is centered near Atlanta, Georgia, in the +00-h composite (Fig. 7b). However, a number of the individual storms show northeasterly flow at the surface from Atlanta northeastward through the Piedmont region of the Carolinas and Virginia, associated with cold air damming along the eastern slopes of the Appalachians. The spatial and temporal

resolution of the radiosonde observations limits the ability to infer cold air damming episodes with radiosonde data (Keeter et al. 1995).

The trough over the central United States has continued to amplify as well as advance eastward in the +00-h composite. At 700 hPa, the trough axis runs from Iowa to the Gulf Coast (Fig. 8c). The lobe of 700-hPa positive vorticity in excess of $13 \times 10^{-5} \text{ s}^{-1}$, which had been located over the Canadian prairies at -12 and -24 h, has moved over the Dakotas and western Nebraska at +00 h (Fig. 8c). At 700 hPa, a region of relative humidity in excess of 70% over northern Alabama and Mississippi is present (Fig. 7b). The +00-h time period is when snow would be expected over the western portion of the study region, including northern Alabama and Mississippi. The wind maxima at 300 and 250 hPa remains have increased in speed and coverage, and advanced northeast from -48 to +00 h, with wind speeds in excess of 70 m s^{-1} at 250 hPa from Delaware extending off the East Coast at +00 h (Fig. 8d). Wind speeds in excess of 40 m s^{-1} at 300 and 250 hPa extend

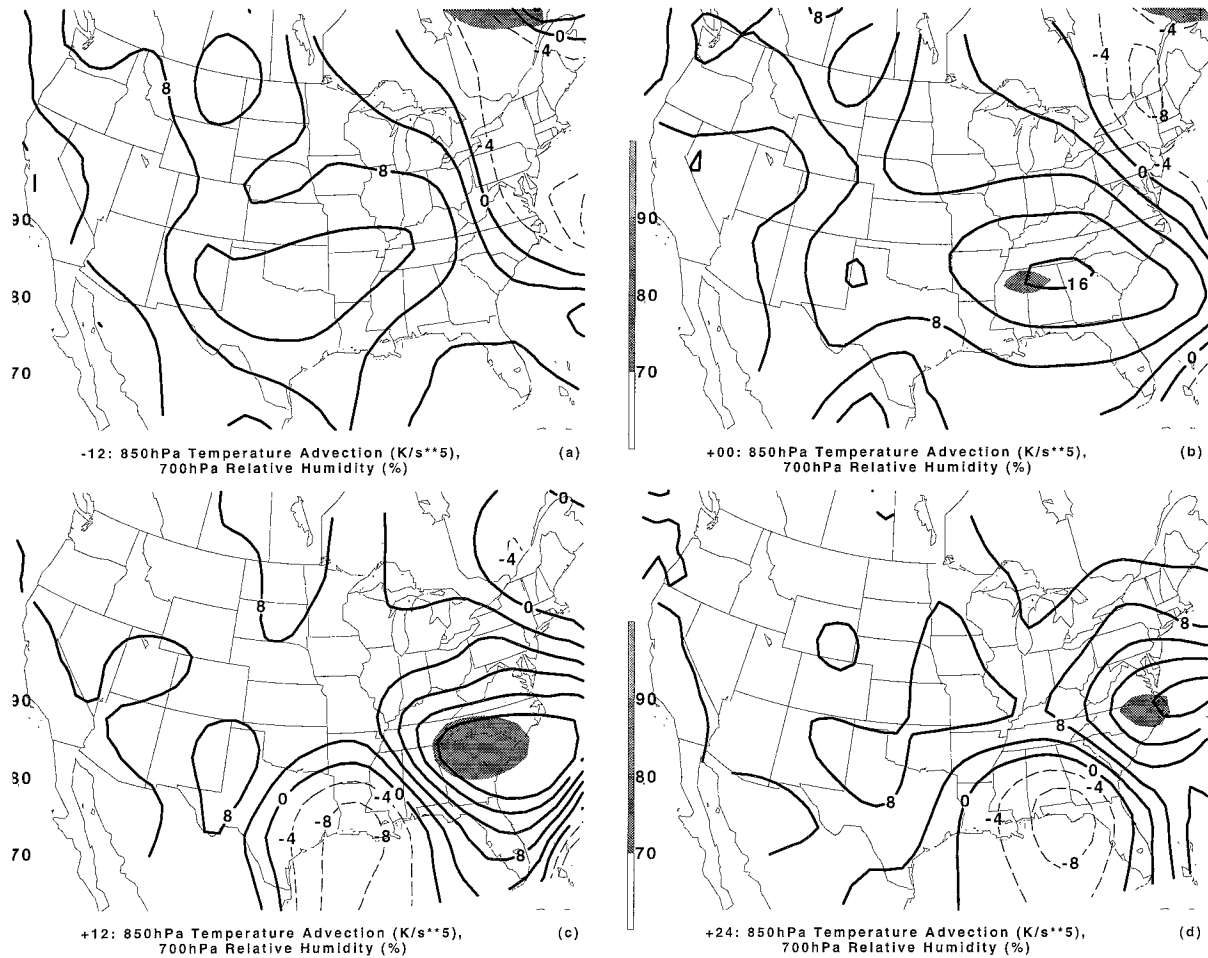


FIG. 7. The 850-hPa temperature advection ($\times 10^{-5} \text{ K s}^{-1}$) and 700-hPa relative humidities for the (a) -12 -h composite, (b) $+00$ -h composite, (c) $+12$ -h composite, and (d) $+24$ -h composite.

from eastern Texas northeastward into Michigan and cover most of the eastern third of the United States in the $+00$ -h composite (Fig. 8d).

6) THE $+12$ -H COMPOSITE

The surface anticyclone appears to be moving southward across the plains and into the eastern Great Lakes in the $+12$ -h composite. One center of high pressure is near Kansas City, Missouri (1028 hPa), and a second is located over eastern Ontario (1028 hPa) (Fig. 9a). A 1012-hPa surface low is apparent by examining individual grid points in the Gulf of Mexico, west of Tampa Bay, Florida. Although this low is not indicated by a closed isobar, a distinct minimum in the sea level pressure grid is present south of the Florida panhandle (Fig. 9a). The location of the surface cyclone and anticyclone in the $+12$ -h composite closely matches the composite sea level pressure field associated with the onset of heavy snow in the Southeast given by Brandes and Spar (1971). At 850 hPa, the lowest geopotential heights are

located over eastern Tennessee (Fig. 9b). The low is on the warm side of a tight temperature gradient at 850 hPa, ranging from 0°C over Atlanta to 12°C over Tampa Bay. Strong WAA at 850 hPa continues into southern Georgia and the coastal region of the Carolinas. A WAA maximum of $26 \times 10^{-5} \text{ K s}^{-1}$ is located near Columbia, South Carolina, in the $+12$ -h composite, which indicates an advective change in temperature of 1°C h^{-1} in the composite (Fig. 7c). The western half of the Southeast is undergoing CAA, with the 850-hPa 0°C isotherm cutting through Mississippi, Alabama, and Georgia.

