The Interaction of Jet Streak Circulations during Heavy Snow Events along the East Coast of the United States

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ABSTRACT

The interaction of transverse vertical circulations associated with two separate jet streak/trough systems is found to be a common feature of cyclogenetic events which produce heavy snow along the East Coast of the United States. The transverse circulations are identified for eight cases that span the period from 1960 to 1987 utilizing an isentropic analysis of the operational radiosonde data. The analyses depict the interaction of 1) a direct circulation located within the confluent entrance region of an upper-level jet streak over the northeastern United States or southeastern Canada with 2) an indirect circulation in the diffluent exit region of a jet streak associated with a trough nearing the East Coast. This interaction contributes to differential moisture and temperature advections and vertical motions necessary to produce heavy snowfall along the coast. It is suggested that the circulation patterns associated with the jet streaks establish an environment within which boundary layer processes (e.g., cold-air damming, coastal frontogenesis the development of a low-level jet streak) can further contribute to cyclogenesis and the development of severe winter weather conditions.

1. Introduction

Severe snowstorms are perhaps the greatest weather concern for the residents of the major urban centers along the East Coast of the United States. These storms, typically accompanied by high winds and cold temperatures, may maroon millions at home or in transit, severely disrupt vital services and commerce, and endanger the lives of those who venture outdoors.

These severe East Coast snowstorms are often associated with rapidly intensifying cyclones and cold anticyclones of Canadian or polar origin. In addition, such storms are marked either by 1) a primary surface low-pressure center that propagates northeastward along the Gulf and Atlantic coasts or 2) a primary low that tracks toward the Appalachian Mountains and subsequently weakens as a secondary surface low develops along the southeast or Middle Atlantic coast, as shown in numerous cases by Miller (1946) and more recently by Kocin and Uccellini (1985a,b). The cyclones interact with a strong surface anticyclone poised to the north of New York and New England, in which the anticyclone provides a source of cold air near the earth's surface. An associated narrow surface high-pressure ridge usually extends southward along the East Coast between the coastline and the mountains prior to cyclogenesis. The pressure ridge which is indicative of the cold air that is trapped or "dammed" at low levels increases the potential for frozen, rather than liquid, precipitation (Richwien, 1980; Forbes et al, 1987; Stauffer and Warner, 1987). Frontogenesis along the boundary between the cold air dammed along the coastal plain and warmer air over the ocean is also a common feature that appears to provide for an enhanced low-level baroclinic zone which favors the development of coastal cyclones (Bosart et aL, 1972; Bosart, 1975; Ballantine, 1980).

In a study of 18 intense snowstorms along the East Coast, Kocin and Uccellini (19854,) show that there are similarities in the patterns of surface weather features, upper-level winds, and geopotential heights exhibited by many of the snowstorms. In general, heavy snowfall occurs to the north and northwest of the coastal surface low, downwind of an upper-level trough nearing the East Coast characterized by the lateral divergence of the height contours (or diffluence), and within the exit region of an upper-level jet streak (see schematic in Fig. I). The surface anticyclone or associated ridge line to the north of the developing storm system is typically located beneath converging height contours (confluence) within the entrance region of a separate jet streak located upwind of a trough axis over southeastern Canada. Heavy snowfall is found between the exit and entrance regions of the two separate jet streaks, which is similar to the results of a separate study that examined the orientation of light to moderate snow events in the Midwest with respect to the locations of upper-level jet streaks (Uccellini, 1976).

The persistent patterns of heavy snowfall, jet streaks, and other surface and upper-level features depicted in Fig. 1 suggest that vertical transverse circulations which are associated with the upper-level jet streaks and span the depth of the troposphere may be a link between the configuration of surface and upper-level features and the development of heavy snow. The purpose of this paper is to present supporting evidence for this supposition utilizing analyses of several of the 18 cases described by Kocin and Uccellini (1985a,b), and for several more recent cases

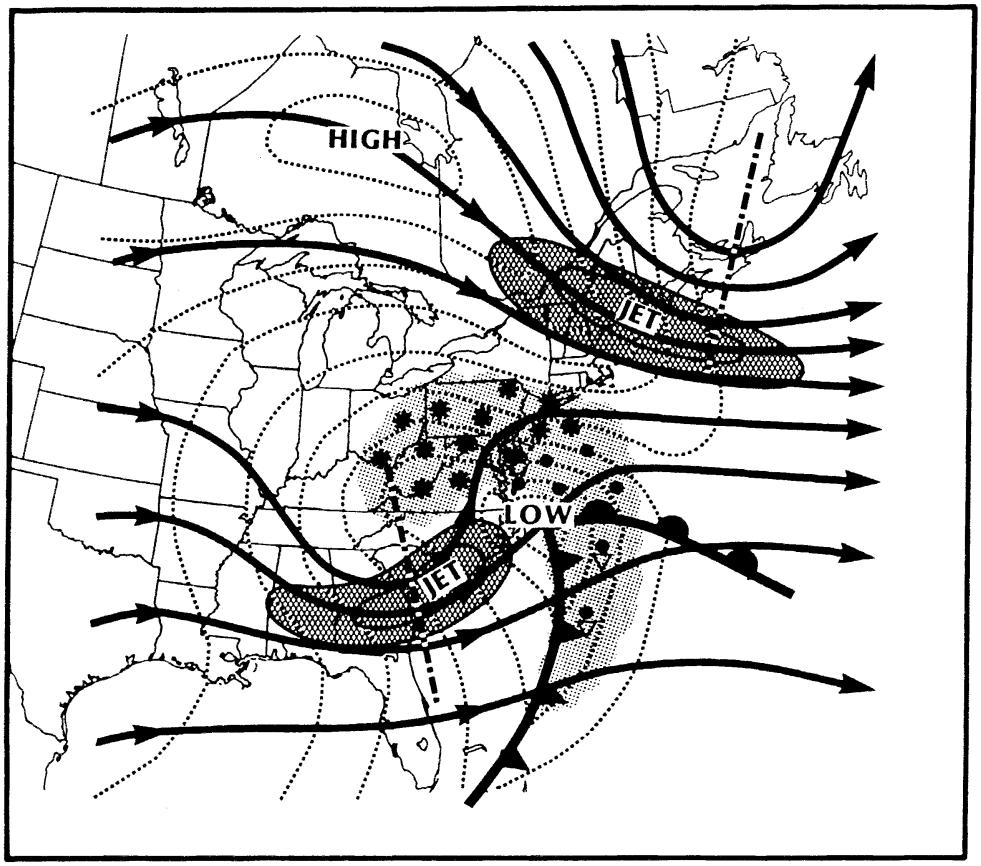


FIG. 1. Schematic of surface cold and warm fronts, high and low pressure centers, sea level isobars (dotted), precipitation (shading—asterisks represent snowfall; dots represent rain), upper-level flow (arrows), upper-level trough axes (dot-dashed), and jet streaks (cross-hatched shading) associated with a "typical" heavy snow event along the East Coast.

from the 1986/87 winter season. A brief review of the patterns of divergence, ageostrophic flow, and descriptions of vertical circulations associated with upper-level troughs and jet streaks is presented in section 2. Brief synoptic analyses and two-dimensional descriptions of vertical circulations are then described in section 3 for eight snowstorms, to provide evidence that the interaction of jet streak circulation patterns characterizes many heavy snow events along the East Coast. In addition, the ease and difficulties of isolating these patterns with the 12-h operational database are also illustrated. The results of the study are summarized in section 4.

2. Ageostrophic wind, divergence, and circulation patterns associated with trough-ridge systems and jet streaks

A net reduction in mass is required for surface cyclones to develop, whereby upper-tropospheric mass divergence exceeds low-level convergence. Bjerknes and Holmboe (1944), and more recently Newton and Trevisan (1984), relate the structure of troughs and ridges within upper-level waves and associated "longitudinal" (or alongstream) ageostrophic wind components to a pattern of upper-level divergence (convergence) downwind (upwind) of a trough axis that is conducive to surface cyclogenesis (anticyclogenesis), as illustrated in Fig. 2. Bjerknes and Holmboe also emphasize that decreasing wavelength, increasing wind with height, and diffluence (confluence) in the streamlines all act to enhance the divergence (convergence) aloft. Given the problem of diagnosing the divergence with the early radiosonde network, these processes have been inferred through the use of the vorticity and thermodynamic equations, forming the basis of the Sutcliffe (1947) and Petterssen (1956) development equations and the quasi-geostrophic geopotential tendency and omega equations (described by Holton, 1979, Chapter 7). Within these frameworks, the divergence in the upper levels is approximated by the vorticity advection fields, with cyclonic or positive (anticyclonic or negative) vorticity advections associated with divergence (convergence) (see also Palmen and Newton, 1969, pp. 318-319).

In addition to the contribution of the longitudinal or alongstream ageostrophic components to divergence within

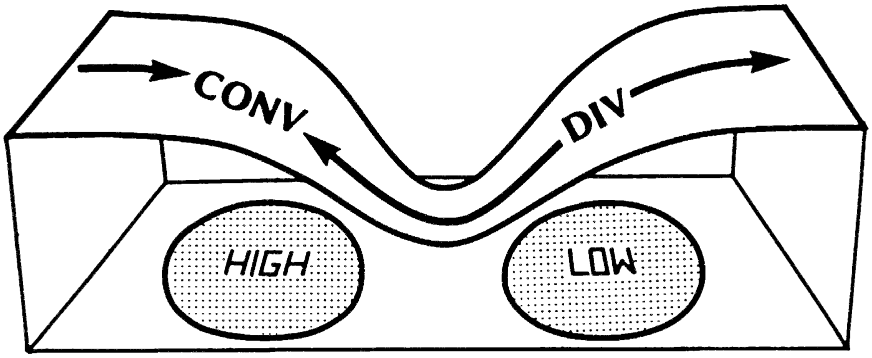


FIG. 2. Schematic relating the alongstream ageostrophic wind (arrows) to patterns of divergence associated with an upper-level trough/ridge system and surface high and low-pressure couplet (after Bjerknes and Holmboe, 1944).

trough-ridge patterns, Bjerknes (1951) discusses the likely contribution of "transverse" or cross-stream ageostrophic components in the entrance and exit regions of jet streaks to surface cyclones and anticyclones. As defined by Namias and Clapp (1949), Bjerknes (1951). Murray and Daniels (1953), Uccellini and Johnson (1979), and others, the entrance region of an idealized jet streak is marked by a transverse ageostrophic component directed toward the cyclonic-shear side of the jet (Fig. 3a). This component represents the upper branch of a direct transverse circulation that converts available potential energy into kinetic energy for parcels accelerating into the jet. The direct circulation is marked by rising (sinking) motion on the anticyclonic or warm (cyclonic or cold) side of the jet (Fig. 3b), a pattern which is consistent with vorticity advection concepts described by Riehl et aL (1952) and illustrated in Fig. 3c. Conversely, in the exit region, the ageostrophic components in the upper troposphere are directed toward the anticyclonic-shear side of the jet (Fig. 3a), representing the upper branch of an indirect transverse circulation pattern (Fig. 3b) that converts kinetic energy to available potential energy as parcels decelerate upon exiting the jet. Associated with this circulation pattern is rising (sinking) motion on the cyclonic or cold (anticyclonic or warm) side of the jet, which again is in agreement with the vorticity advection patterns (Fig. 3c).

The possible influence of curvature effects in masking the contribution of jet streaks to upper-level ageostrophy, divergence, and associated vertical motion fields is discussed by Beebe and Bates (1955), Shapiro and Kennedy (1981), Newton and Trevisan (1984), Uccellini et al. (1984), Keyser and Shapiro (1986), and Kocin et al. (1986). These more recent studies indicate that although the transverse circulations are normally depicted on a two-dimensional vertical plane, the existence of indirect and direct circulations is a consequence of three-dimensional variations in the ageostrophic winds and upper-level divergence that cannot be fully described in terms of simple two-dimensional, straight-line jet streak dynamics There is also increasing evidence from numerical model studies (e.g., Cahir, 1971; Uccellini et aL, 1987) that diabatic processes (especially associated with the release of latent heat) can significantly increase the vertical motions associated with jet streak-induced transverse circulations. This type of feedback between dynamical and diabatic processes could add to the difficulties involved in isolating the relative contribution of upper-level jets to the vertical motion field at any given time.

Despite the complications of curvature and diabatic processes, there remains a need to demonstrate that these circulation patterns exist and can be identified for a large number of cases. The idealized model of upper-level mass divergence (i.e., Figs. 3a and b) associated with a relatively straight upper-level jet has been identified in a case study and numerical model experiment (Uccellini and Johnson, 1979; Brill et aL, 1985). Furthermore, there is growing recognition that jet streak-induced circulations play a role in cyclogenesis For example, in climatological studies of cyclones in the lee of the Rocky Mountains, Hovanec and Horn (1975) and Achtor and Horn (1986) show that most of the cyclones from a 60-day sample form in the left-front exit region of jet streaks propagating across the western United States (Fig. 4a). They also show that development of these storms occurs within an area marked by diverging longitudinal ageostrophic wind fields downstream of a trough axis (Fig. 4b) and diverging transverse ageostrophic components within the exit region of the upper-level jet streak (Fig. 4c). Mattocks and Bleck (1986) emphasize the role of the indirect circulation pattern in the exit region of upper-level jet streaks in the development of cyclones in the lee of the Alps and the Gulf of Genoa. Finally, in an analysis of several cyclones in the northern Pacific, Sinclair and Elsberry (1986) conclude that the entrance and exit regions of jet streaks are important for providing the environment in which these particular storms can grow rapidly.

While much of the literature has focused on the roles of the exit region of jet streaks in the development of

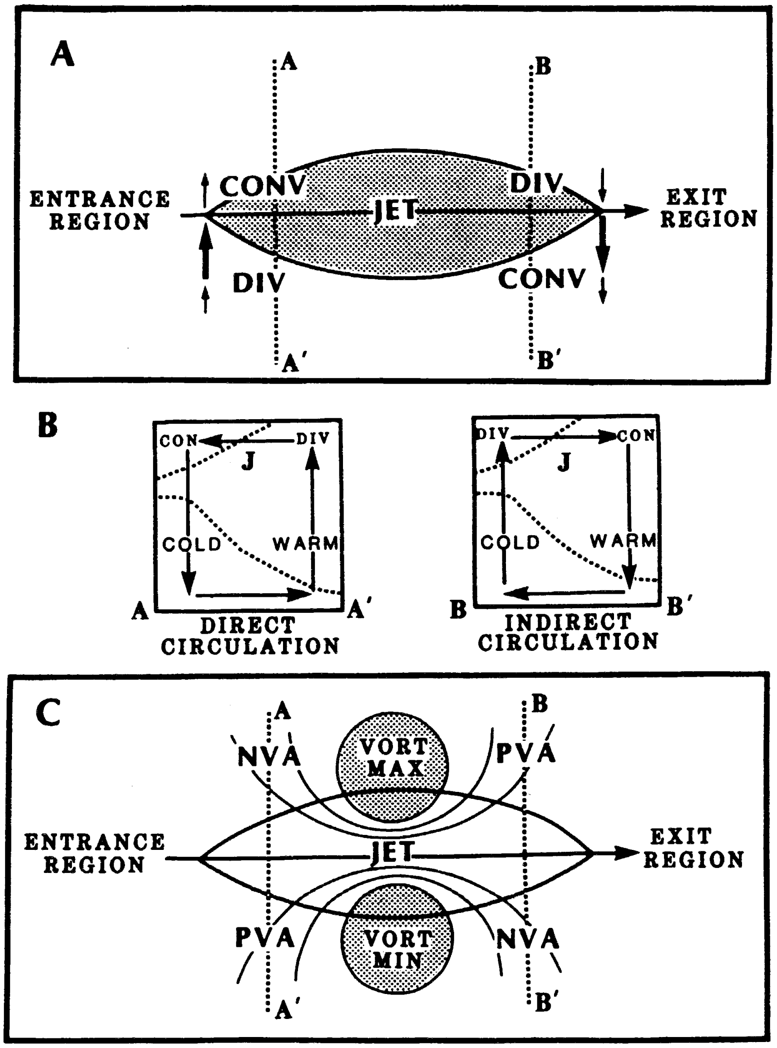
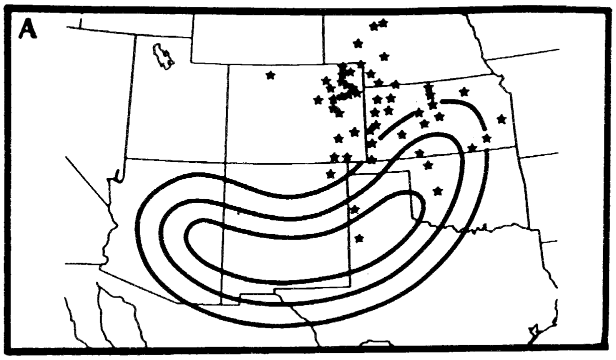


FIG. 3. (a) Schematic of transverse ageostrophic wind components and patterns of divergence associated with the entrance and exit regions of a straight jet streak [after Bjerknes (1951)]. (b) Vertical cross section illustrating direct and indirect circulations in the entrance region [along dotted line labeled A-A′ in (a)] and exit region [along dotted line labeled B-B′ in (a)] of a jet streak. Cross sections include two representative isentropes (dotted), upper-level jet location (marked by a J), relative positions of cold and warm air, upper-level divergence, horizontal ageostrophic components, and vertical motions (arrows) within the plane of each cross section. (c) Schematic of maximum (cyclonic) and minimum (anticyclonic) relative vorticity centers and associated advection patterns associated with a straight jet streak. (NVA represents negative or anticyclonic vorticity advection; PVA represents positive or cyclonic vorticity advection.