By $+12$ h, the trough has continued to amplify and has become almost vertically stacked from 700 to 200 hPa, with the trough axis through the Mississippi Valley at 700 hPa (Fig. 9c). The area with wind speeds in excess of 60 m s^{-1} at 250 and 300 hPa has moved eastward, and the wind maximum has migrated northward to just east of the New Jersey coastline. The region of wind speeds in excess of 40 m s^{-1} extends around the base of the trough, likely indicating multiple, smaller wind maxima passing through the trough that are often as-

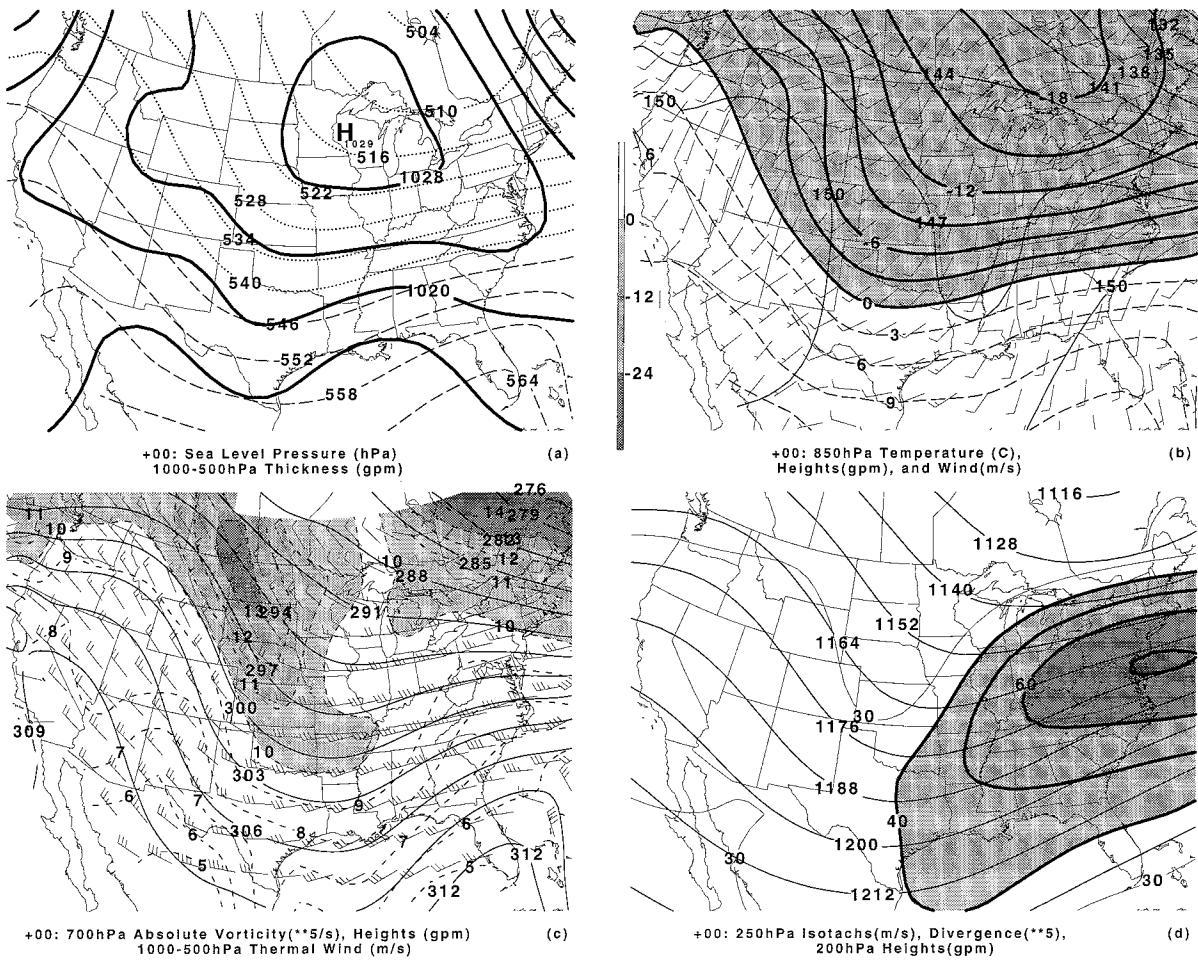


FIG. 8. Same as in Fig. 3 except for the +00-h composite.

sociated with Northeast snowstorms (Kocin and Uccellini 1990). A region of 250-hPa divergence is located over the region of maximum upward vertical velocities as indicated by the Trenberth quasigeostrophic approximation (Carlson 1991) (Figs. 9c and 9d). A large region of 700-hPa relative humidity in excess of 70% covers all of South Carolina, northern Georgia, southern and western North Carolina, and extreme eastern Tennessee (Fig. 7c) and is associated with the region where heaviest snowfall typically occurs at +12 h.

7) THE +24-H COMPOSITE

A distinct surface low is present east of the Carolina coast, with a central sea level pressure of 1011 hPa in the +24-h composite (Fig. 10a). Some individual storms had a surface cyclone approximately 20 hPa deeper than the composite. Small variations in the location of the cyclone's center at +12 h result in a composite sea level pressure field with a cyclone that is more broad, but not as deep as cyclones found in individual storms. The surface anticyclone is now most evident in the southern

plains, with a 1026-hPa high located near Dallas (Fig. 10a). A closed height contour is no longer apparent at 850 hPa, but the minimum heights are located along the coastline of the mid-Atlantic states (Fig. 10b). This change in the 850-hPa height field may represent a problem with our data sources, as the 850-hPa low approaches the relatively data-sparse Atlantic Ocean. Nearly all of the Southeast is under CAA by +24 h, and the maximum of WAA ($20 \times 10^{-5} \text{ K s}^{-1}$) is located just ahead of the rapidly developing surface low off the coast of North Carolina (Fig. 7d).

The trough through the eastern United States has stopped amplifying by +24 h, and the axis of the trough is located through the Appalachian Mountains at 700 hPa (Fig. 10c). A 700-hPa vorticity maximum associated with the trough extends from western Ontario southward toward St. Louis, Missouri, and eastward through the central Appalachians (Fig. 10c). The developing surface low continues to be located on the nose of maximum thermal vorticity advection (Figs. 10a and 10c). The area of relative humidity in excess of 70% at 700 hPa has decreased in size during the previous 12 h