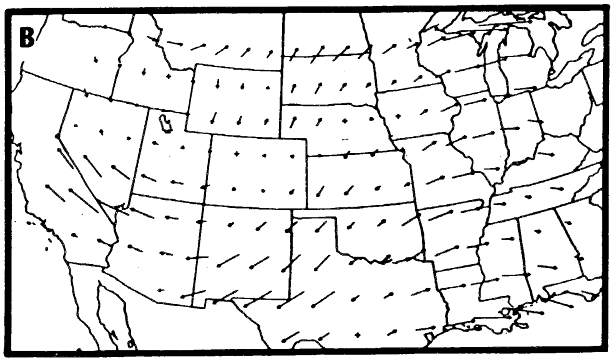
cyclones, relatively little attention has been paid to the relationship of the entrance region to surface anticyclogenesis, except for Reiter (1963). In section 3, the roles of both jet streak exit and entrance regions and their associated indirect and direct circulations, respectively, are examined and related to outbreaks of very heavy snowfall along the East Coast of the United States.

3. Examples of transverse circulations in East Coast snowstorms

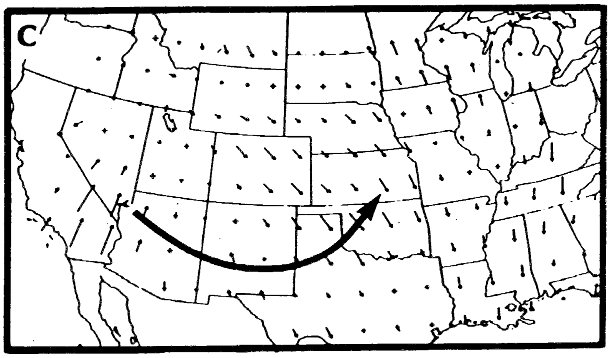
In this section, analyses of heavy snow events along the East Coast of the United States are presented to show 1) that distinct two-cell transverse circulations associated with upper-level jet streaks can be identified utilizing the operational radiosonde network, 2) that these circulations



after Havanec and Horn (1975)



from Achtor and Horn (1986)



from Achtor and Horn (1986)

FIG. 4. (a) Mean 300-mb isotach field superimposed on sites of cyclogenesis for cases of cyclogenesis during the spring season in Colorado [after Havanec and Horn (1975)]. (b) Longitudinal ageostrophic component and (c) transverse ageostrophic component derived for a subsample of the spring season Colorado cyclones [from Achtor and Horn (1986)].

appear to be a common characteristic of many heavy snow events, and 3) the means by which jet streak circulation patterns appear to contribute to establishing conditions conducive to heavy snowfall.

The analyses are performed on several cases included in a review of major snow events by Kocin and Uccellini (1985a,b) and on more recent cases from the winter of 1986/87. Examples of jet streak circulation patterns at 1200 UTC 11 February 1983, 0000 UTC 12 December 1960, 0000 UTC 4 February 1961, 1200 UTC 7 February 1967, 0000 UTC 26 January 1987, and 0000 UTC 23 February 1987 are shown to document a correspondence between the locations of heavy snowfall, surface cyclones, and anticyclones within the exit and entrance regions of upper-level jet streaks, as Illustrated in the schematic in Fig. 1. Vertical cross sections of tangential ageostrophic wind components, vertical motion, and potential temperature demonstrate a link between these surface and upper-level features and the transverse vertical circulations. In particular, the so-called “megalopolitan” snowstorm of February 1983 (Sanders and Bosart, 1985a,b; Bosart and Sanders, 1986) is used to provide an in-depth description of the links between the surface, upper-level features, and vertical circulations with a discussion as to how such patterns are conducive for heavy snow. The other cases are briefly described and used to note that the circulation patterns can be identified for a variety of cases, although case-by-case differences do exist, as will also be discussed. Analyses from the widely studied “Presidents’ Day” storm of February 1979 are shown to present evidence that the dual circulation pattern may arise in scenarios more complicated than the situation just described. Finally, an example where the dual circulation pattern is not fully developed is presented to indicate that either exceptions to the general scenario exist or that the use of the operational radiosonde network to diagnose circulation patterns on a routine basis may be limited.

All the analyses in this section are based on the Petersen (1986) isentropic objective analysis scheme which is used to produce gridded temperature and wind fields on a 2° X 2° grid. The vertical motion fields are derived by vertically integrating the continuity equation in pressure coordinates and applying the O’Brien (1970) correction method. All cross-section analyses are derived by interpolating the parameters from the 2° X 2° grid to the cross section using cubic splines.

a. 11 February 1983

The “megalopolitan” storm of February 1983 produced some of the greatest single storm snowfall amounts ever recorded for the large urban centers that span the coastal region of the Middle Atlantic states and southern New England, with Washington, D.C., Baltimore, Maryland, Philadelphia, Pennsylvania, and New York, New York, receiving accumulations in excess of 50 cm. At 1200 UTC 11 February 1983, the snowstorm was in progress across Virginia, West Virginia, and Maryland with rain located over the southeastern United States. The 300 mb analysis at 1200 UTC 11 February 1983 (Fig. 5) shows that the axis of an upper-level trough extends from the Ohio Valley to the southeastern United States coast with an upper-level jet streak centered near the base of the trough

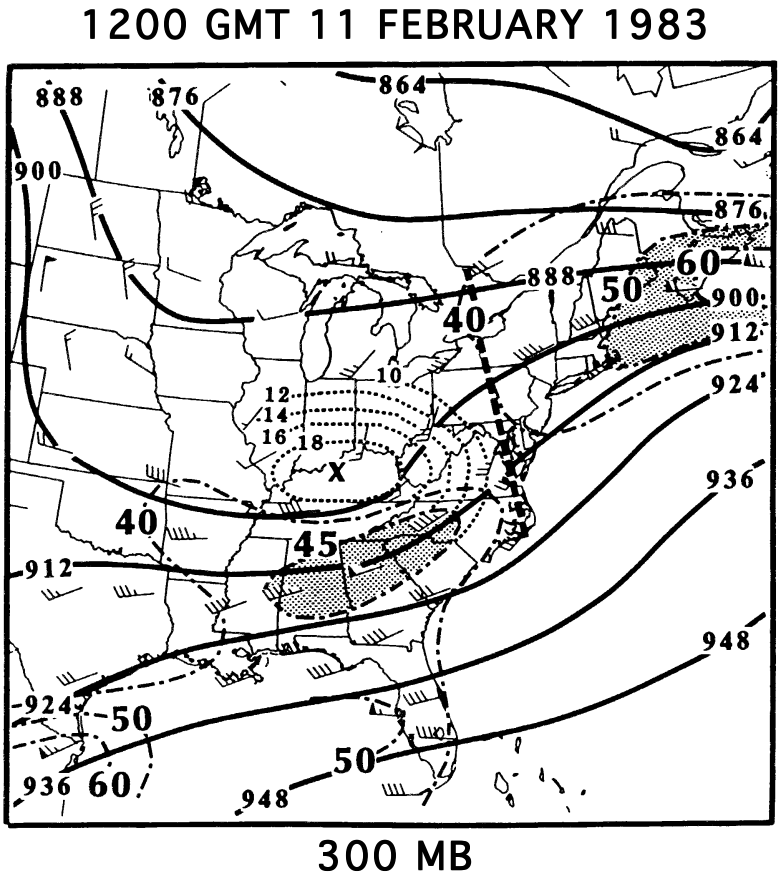


Fig. 5. The 300-mb geopotential height analysis (solid; 888 = 8880 m), isotachs (dot-dashed; 40 = 40 m s^{-1}), and selected isopleths of absolute vorticity (dotted; 18 = 18 x 10^{-5} s^{-1}) with vorticity maximum indicated by "X" at 1200 UTC 11 February 1983. Each flag denotes 25 m s^{-1}; each full barb denotes 5 m s^{-1}; each half-barb denotes 2.5 m s^{-1}; and shading represents wind speed intervals to depict jet streaks. Thick dashed line represents axis of cross section shown in Fig. 8.

over Alabama, northern Georgia, and the western Carolinas and diffluence over the Middle Atlantic states. Confluent geopotential heights over the northeastern United States mark the entrance region of a separate 60 m s^{-1} polar jet streak extending eastward to a position just south of Nova Scotia. The combination of the horizontal wind shear associated with the jet streaks in the trough over the southeastern United States and in the downstream ridge yielded an absolute vorticity maximum over Kentucky (as indicated in Fig. 5) and minimum off the East Coast, with positive vorticity advection (PVA) dominating the Middle Atlantic region.