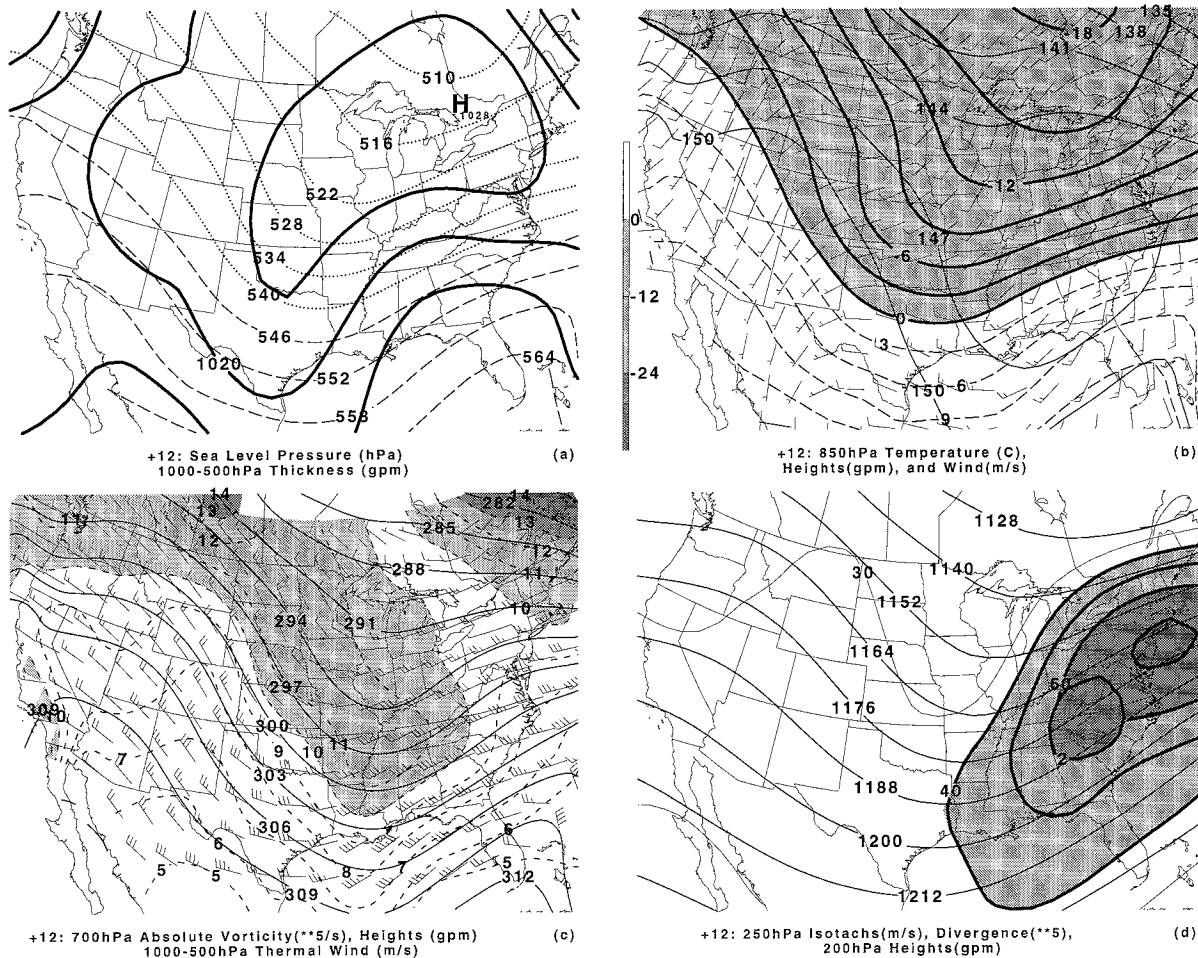


FIG. 9. Same as in Fig. 3 except for the +12-h composite.

and only covers the coastal region of North Carolina by +24 h (Fig. 7d). The 250-hPa wind maximum is located southeast of Cape Cod by +24 h, with the axis of highest wind speeds located almost directly over the south Atlantic coastline (Fig. 10d).

4. Discussion

a. Uplift mechanisms

The composite maps indicate that warm air advection (isentropic upglide) seems to be an important mechanism for producing upward motion in these storms. In order to closely examine the composites for significant lifting mechanisms, a series of isentropic maps and cross sections were examined for the -12- to +24-h composites.

The region of maximum uplift is closely associated with isentropic upglide and in some cases the formation of a low-level jet stream. The composite time series of 292-K pressure and mixing ratio maps demonstrates the role of isentropic upglide in these storms. The LLJ is evident in the isotach field of the composite maps from

-12 to +24 h (not shown). At -12 h, the LLJ crosses the Texas coastline with a maximum wind speed of 11 m s^{-1} over the Gulf of Mexico. An 11 m s^{-1} wind maximum is not impressive for an individual storm; Djuric and Ladwig (1983) found LLJ wind maxima between 13 and 34 m s^{-1} over the southern plains during the winter of 1977. For individual storms included in the composite, the wind maximum was in excess of 20 m s^{-1} . At +00 h the LLJ crosses the Louisiana and Mississippi coastlines with a wind maximum of 15 m s^{-1} . The LLJ flows nearly parallel to the Georgia coastline by +12 h with a maximum speed of 17 m s^{-1} . By the +24-h composite, the LLJ is off the South Carolina coast with a maximum speed of nearly 20 m s^{-1} .

In the -12-h composite, adiabatic ascent is present through most of Texas from 900 to 800 hPa while mixing ratios of 6 g kg^{-1} approach the Texas coastline. However, the New Orleans, Louisiana (NEW), to Cape Hatteras, North Carolina (HAT), cross section shows little uplift and no relative humidities above 70% (not shown). By +00 h, the axis of maximum upslope flow is through Mississippi, Alabama, and Tennessee, with