At the surface, heavy snow in the Middle Atlantic region is occurring to the north-northwest of a developing low along the North Carolina coast with a surface high-pressure system located over southern Quebec (Fig. 6). The surface low near the North Carolina coast is located beneath the diffluent exit region of the upper-level jet streak over the southeastern United States. A wedge of high pressure associated with very cold air over the northeastern United States (temperatures ranged between -25°C over northern New England to -5°C over Virginia) is located beneath the confluence in the entrance region of the upper-level jet streak located just south of Nova Scotia. The widespread area of heavy snow is located between the two jet streaks, in the left-front quadrant of the exit region of the polar jet in the southeastern United States and in the right rear quadrant of the polar jet in the northeastern United States. The occurrence of precipitation in this region suggests that the rising branches of both indirect and direct transverse circulations associated with these jet streaks could be contributing to the ascent needed for the development of such an extensive area of snowfall.

An analysis of the 300 mb ageostrophic wind at 1200 UTC 11 February 1983 (Fig. 7) is consistent with the basic pattern associated with trough-ridge systems as described by Bjerknes and Holmboe (1944) and depicted in Fig. 2. In the trough over the lower Ohio and Tennessee valleys,

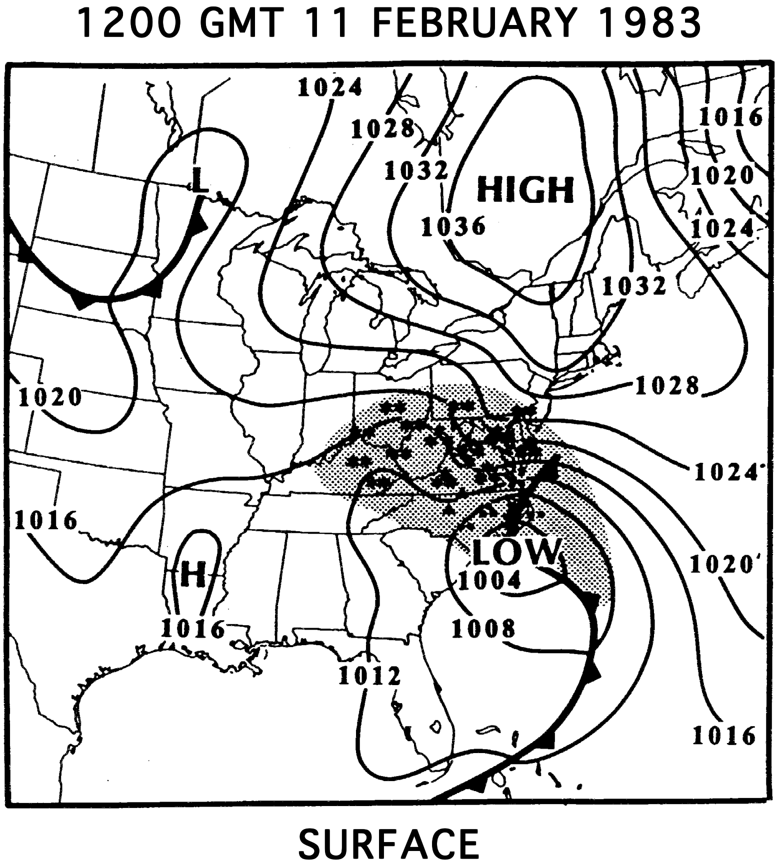


FIG. 6. Surface frontal and isobaric (solid, mb) analysis at 1200 UTC 11 February 1983. Shading represents precipitation.

an ageostrophic component is directed from the east-northeast against the flow from West Virginia to Mississippi, which reflects the subgeostrophic winds found in association with cyclonic curvature. Over New England, the ageostrophic flow is from a south to southwesterly direction in a weakly defined ridge downstream of an upper-level trough east of Nova Scotia. The alongstream component of the ageostrophic wind is in the same direction as the total wind and reflects supergeostrophic wind speeds normally associated with anticyclonic curvature.

There is also evidence in Fig. 7 of cross-contour flow consistent with the idealized model of ageostrophic motion associated with jet streaks For example, cross-contour ageostrophic flow exceeding 15 ms^{-1} over New York is directed toward lower heights in the confluent entrance region of the jet streak in the northeastern United States. Meanwhile, the ageostrophic flow over Virginia and the Carolinas is directed toward higher heights in the exit region of the jet streak over the southeastern United States. The combination of these ageostrophic components yields a noticeable anticyclonic ageostrophic flow pattern diverging from a point located in the Middle-Atlantic states where 300 mb divergence approaches 6 X 10^{-5} s^{-1} over West Virginia, which also coincides with the area of PVA (see Fig. 5) as expected.

To illustrate the interaction of the transverse circulations in the exit and entrance regions of the two jet streaks, vertical motions and ageostrophic wind components are depicted along the plane of a vertical cross section constructed from a point immediately north of Lake Ontario to a position off the North Carolina coast (see Fig. 5). The cross section (Fig. 8) depicts a distinct two-cell circulation pattern oriented normal to the axes of both jet streaks.

A direct transverse circulation is diagnosed in the confluent entrance region of the polar jet across the northeastern United States (marked with a “D” in Fig. 8). The ageostrophic wind components at upper levels are directed toward the cyclonic-shear side of the jet, while the low-level return ageostrophic flow is directed toward the anticyclonic-shear side of the jet. Subsidence is diagnosed in the coldest air immediately above the surface anticyclone in southern Canada. Ascent, with maximum values of -8 µb s^{-1}, is diagnosed in the relatively warmer air where the isentropes are sloped downward toward

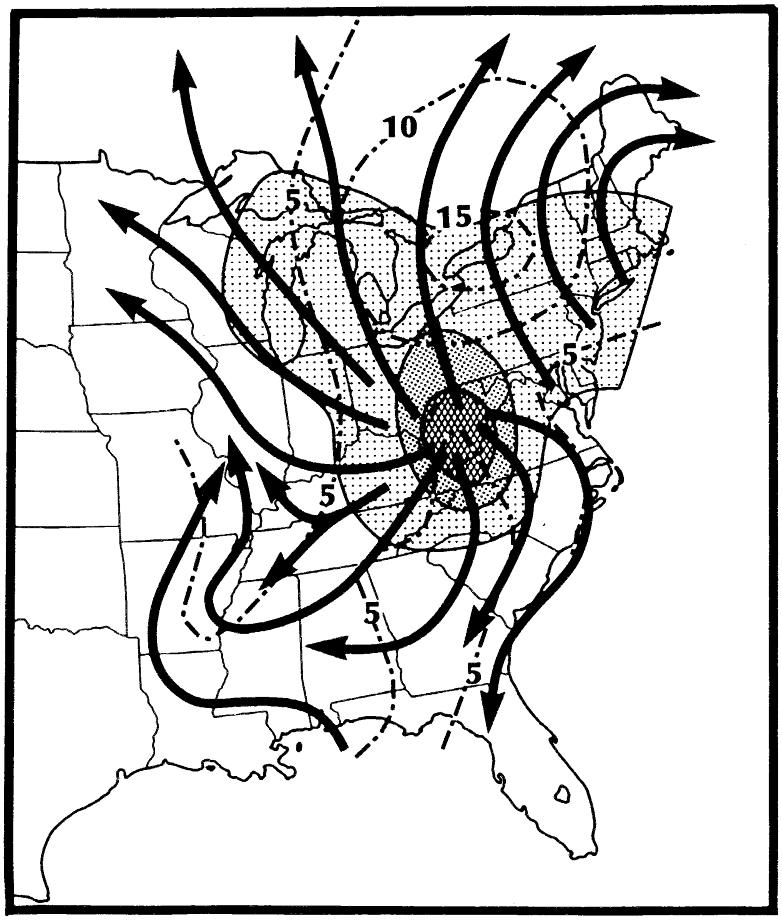


FIG. 7. The 300-mb ageostrophic wind streamlines (arrows), isotachs (dot-dashed, m s^{-1}) and divergence (shaded) at 1200 UTC 11 February 1983. Intervals of shading represents increasing values of divergence (lightly dotted, 0 to 2 x 10^{-5} s^{-1}; heavily dotted, 2 to 4 x 10^{-5} s^{-1}; cross-hatched, exceeding 4 x 10^{-5} s^{-1}).

higher pressure. The ageostrophic components in the lower troposphere appear to contribute to the advection of cold air from New York toward Virginia. Furthermore, the increasing magnitude of these vectors south of the New York-Pennsylvania border indicates that damming effects east of the Appalachian Mountains might also be an important factor for this case. The flow pattern associated with damming could provide a significant contribution to the cold-air advection between the mountain range and coastline as described by Richwien (1980) and Forbes et al. (1987).

The cross section also displays an indirect transverse circulation (marked with an "I" in Fig. 8) in the exit region of the jet streak over the southeastern United States.[1] In the upper troposphere, the tangential ageostrophic wind components are directed to the anticyclonic-shear side of the jet. The pattern of ascent is now located in the relatively colder air and upper-level subsidence is located in the relatively warmer air with respect to the position of this jet streak. The lower branch of the indirect circulation is characterized by a 15 m s^{-1} southerly ageostrophic wind component directed from the coastal region up sloping isentropic surfaces to Virginia and Maryland generally within the 950 to 700 mb layer. The lower branch of the indirect circulation acts to transport moisture from the Atlantic Coast toward the region of heavy snow in a manner similar to that described for the Presidents' Day storm by Uccellini et al. (1984) and for severe weather events by Uccellini and Johnson (1979).

The two circulations interact to produce a sloped ascending flow over Maryland and Virginia in which warm,

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[1] This portion of the cross section depicts a transverse circulation pattern that is nearly identical to the analysis presented by Emanuel (1985, Fig. 8) and Sanders and Bosart (1985a, Figs. 6a, 6b, and 6e), although the circulation is reflected to as a direct circulation by Sanden and Bosart and no reference is made in either paper as to the possible role of jet streaks in producing this circulation pattern.

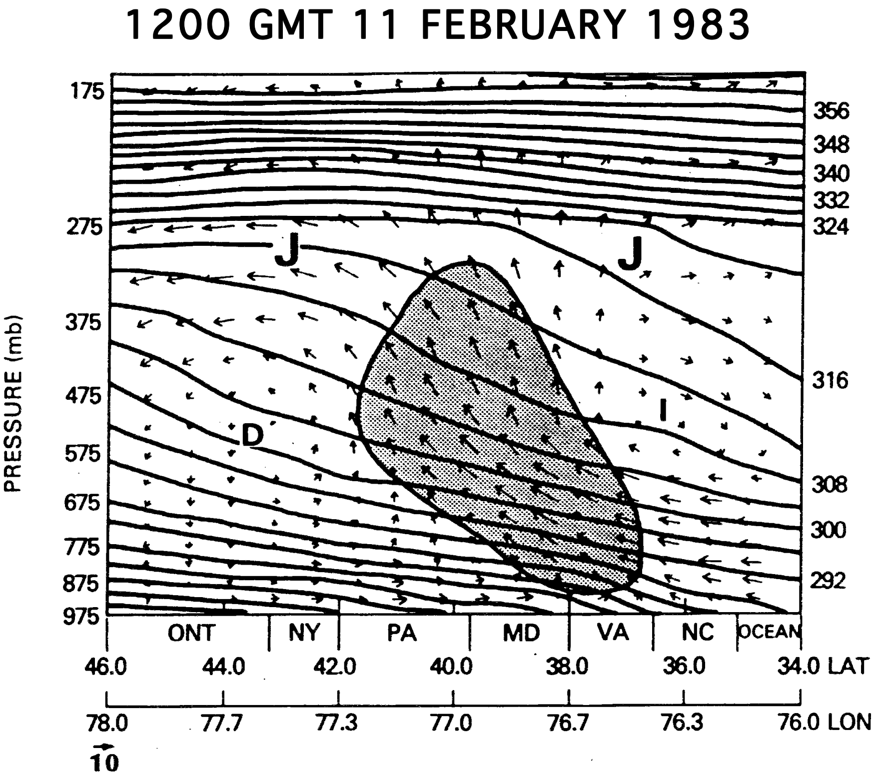

FIG. 8. Vector representation of vertical motions and ageostrophic wind components tangential to the plane of the cross section shown in Fig. 5 at 1200 UTC 11 February 1983, including isentropes (K) at 4 K increments. The horizontal vector components are scaled at the bottom of the figure (m s^{-1}). Shading represents ascent in excess of -5 μb s^{-1}. Positions of upper-level jet streaks are indicated by J. D and I denote centers of direct and indirect circulation, respectively.

moist air from the Atlantic and Gulf coast regions flows northward within the lower branch of an indirect circulation over much colder air moving southward from Canada within the lower branch of the direct circulation. The area of maximum ascent over Maryland and Virginia corresponds to the area where heavy snow was observed at 1200 UTC 11 February 1983.

This case illustrates that 1) the circulation patterns can be identified for both jet streaks using the operational radiosonde database, 2) the two jet streaks yield a broad, sloped region of ascent that is conducive for heavy precipitation, and 3) the lower branches of the circulations appear to enhance moisture transports and provide for the interaction of very cold and very warm air, creating a favorable environment for the development of heavy snowfall. As noted earlier, the two-dimensional depiction of these circulation patterns, which emphasize the cross-stream ageostrophic wind components, should not detract from the recognition that the alongstream wind component also contributes to the upper-level divergence and associated ascent patterns. Furthermore, other physical processes, including the release of latent heat within the ascending branch, can enhance and focus the region of maximum ascent in the Middle Atlantic states, as discussed for this case by Emanuel (1985) and modeled for other jet streak systems by Cahir (1971) and Uccellini et al. (1987).

b. *Other examples*

Analyses of the five cases shown in Figs. 9 through 13 are used to illustrate that the two-cell pattern appears to be a consistent signature for the heavy snowstorms that affect the East Coast. These cases, which include the storms of 12 December 1960, 4 February 1961, 7 February 1967, and the recent storms of 26 January 1987 and 23 February 1987, are illustrated by the use of 300-mb geopotential height and wind analyses, surface weather charts, and a selected vertical cross section of tangential ageostrophic wind, vertical motion, and potential temperature. Analyses were performed at one time during each storm period. It was found that the upper-level trough/jet streaks that interact to produce heavy snow along the East Coast were typically located over the data-void Atlantic Ocean, presenting an obstacle to a thorough diagnosis of some of

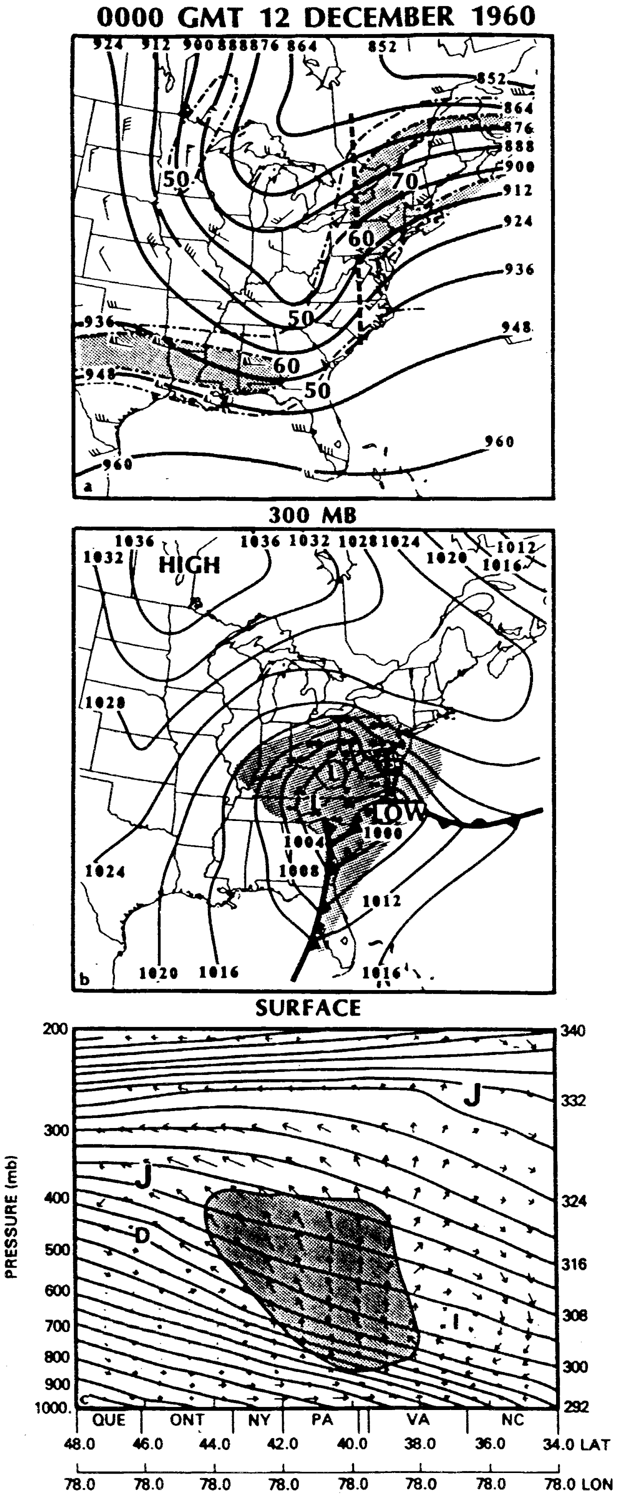

Fig. 9. (a) the 300-mb geopotential height and wind analysis at 0000 UTC 12 December 1960. thick dashed line represents axis of cross section in c. See Fig. 5 caption for details. (b) Surface frontal and isobaric analyses at 0000 UTC for 12 December 1960 (see Fig. 6 caption for details). (c) Vector representation of vertical motions and ageostrophic wind components tangential to the plane of the cross section shown in a at 0000 UTC 12 December 1960 (see Fig. 8 caption for details).

the components of the circulation patterns. Consequently, considerable care was used to select times during the early stages of each snowstorm to ensure that all components of the two-cell circulation pattern could be identified over relatively data-rich areas.