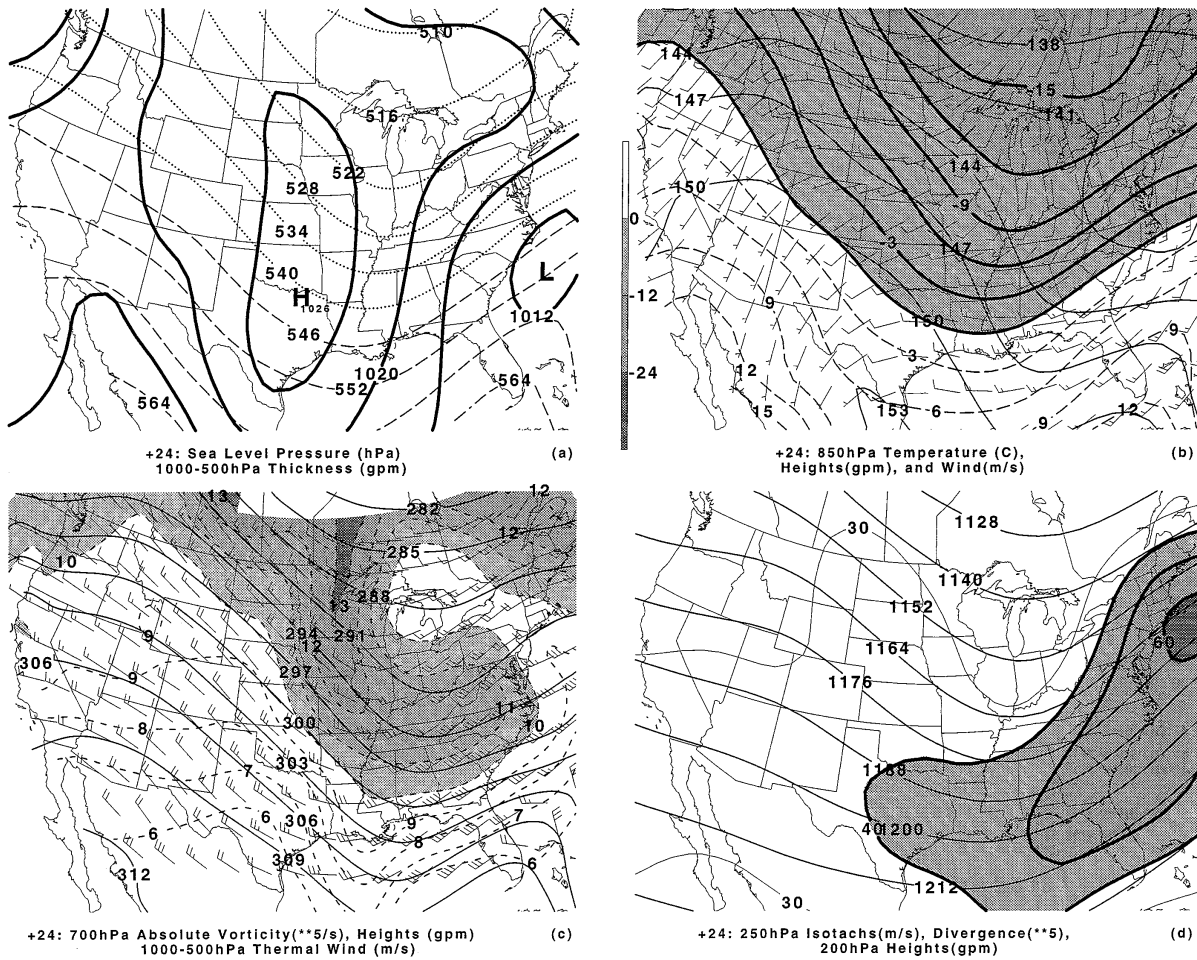


FIG. 10. Same as in Fig. 3 except for the +24-h composite.

upslope flow extending eastward into Georgia (Fig. 11a). West Texas begins to experience isentropic downglide and decreasing mixing ratios. Moisture continues to flow into Mississippi, Alabama, and Georgia, with 4 g kg^{-1} mixing ratios as far north as a line from Jackson, Mississippi, to Savannah, Georgia. The NEW to HAT cross section begins to show a wedge of relative humidities above 70% roughly bounded by the 290- and 298-K isentropes ascending over the Florida panhandle and into Georgia (Fig. 11b). Isentropic downglide on the 292-K isentropic surface is present throughout eastern Texas as well as portions of Arkansas and Louisiana by +12 h, while maximum isentropic upglide is located over eastern Georgia, the Carolinas, and southern Virginia (Fig. 12a). Mixing ratios as high as 6 g kg^{-1} in the composite time series are evident over southern Georgia. A large wedge of upslope flow and relative humidity in excess of 70% are shown across Georgia and the Carolinas in the +12-h composite (Fig. 12b). The period between +00 and +12 h, which corresponds to the period of heaviest snowfall in the Southeast, is also the period of greatest isentropic upglide. At +24

and +36 h, the region of maximum isentropic upglide has moved off the Atlantic coast, while downglide conditions move into Mississippi, Alabama, and Georgia.

A series of composite cross sections, taken from NEW to HAT, were examined for evidence of jet streak-induced circulation producing uplift in the vicinity of heavy snowfall. Only weak downward motion is indicated across the Southeast through -12 h (not shown). A region of ascent (negative ω) exceeding $2 \mu\text{b s}^{-1}$ from 850 to near 500 hPa develops with the region of isentropic upglide over the Gulf Coast and Georgia in the +00-h composite, with downward motion over the eastern Carolinas (Fig. 13a). The region of maximum ascent reaches $4 \mu\text{b s}^{-1}$ in the +12-h composite over western South Carolina (Fig. 13b). However, the ageostrophic circulation at +12 h indicates that isentropic upglide is not solely responsible for the upward motion.

The central and southern Appalachians are also located under a region of upper-level divergence clearly associated with the right entrance region of a jet streak located off the mid-Atlantic coast. Uccellini and Kocin (1987) demonstrated that the coupling of the transverse

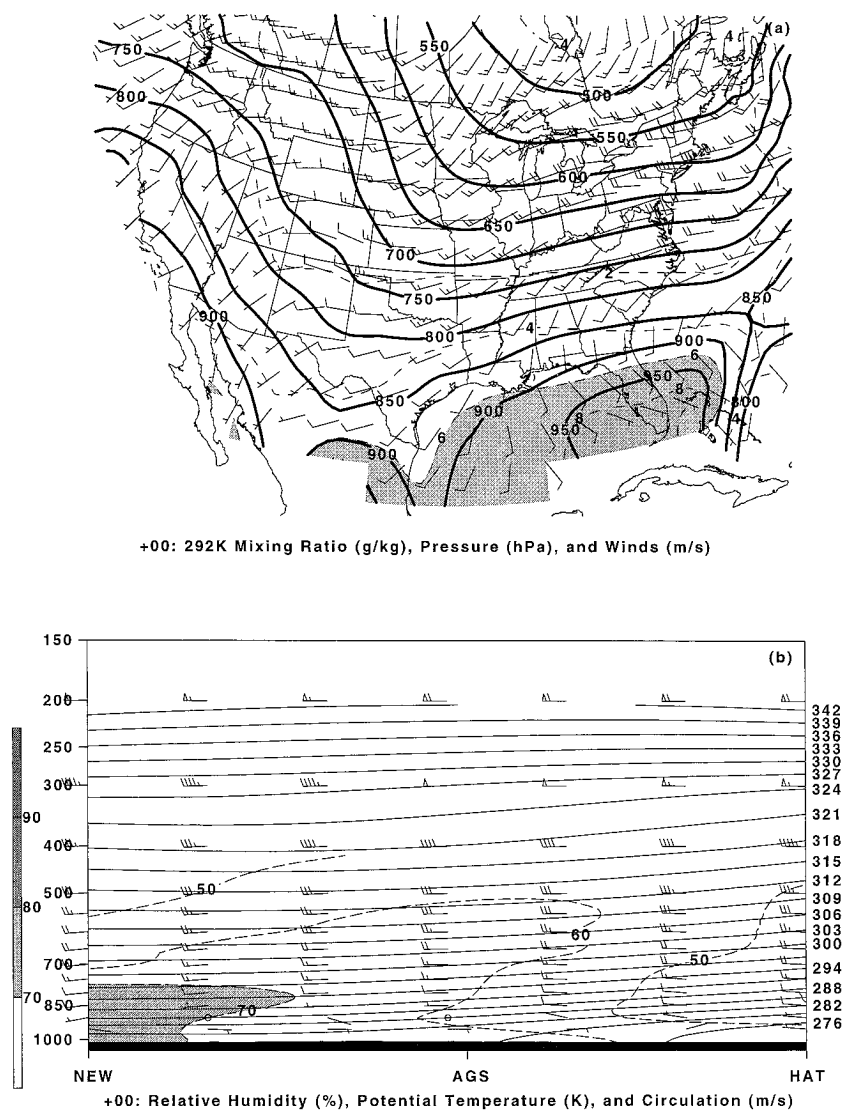


FIG. 11. A +00-h composite of (a) pressure (hPa), mixing ratio (g Kg^{-1}), and wind barsbs (m s^{-1}) on the 292-K isentropic surface, and (b) New Orleans, LA, to Cape Hatteras, NC, cross section of potential temperature (K), relative humidity, and circulation wind barsbs (m s^{-1}).