1) 0000 UTC 12 December 1960

The heavy snowstorm of 11 - 12 December 1960 is noteworthy as a relatively early winter season snow event for the northeastern United States, with snowfall exceeding 25 cm from northern Virginia to southern New England. The 0000 UTC 12 December data were selected for this case since the storm was in its early stages of development and producing a wide variety of winter weather conditions along the East Coast (Fig. 9). Two separate jet streaks were observed across the eastern United States at 300 mb (Fig. 9a). A 60 to 65 $\mathrm{m\ s^{-1}}$ jet streak was located across the southern United States at the base of an upper-level trough nearing the East Coast. A secondary low was developing rapidly across eastern North Carolina at this time within the diffluent exit region of the jet streak crossing the southern United States (Fig. 9b). During the following 12 to 24 h, this low center deepened explosively as it propagated northeastward off the Middle-Atlantic and southern New England coasts. A second upper-level jet streak was analyzed over Maine at 300 mb (Fig. 9a) with maximum wind speeds of 75 to 80 $\mathrm{m\ s^{-1}}$. A sea level high-pressure ridge line, extending from a 1040-mb anticyclone over south central Canada to New England (Fig. 9b), was located beneath the confluent entrance region of this jet streak. A widespread region of snow, ice pellets, freezing rain, and rain was occurring in the region located between the exit region of the jet over the southeastern United States and the entrance region of the jet over New England.

A vertical cross section (Fig. 9c) was constructed from western Quebec to the North Carolina-South Carolina coastline, bisecting the entrance region of the jet streak over New England and the exit region of the jet streak across the southeastern United States (the axis of the cross section is seen in Fig. 9a). The cross section depicts a two-cell circulation pattern with a direct, transverse circulation (indicated by "D") which extended southward from Quebec to Pennsylvania and an indirect circulation (indicated by "I") from Pennsylvania to North Carolina. The horizontal and vertical branches of the circulations were in the same sense as those shown for the February 1983 analysis (Fig. 8), with the rising branches of both circulations appearing to merge above the region from Pennsylvania southward to Virginia, contributing to the ascent responsible for the widespread region of snow, sleet, and freezing rain. The low-level ageostrophic branch of the direct circulation extended from the Canadian border to Virginia and contributed to cold-air advection in the regions of frozen

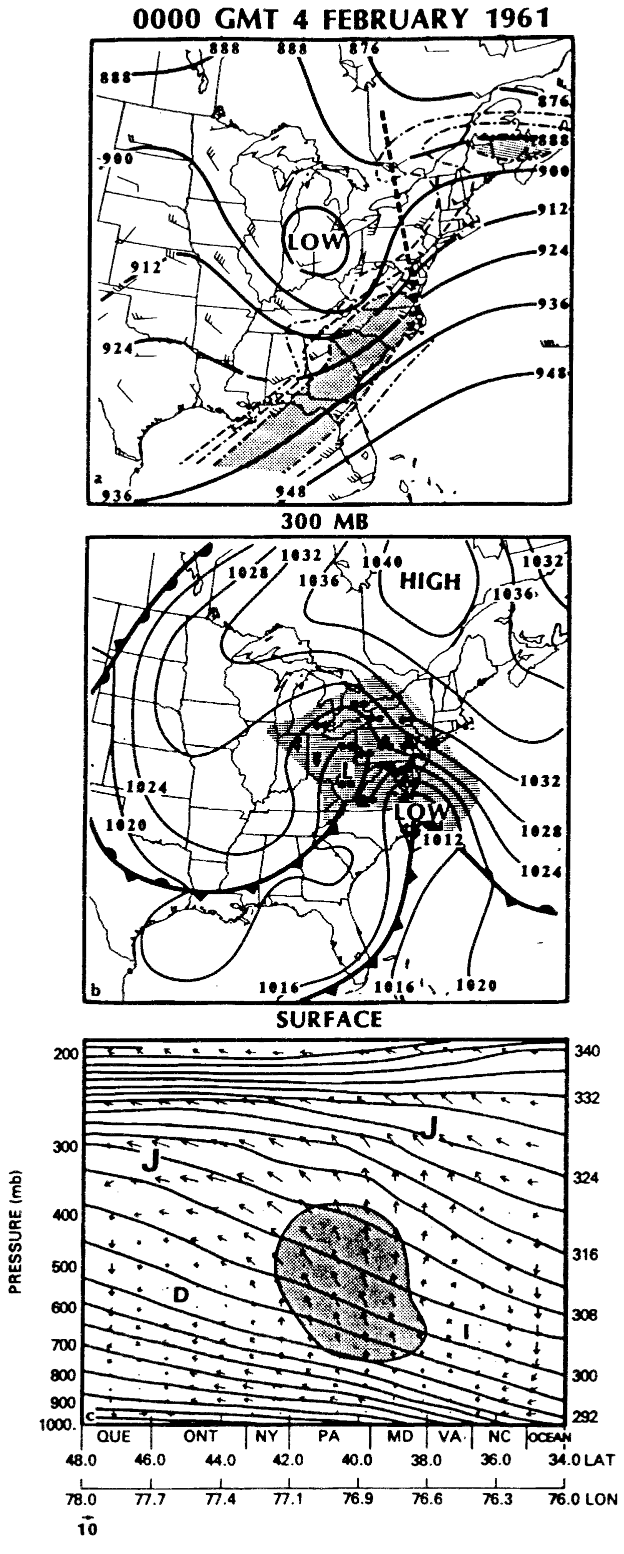

FIG. 10. As in Fig. 9 except for 0000 UTC 4 February 1961.

precipitation. The relatively large magnitudes of the lower-tropospheric ageostrophic components from New York to Virginia may again indicate the influence of cold-air damming east of the Appalachian Mountains in enhancing the magnitude of the lower branch of the direct circulation.

2) 0000 UTC 4 FEBRUARY 1961

The storm of 3-4 February 1961 was the final major storm in a series of major snowstorms to strike the northeastern United States during a prolonged period of unseasonably cold weather and snowfall that lasted from mid-January through early February 1961. The snowstorm occurred as a secondary cyclone deepened rapidly off the Middle Atlantic coast and produced record-setting snowfall accumulations in New York, New Jersey, and southern New England.

The time selected for the analyses of the transverse circulation in this case was 0000 UTC 4 February (Fig. 10), which marked the initial development of the secondary surface cyclogenesis along the Middle Atlantic coast The 300-mb analysis (Fig. l0a) again revealed the familiar pattern of an upper-level trough nearing the East Coast and a region of upper-level confluence across New England and southeastern Canada which was associated with two pronounced jet streaks. The 65 m s^{-1} jet streak extending from the eastern Gulf of Mexico to southeastern Virginia may be a reflection of both a subtropical jet over the southeastern United States and a polar jet rounding the base of the trough nearing the coast. The surface low-pressure center which developed over eastern North Carolina (Fig. 10b) was located within the diffluent exit region of this jet streak. In the following 12 to 24 h, this cyclone intensified rapidly off the Middle Atlantic coast and produced widespread heavy snow accumulations from northern Virginia to southern New England. The source of cold air for the heavy snow event was a large 1044-mb anticyclone poised to the north of New England (Fig. 10b), which was also located beneath the confluent entrance region of a separate 60 m s^{-1} jet streak across Maine and Nova Scotia (Fig. 10a).

A vertical cross section was constructed from western Quebec to eastern North Carolina, nearly normal to the jet streak over Maine, but not quite perpendicular to the axis of the jet streak over the southeastern United States (Fig. 10c). The cross section provided evidence of a direct transverse circulation over the northeastern United States and an indirect circulation centered over southern Virginia. The rising branches of both circulations, with ascent greater than -5 $\mu b\ s^{-1}$, were observed to extend from Virginia to New York, corresponding to the extensive area of snow, ice pellets, and rain across the region (Fig. 10b). However, the lower horizontal branch of the direct circulation and the upper horizontal branch of the indirect circulation were not as well defined as in the previous two cases. Difficulties in producing a distinct representation of all of the components of the circulations for this case may be related to the possibility that the divergence was related to variations in the alongstream ageostrophic wind component, or due to the limitations of selecting one cross section to view both circulations, inadequate data coverage, or missing data, all of which will be discussed in more detail toward the end of this section. Nevertheless, the general similarities of this cross section to others constructed for the previous cases (Figs. 8 and 9c) appear to indicate that processes associated with the two-cell circulation pattern were contributing to conditions conducive to heavy snowfall for this case.