ageostrophic circulations from upper-level jet streaks over the Northeast and the Southeast result in an area of enhanced upward motion often associated with heavy snowfall. Shea and Przybylinski (1995) demonstrated the role of jet streak coupling in enhancing snowfall during a Midwest snowstorm, and Funk et al. (1995) did the same for a snowstorm over the Ohio Valley. In addition to the NEW to HAT cross sections, numerous cross sections were examined for ageostrophic circulation, including Indianapolis, Indiana, to Tallahassee, Florida, and Cleveland, Ohio, to Savannah, Georgia. It does not appear that the coupling of jet streaks is present in any of the composite cross sections. In some individual storms, there is an indication for jet streak coupling, but it does not appear to be common to most Southeast snowstorms. However, it does appear that en-

hanced upward motion is associated with the upper-level divergence associated with the right entrance region of a streak in the polar jet (Fig. 8d). Lapenta and Seaman (1990) found that "the ageostrophic accelerations induced in the upper-level jet streak (acting without the important support of the exit region circulation of a second jet streak) are capable of supporting mesoscale frontogenesis, heavy precipitation, and cyclogenesis along the east coast." Nevertheless, jet streak coupling may be significant in enhancing snowfall in some of the Southeast storms. Because of the spatial scale of the jet streaks, the temporal averaging of the wind fields may not allow us to define the location of the jet streak precisely enough to identify left and right entrance regions. Moreover, there is some evidence in the time-relative composites that weaker jet streaks upstream of

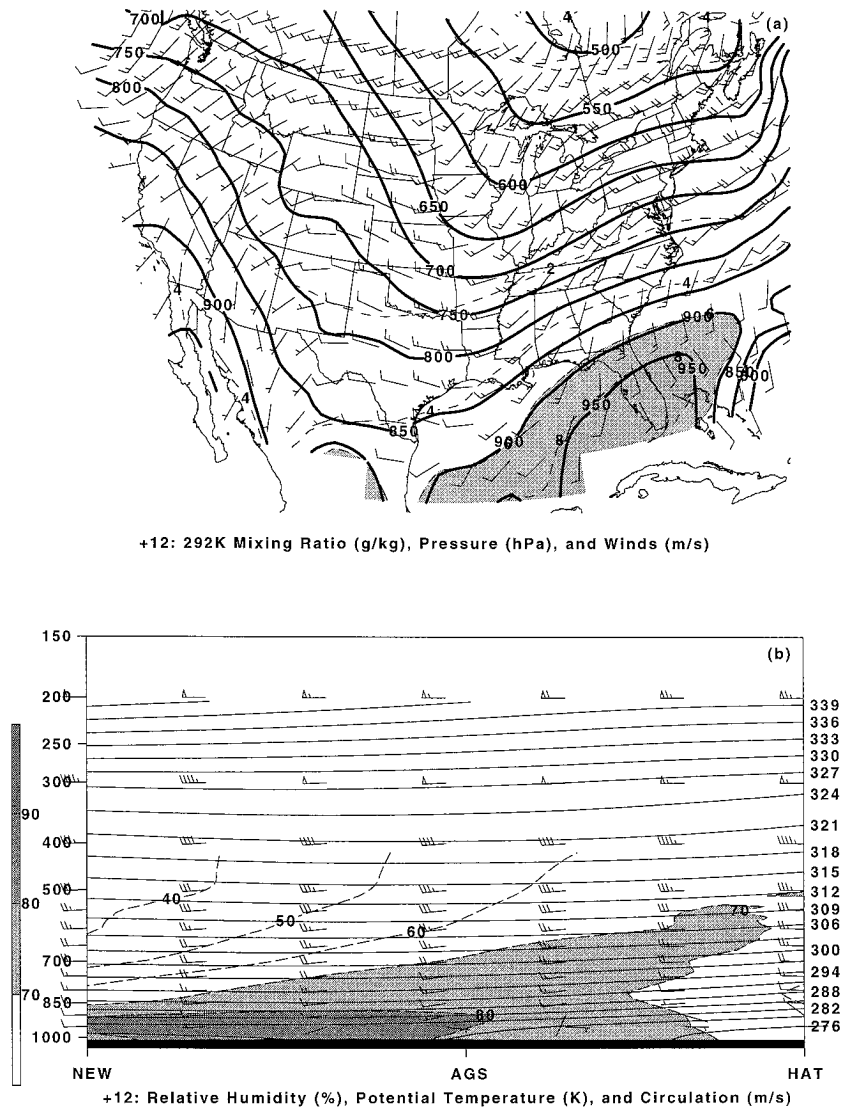


FIG. 12. Same as in Fig. 11 except for the +12-h composite.

the surface cyclone may be present, which could produce enhanced upward ageostrophic circulation under their left exit regions. An examination of the 250-hPa winds for individual storms shows that the upstream jet streak typically has much lower wind speeds than the jet streak across the East Coast. Further study of the effect of jet streaks on enhancing winter precipitation over the Southeast is necessary.

Low-level cyclogenesis, as indicated by positive vorticity advection by the geostrophic wind, appears to play a minor role in producing upward motion in these storms. In the +12-h composite, a maximum of positive absolute vorticity at 700 hPa near Memphis, Tennessee, and positive vorticity advection (PVA) is present over the central and southern Appalachians and the Piedmont region of the Carolinas and Virginia (Fig. 9c). In a number of the storms, the region of strongest PVA is located

to the west of the heaviest snowfall, while WAA appears to dominate the creation of upward motion. Homan and Uccellini (1987) cautioned against always viewing WAA as a separate physical process from upper-level forcing related to PVA and upper-level jet streaks. To a first approximation in a baroclinic environment, maximum ascent does not occur directly beneath the maximum of upper-level divergence, but follows sloped isentropic surfaces toward the region of maximum divergence (Homan and Uccellini 1987). The region of upper-level divergence attributable to the right entrance region of the upper-level jet streak is located north of the region of maximum ascent associated with the southerly LLJ. This is consistent with flow along sloped isentropic surface toward the divergence maximum (Uccellini and Johnson 1979). However, the PVA maximum is located to the west of the maximum ascent

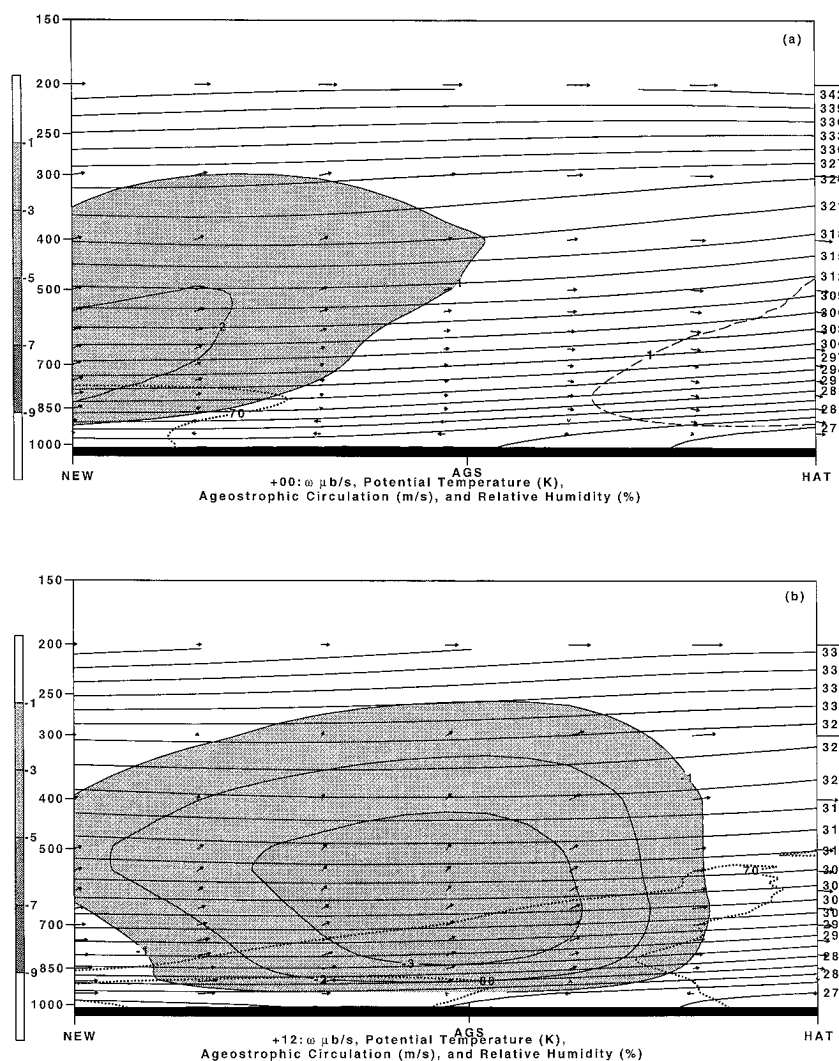


FIG. 13. New Orleans, LA, to Cape Hatteras, NC, cross sections of potential temperature (K), ω ($\mu\text{b s}^{-1}$), and ageostrophic circulation wind barbs (m s^{-1}) for (a) the +00-h composite and (b) the +12-h composite.

from the southerly LLJ. Thus, the PVA maximum is not situated so that it significantly contributes to the isentropic upglide. Thermal vorticity advection does well at diagnosing regions of maximum upward motion due to the inclusion of thermal advctions rather than solely geostrophic vorticity advection.

b. Moisture

The moisture that results in snowfall is carried along the LLJ that subsequently experiences adiabatic ascent. The moisture source for the LLJ is the Gulf of Mexico, where a plume of moisture rises from the surface to the 700–600-hPa level over the Carolinas. A cross section from Tri-Cities, Tennessee (TRI), to Wilmington, North Carolina (ILM), shows two clear moisture plumes: the upper plume is associated with moisture that originates from the Gulf, while the lower plume is from moisture

advected from the southeast off the Atlantic Ocean (Fig. 14). The low-level moisture from the Atlantic Ocean is advected by a southeasterly flow near 900 hPa but undergoes little uplift by the +12-h time period (Fig. 13b) and may be pooling against the eastern slopes of the Appalachians. The low-level southeasterly flow may be the initial stages of a cold conveyor belt that develops off the Atlantic in many coastal storms that affect the Northeast (Kocin and Uccellini 1990). Low-level Atlantic moisture and low- to midlevel Gulf moisture overrunning cold air dammed near the surface is often associated with winter weather over the Carolinas (Keeter et al. 1995). Lapenta and Seaman (1990) also found two moist airstreams during a case of East Coast cyclogenesis off the Carolina coast during 27–28 February 1982. That study is similar to our findings in that the authors found a moist, easterly flow over cold air dammed against the Appalachians. The studies differ in

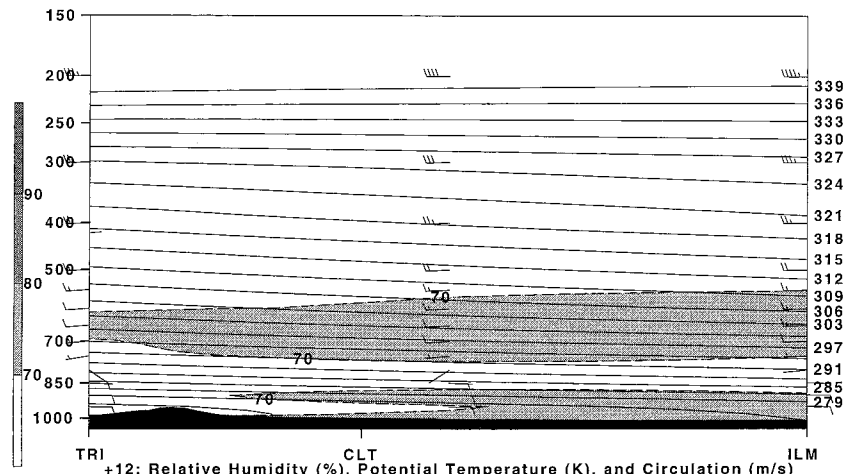


FIG. 14. A Tri-Cities, TN, to Wilmington, NC, cross section of potential temperature (K), relative humidity, and ageostrophic circulation wind barbs (m s^{-1}).

Lapenta and Seaman's (1990) finding that the second moisture plume also originated over the Atlantic rather than the Gulf of Mexico.

The low-level moisture originating from the Atlantic likely reduces evaporative cooling that is necessary to maintain conditions cold enough for snowfall. Temperatures in the central Carolinas in the +12-h composite are nearly isothermal and slightly above 0°C from the surface to nearly 700 hPa. Evaporative cooling is necessary to maintain temperatures low enough for snowfall. Keeter et al. (1995) showed that deep layers that are nearly isothermal and near 0°C can support snowfall in the Carolinas and Virginia. In some cases, temperatures in these storms are often below 0°C in the lowest 50–100 hPa, due to cold air damming along the Appalachians, and above 700 hPa due to adiabatic cooling during ascent. Temperatures may stay above 0°C between 900 and 800 hPa where high relative humidities with the southeasterly flow off the Atlantic limit evaporative cooling. A +12-h composite radiosonde sounding from Greensboro, North Carolina, shows a northerly ageostrophic surface wind, a southeasterly ageostrophic wind at 900–800 hPa, and a southerly ageostrophic wind at 800–600 hPa (not shown). The result often is a region of freezing rain or sleet in the Carolinas along the southern and eastern periphery of the heavy snowband (Forbes et al. 1987).

c. Cyclone tracks and cyclogenesis

Most of the snowstorms were associated with a developing cyclone in the Gulf of Mexico, typically along the leading edge of an arctic anticyclone centered over the southern Great Plains. Weak surface cyclones in some cases appeared to advance over the Gulf of Mexico and develop further. In other instances, the surface low appeared to redevelop over the Gulf of Mexico as fa-

vorable upper-level dynamics overran the lower-tropospheric baroclinic zone in the Gulf.