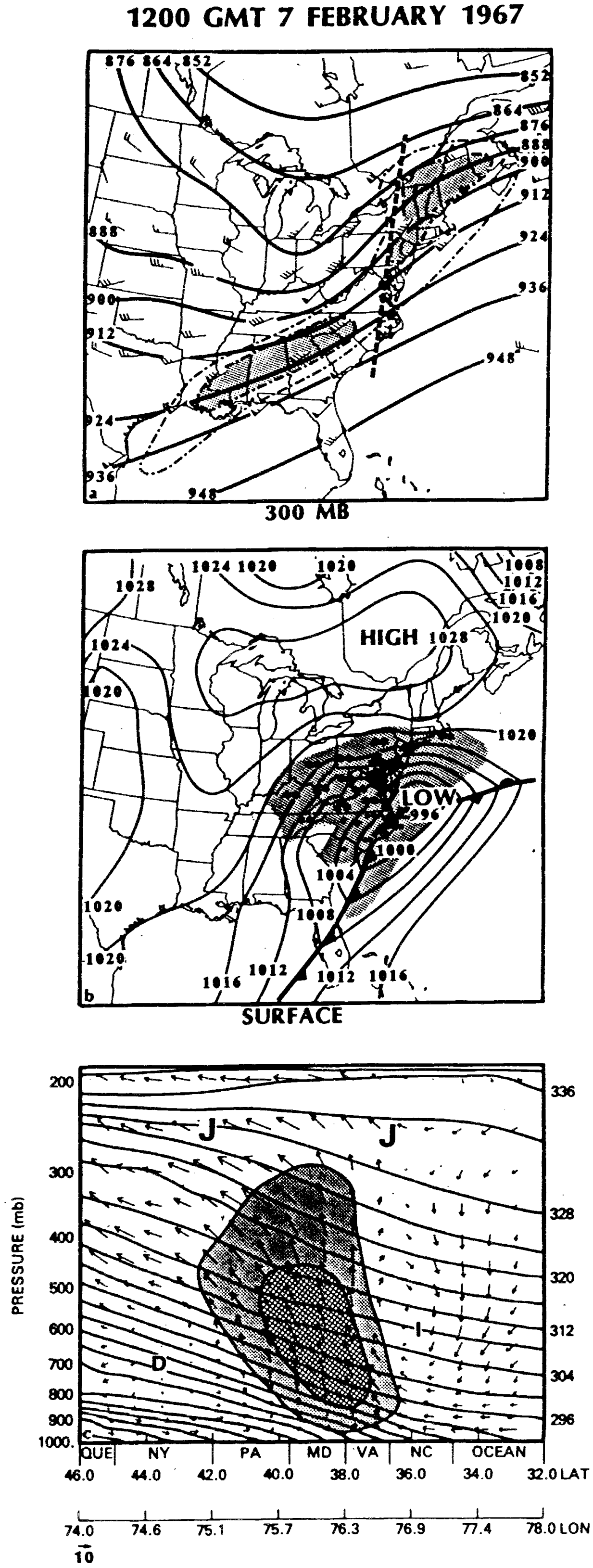

FIG. 11. As in Fig. 9 except for 1200 UTC 7 February 1967. Hatched shading in c represents ascent in excess of -10 μb s^{-1}.

3) 1200 UTC 7 FEBRUARY 1967

The snowstorm of 6-7 February 1967 involved a rapidly propagating cyclone that produced relatively short-lived, but intense, blizzard conditions from Virginia to Maine, yielding accumulations of 25 cm across a wide area. The time selected for this case was 1200 UTC 7 February, when intensive deepening of the surface low along the Middle Atlantic coast was occurring (Fig. 11). Aloft, a 75 m s^{-1} jet streak was analyzed over the southeastern United States associated with a trough of modest amplitude at 300 mb (Fig. 11a). A 994-mb surface low pressure was located off the Virginia coast (Fig. 11b), within the diffluent exit region of this jet, and south of a separate 75 m s^{-1} jet over New England (Fig. 11a). A 1030-mb anticyclone north of New England was associated with a very cold air mass (Fig. 11b) and was located beneath the confluent entrance region of the jet streak over New England (Fig. 11a). A region of light to heavy snowfall extended from eastern Tennessee to southern New England (Fig. 11b) between the diffluent exit region of the jet over the southeastern United States and the entrance region of the jet over New England. The development of snowfall between the two jet streaks, in association with a developing cyclone and cold Canadian anticyclone, is again suggestive of the existence of a dual circulation pattern associated with the upper-level jet streaks at this time.

A vertical cross section was constructed from south central Quebec to the North Carolina coast at 1200 UTC 7 February (Fig. 11c) that captured the circulation pattern associated with the two jet streaks. A direct transverse circulation was centered above New York within the confluent entrance region of the jet over New England. An indirect transverse circulation was centered above eastern North Carolina within the exit region of the jet across the southeastern United States. The ascending branches of the two circulations extended from Pennsylvania southward to southern Virginia with values exceeding -10 μb s^{-1} over the region of significant snowfall. The direct circulation showed a strong ageostrophic flow directed toward the cyclonic shear side of the upper-level jet, while the descending branch of the circulation was not

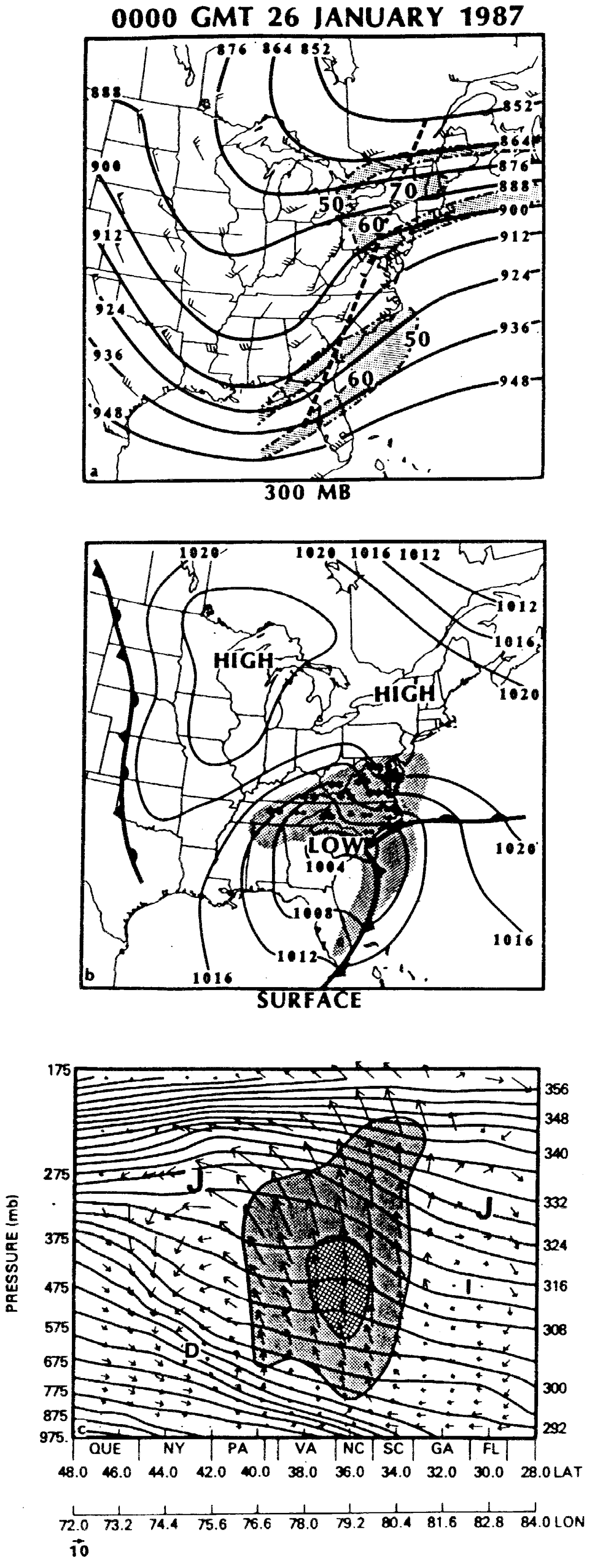

Fig. 12. As in Fig. 9 except for 0000 UTC 26 January 1987. Hatched shading in c represents ascent in excess of -10 µb s^{-1}.

well defined. The indirect circulation showed a particularly weak upper horizontal branch directed toward the anticyclonic shear side of the upper-level jet, but the vertical and lower horizontal branches were well defined. In general, the cross section represented all horizontal and vertical components of both direct and indirect circulations that contributed to temperature and moisture advection patterns in the low levels, and a widespread region of ascent that would be conducive to the development of heavy snowfall in the Middle Atlantic states.