In order to determine the preferred cyclone tracks associated with these storms, storm tracks from the National Climatic Data Center's Global Tropical Extratropical Cyclone Atlas CD-ROM, Version I, were examined (NCDC and U.S. Navy 1994). Extratropical cyclone tracks from the National Oceanic and Atmospheric Administration are not available for storms prior to 1966, so only 12 of the storms included in this study were examined. The preferred cyclone track follows the Gulf Coast, crosses over northern Florida or southern Georgia into the Atlantic Ocean, and follows the East Coast (Fig. 15). The preferred location for the cyclone at +00 h is along the central Gulf Coast, from 85° to 95°W and 25° to 32°N . The mean central pressure of the seven storms that had an identified surface low at +00 h was 1003 hPa. The cyclone atlas did not indicate an identifiable cyclone center at +00 h for the remaining storms. In storms in which most of the snowfall occurred in Virginia and North Carolina, such as the 2–4 March and 9–11 March 1960 storms, analysis of the National Meteorological Center (recently renamed the National Centers for Environmental Prediction) sea level pressure fields shows that the surface cyclone moved into the Gulf Coast states before advancing over the Atlantic Ocean. More commonly, the cyclone advanced across northern Florida or southern Georgia at +12 h and further deepened off the coast of Georgia and the Carolinas at +24 and +36 h. The mean central pressure of the storms fell to 1000 hPa at +12 h and 999 hPa at +24 h but dropped substantially to 992 hPa at +36 h and 985 hPa at +48 h. This rapid deepening of extratropical cyclones off the Carolina coast in the vicinity of the Gulf Stream is a result of the tight thermal gradient that forms between the cold air dammed east of the Appalachians and the relatively warm air over the Gulf

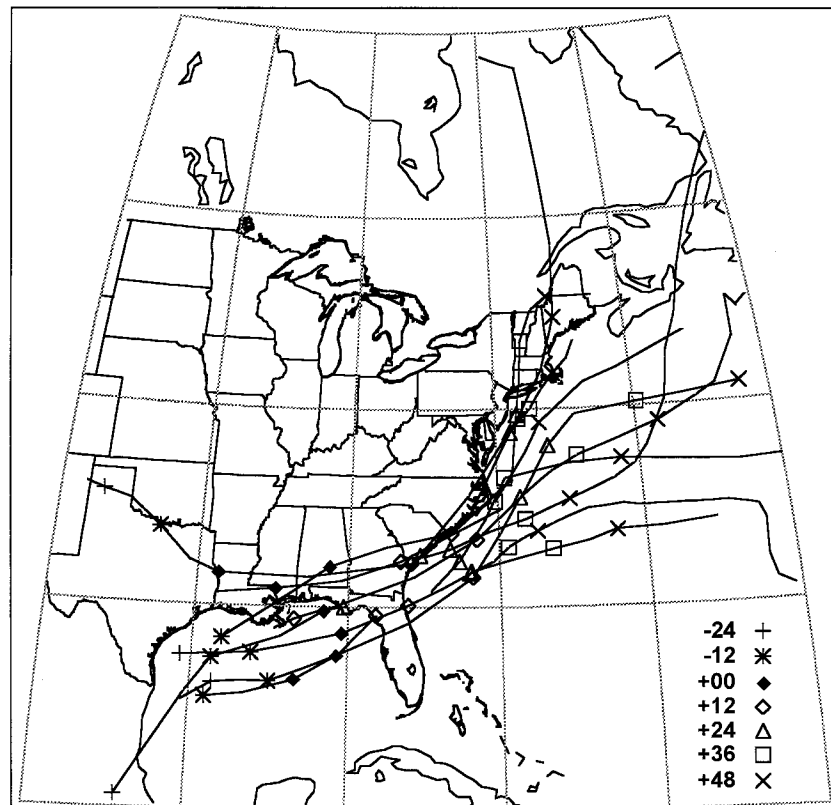


FIG. 15. Cyclone tracks for 11 snowstorms from 1968 to 1988. Symbols indicate the location during given hours in the compositing period.

Stream (Sanders and Gaykum 1980; Cione et al. 1993). In two cases in which significant snowfall occurred as far southeast as northern Georgia, 29–30 January 1966 and 22–23 January 1987, the surface cyclone developed near 25°N. After producing snowfall over the southeastern United States, most of the cyclones either continue along the eastern seaboard, producing snowfall over the Northeast, or move rapidly eastward off the North Carolina coastline.

5. Conclusions

Through an examination of time-relative composites from a series of heavy snowstorms to strike the Southeast, we have identified the common synoptic-scale features associated with these storms. Most of these storms are clearly associated with instances of cyclogenesis in the Gulf of Mexico, usually just preceding the onset of heavy snow. The location of the cyclogenesis is usually just over or just south of the Louisiana coastline between 20° and 30°N latitude. The cyclogenesis is triggered by the outbreak of an arctic air mass that moves south from the prairie provinces of Canada and settles over the southern plains. The offshore flow from the cold air mass meets a warmer gulf air mass, developing a baroclinic zone necessary for cyclogenesis. Accompanying the arctic air mass is an amplifying upper-level short-

wave trough in a southern upper-level jet stream. In many instances, the shortwave produces a weak surface cyclone over northern Mexico or west Texas 12–36 h before cyclogenesis over the gulf. An LLJ that forms in advance of the developing cyclone produces adiabatic ascent over the Gulf Coast region. The adiabatic ascent takes place over a cold, dry air mass in the Northeast. The cold air is often forced southwest along the eastern slopes of the Appalachians. With a sufficiently cold arctic outbreak, snowfall begins in the Mississippi Valley, although it is usually preceded by rain, freezing rain, and/or sleet. The developing surface cyclone and associated upper-level dynamics advance across northern Florida, and the surface cyclone rapidly deepens in the baroclinic zone along the Gulf Stream, off the Georgia and Carolina coasts. Although Atlantic moisture is fed into the low levels of the storm, over the Piedmont region of the Carolinas and Virginia, the low-level moisture may inhibit snowfall. Evaporative cooling is necessary to keep temperatures below 0°C, and the low-level Atlantic moisture may reduce the rate of evaporative cooling from falling precipitation.

The 12–14 March 1993 snowstorm, the so-called storm of the century, was not included in this study because of the unique nature of this storm. We believe the unusually strong surface and upper-level features associated with the March 1993 storm would have dom-

inated the composite analysis. Nevertheless, it is interesting to compare the March 1993 storm with the storms examined in this study. Had the March 1993 storm been included, the 0000 UTC 13 March 1993 observation would be identified as the +00 h for the storm. The location of the rapidly deepening surface low at that time was over the Gulf of Mexico, south of the Louisiana coastline. The location of the surface low is similar to that of other storms, but the March 1993 cyclone was much deeper. Kocin et al. (1995) reported a central sea level pressure of 984 hPa at that time, while other storms in the same location typically reported central pressures in the range of 1000–1005 hPa. As with the storms examined here, the March 1993 storm formed in advance of an amplifying upper-level trough advancing across the Southwest, toward the Gulf of Mexico, with an arctic air mass sinking southward across the plains. The March 1993 storm was enhanced by the coupling of two upper-level jet streaks, one in advance and one trailing the surface cyclone (Kocin et al. 1995). Although jet streak coupling has been found as a common feature in heavy East Coast snowstorms (Uccellini and Kocin 1987), it is apparently uncommon in Southeast snowstorms. In the case of the March 1993 storm, the jet streak coupling combined with strong isentropic upglide produced record snowfalls across the Southeast.

Continued synoptic climatological studies, such as the one presented here, need to be combined with numerical studies to better understand the evolution of winter storms in the Southeast. The sparse network of radiosonde stations is not sufficient to capture significant mesoscale features within these storms, but the improved resolution of numerical models should provide an improved understanding of mechanisms forcing vertical motion and moisture flows into these storms.

Acknowledgments. The authors wish to thank Brian Bossak for his assistance in data processing and Dan Leathers for his comments on early versions of the manuscript. The authors also thank Paul Kocin and Kermit Keeter for their helpful reviews.

REFERENCES

- Barnes, S. L., 1973: Mesoscale objective analysis using weighted time-series observations. NOAA Tech. Memo. ERL NSSL-62, 60 pp. [Available from National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069.]
- Beckman, S. K., 1987: Use of enhanced IR/visible satellite imagery to determine heavy snowfall areas. *Mon. Wea. Rev.*, **115**, 2060–2087.
- Bell, G. D., and L. F. Bosart, 1988: Appalachian cold-air damming. *Mon. Wea. Rev.*, **116**, 137–161.
- Brandes, E. A., and J. Spar, 1971: A search for necessary conditions for heavy snow on the East Coast. *J. Appl. Meteor.*, **10**, 397–409.
- Browne, R. F., and R. J. Younkin, 1970: Some relationships between 850-millibar lows and heavy snow occurrences over the central and eastern United States. *Mon. Wea. Rev.*, **98**, 399–401.
- Carlson, T. N., 1991: *Mid-Latitude Weather Systems*. Routledge, 507 pp.
- Cione, J. J., S. Raman, and L. J. Pietrafesa, 1993: The effect of Gulf Stream-induced baroclinicity on U.S. east coast winter cyclones. *Mon. Wea. Rev.*, **121**, 421–430.
- Cook, B. J., 1980: Snow index using 200 mb warm advection. *Natl. Wea. Digest*, **5**, 29–40.
- desJardins, M. L., K. F. Brill, S. Jacobs, S. S. Schotz, and P. Bruehl, 1994: GEMPAK5 User's Manual. Version 5.2. Unidata Program Center, Boulder, CO, 277 pp. [Available from Unidata: UCAR, P.O. Box 3000, Boulder, CO 80307.]
- Djuric, D., and D. S. Ladwig, 1983: Southerly low-level jet in the winter cyclones of the southwestern Great Plains. *Mon. Wea. Rev.*, **111**, 2275–2281.
- EarthInfo, Inc., 1993: NCDC summary of the day central 1993 and east 1993. CD-ROMs.
- Fawcett, E. B., and H. K. Saylor, 1965: A study of the distribution of weather accompanying Colorado cyclogenesis. *Mon. Wea. Rev.*, **93**, 359–368.
- Forbes, G. S., R. A. Anthes, and D. W. Thompson, 1987: Synoptic and mesoscale aspects of an Appalachian ice storm associated with cold-air damming. *Mon. Wea. Rev.*, **115**, 564–591.
- Funk, T. W., C. W. Hayes, M. B. Scholz, and K. A. Kostura, 1995: Vertical motion forcing mechanisms responsible for the production of a mesoscale very heavy snow band. Preprints, *14th Conf. on Weather Analysis and Forecasting*, Dallas, TX, Amer. Meteor. Soc., 176–181.
- Goree, P. A., and R. J. Younkin, 1966: Synoptic climatology of heavy snowfall over the eastern and central United States. *Mon. Wea. Rev.*, **94**, 663–668.
- Gurka, J. J., E. P. Auciello, A. F. Gigi, J. S. Waldstreicher, K. K. Keeter, S. Businger, and L. G. Lee, 1995: Winter weather forecasting throughout the eastern United States. Part II: An operational perspective of cyclogenesis. *Wea. Forecasting*, **10**, 21–41.
- Homan, J., and L. W. Uccellini, 1987: Winter forecast problems associated with light to moderate snow events in the mid-Atlantic states on 14 and 22 February 1986. *Wea. Forecasting*, **2**, 206–228.
- Keeter, K. K., and J. W. Cline, 1991: The objective use of observed and forecast thickness values to predict precipitation type in North Carolina. *Wea. Forecasting*, **6**, 456–469.
- , S. Businger, L. G. Lee, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part III: The effects of topography and the variability of winter weather in the Carolinas and Virginia. *Wea. Forecasting*, **10**, 42–60.
- Koch, S. E., M. desJardins, and P. J. Kocin, 1983: An interactive Barnes objective map analysis scheme for use with satellite and conventional data. *J. Climate Appl. Meteor.*, **22**, 1487–1503.
- Kocin, P. J., and L. W. Uccellini, 1990: *Snowstorms along the Northeastern Coast of the United States: 1955 to 1985*. Amer. Meteor. Soc., 280 pp.
- , P. N. Schumacher, R. F. Morales Jr., and L. W. Uccellini, 1995: Overview of the 12–14 March 1993 superstorm. *Bull. Amer. Meteor. Soc.*, **76**, 165–182.
- Lapenta, W. M., and N. L. Seaman, 1990: A numerical investigation of East Coast cyclogenesis during the cold-air damming event of 27–28 February 1982. Part I: Dynamic and thermodynamic structure. *Mon. Wea. Rev.*, **118**, 2668–2695.
- Maglaras, G. J., J. S. Waldstreicher, P. J. Kocin, A. F. Gigi, and R. A. Marine, 1995: Winter weather forecasting throughout the eastern United States. Part I: An overview. *Wea. Forecasting*, **10**, 5–20.
- NCAR and University of Washington, 1990: National Meteorological Center Grid Point Data Set. Version II. CD-ROM.
- NCDC, 1994: Radiosonde data of North America 1946–1993. Version 1.0 (updated). CD-ROMs.
- , and NREL, 1993: Solar and Meteorological Surface Observation Network 1961–1990. Version 1.0. CD-ROM.
- , and U.S. Navy, 1994: Global tropical extratropical cyclone climatic atlas. Version 1.0.

- Richwein, B. A., 1980: The damming effect of the southern Appalachians. *Natl. Wea. Dig.*, **5**, 2–12.
- Sanders, F., and J. R. Gaykum, 1980: Synoptic-dynamic climatology of the “bomb.” *Mon. Wea. Rev.*, **108**, 1589–1606.
- Shea, T. J., and R. W. Przybylinski, 1995: Forecasting the northern extent of significant snowfall in a major winter storm: An operational forecasting problem. Preprints, *14th Conf. on Weather Analysis and Forecasting*, Dallas, TX, Amer. Meteor. Soc., 280–285.
- Suckling, P. W., 1991: Spatial and temporal climatology of snowstorms in the Deep South. *Phys. Geog.*, **12**, 124–139.
- Uccellini, L. W., and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective storms. *Mon. Wea. Rev.*, **107**, 682–708.
- , and P. J. Kocin, 1987: Interaction of jet streak circulation during heavy snow events along the east coast of the United States. *Wea. Forecasting*, **2**, 289–308.
- Younkin, R. J., 1968: Circulation patterns associated with heavy snowfall over the western United States. *Mon. Wea. Rev.*, **96**, 851–853.