4) 0000 UTC 26 January 1987

The snowstorm of 25-26 January 1987 was the second major snowstorm in only 4 days to affect the Middle Atlantic states, with accumulations exceeding 25 cm across Virginia, Maryland, Delaware, New Jersey, and southeastern Massachusetts. At 0000 UTC 26 January, heavy snows were beginning to develop across Virginia and southern Maryland during the early stages of the storm (Fig, 12). At 300 mb (Fig. 12a), a 70 m s^{-1} jet streak over New England was located within a pronounced region of confluent geopotential heights. A separate 60 m s^{-1} jet streak was analyzed over northern Florida and southern Georgia to the east of a trough nearing the southeast coast. A surface high-pressure ridge extending from a 1026-mb anticyclone over northern Wisconsin east-southeastward to New England (Fig. 12b) was located beneath the 300-mb confluent height field within the entrance region of the 70 m s^{-1} jet over New England. A 1002-mb surface low was located over South Carolina (Fig. 12b), beneath the diffluent exit region of the 60 m s^{-1} jet streak over Georgia and Florida. A region of rain, ice pellets, and snow over the Middle-Atlantic states was located between the exit and entrance regions of the two jet streaks

A vertical cross section constructed on a northeast-southwest line from southern Quebec to the Florida Gulf Coast showed the presence of the dual circulation pattern for this case (Fig. 12c). A well-defined direct circulation was centered above New York within the confluent entrance region of the upper-level jet over New England, while an indirect circulation was centered over Georgia within the exit region of the jet across the southeastern United States. The rising branches of the two circulations were marked by ascent greater than -10 µb s^{-1} above North and South Carolina, where the lower-ageostrophic branches of the direct and indirect circulations converged and where the maximum precipitation was occurring.

The construction of one cross section to show the interaction of both direct and indirect circulations presented some difficulties. While the direct circulation associated with the 70 m s^{-1} jet streak across the northeastern United States was easily diagnosed utilizing any number of different cross sections, the indirect circulation was difficult to define for this case. The difficulty may be due to the fact that the upper-level jet streak over the southeastern United States could not be well represented across the data-void Gulf of Mexico and Atlantic Ocean by the available radiosonde network. In addition, wind reports were missing at two critical reporting stations (Charleston, South Carolina, and Tampa, Florida), which likely had a negative impact on the ability of the objective analysis scheme to resolve adequately the spatial structure of the upper-level jet over the Southeast. While the indirect circulation was difficult to define, the analyses of a distinct direct circulation associated with the jet streak over New England and analyses of a cyclone within the exit region of the jet streak over the southeastern United States provided supporting evidence that a dual circulation pattern was contributing to the heavy snowfall observed across the Middle Atlantic states at this time.

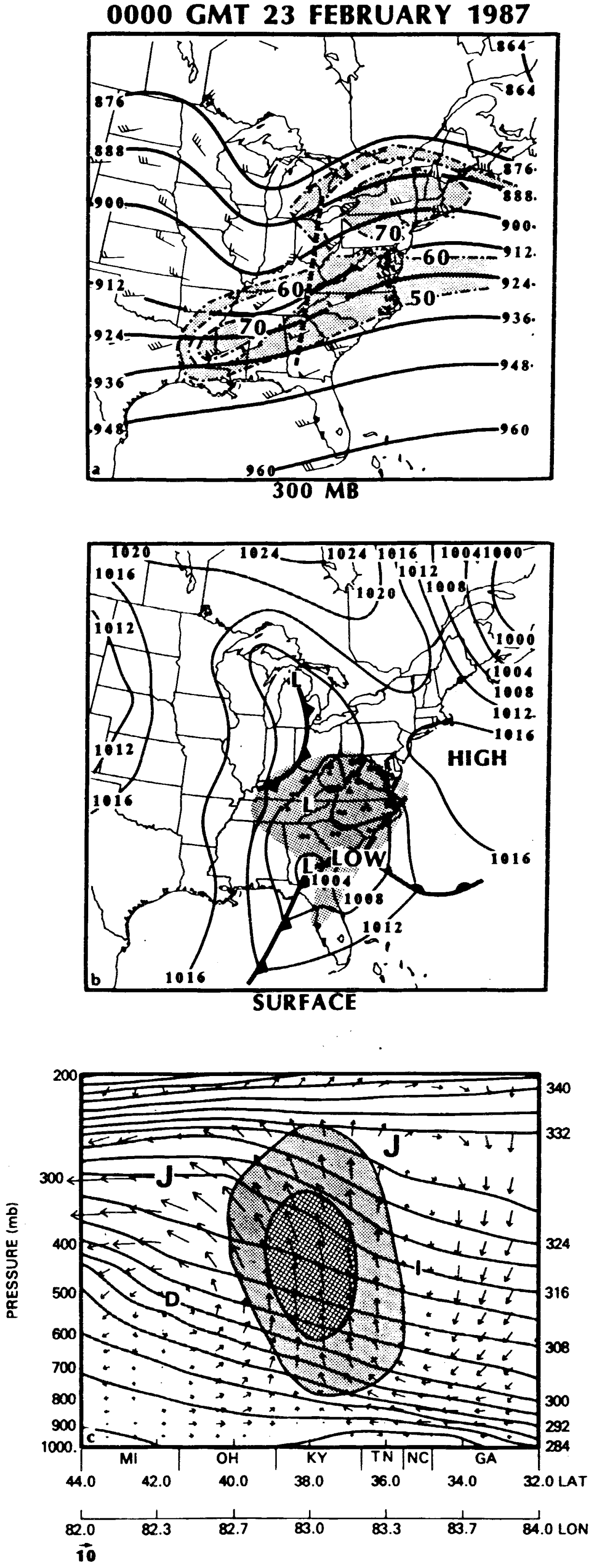

FIG. 13. As in Fig. 9 except for 0000 UTC 23 February 1987. Hatched shading in c represents ascent in excess of $-10\ \mu b\ s^{-1}$.

5) 0000 UTC 23 February 1987

The case is another recent East Coast snowstorm that was unusual in that heavy snow occurred over the Middle Atlantic states during the night of 22-23 February 1987 despite the lack of a “cold” anticyclone poised to the north of this area. Heavy, wet snowfall accumulated to depths generally between 25 and 50 cm with nighttime temperatures hovering at or just below 0°C, resulting in downed trees and power lines and loss of electricity to hundreds of thousands of people throughout northern Virginia, Maryland, Delaware, southeastern Pennsylvania, and New Jersey. What was remarkable was that the snowfall was preceded and followed by relatively mild conditions, with daytime temperatures immediately before and after the late-night snowstorm approaching 7° to 10°C.

Despite mild temperatures and the atypical lack of a large cold anticyclone, the configuration of jet streaks in this case was very similar to the heavy snow situations presented earlier. At 0000 UTC 23 February, the axis of an upper-level trough extended from Lake Superior to Mississippi at 300 mb (Fig. 13a). A 75 $m\ s^{-1}$ jet streak was centered over Mississippi at the base of the trough. A complex surface low-pressure system (Fig. 1 3b) was located downwind of the trough axis within the diffluent exit region of the jet streak. One low-pressure center was developing near the South Carolina coast, as a region of rain across the southeastern United States turned to sleet and snow across portions of West Virginia and Virginia. This region of precipitation would soon blossom into an expanding region of heavy snowfall from Virginia to New Jersey in the following 6 h as the surface low over South Carolina began to move northeastward and deepen explosively. A separate 75 $m\ s^{-1}$ jet streak was located over the northeastern United States (Fig. 1 3a), although a corresponding surface high-pressure ridge line in this region (Fig. 13b) was not well defined and not particularly cold. Nevertheless, as in the previous cases, the rapidly developing region of heavy snowfall occurred between the exit region of the jet approaching the East Coast from Mississippi-Tennessee and the entrance region of the jet across the northeastern United States.

A vertical cross sections constructed from eastern Michigan southward to western Georgia, is shown in Fig. 13c. This cross section extends through both the entrance region of the upper-level jet streak across the northeastern United States and the exit region of the jet streak across the southern United States. A distinct two-cell circulation pattern was diagnosed along the cross section with a direct circulation centered above the Michigan-Ohio border and an indirect circulation centered above Tennessee, western North Carolina. and Georgia. The rising branches of the two circulations were associated with vertical motions exceeding -10 μb s^{-1} from southern Ohio to northern Tennessee, corresponding to the area of rain across the lower Ohio and Tennessee valleys; the lower branch of the direct circulation appeared to be particularly weak near the earth's surface. This may be due, in part, to the lack of cold-air damming, since the cross section was constructed to the west of the Appalachians, where damming was not observed. Meanwhile, the lower branch of the indirect circulation was associated with ageostrophic wind speeds exceeding 10 m s^{-1} over northern Georgia that again acted to augment moisture transports toward the developing precipitation area further north. This case provides one of the best examples of a well-defined pair of transverse circulations associated with jet streaks, upstream of, and prior to, rapid cyclogenesis. The ability to diagnose this circulation pattern is perhaps related to the fact that the alongstream variation in the wind field was well defined in both the entrance and exit regions of the jet streaks. Furthermore, the curvature effects may be of lesser importance in this case given the lower-amplitude wave pattern.

A two-cell circulation pattern could not be resolved east of the Appalachian Mountains at this time, when precipitation was only beginning to develop across the Middle Atlantic states. While the two-cell pattern was diagnosed to the west of the Appalachian Mountains at 0000 UTC 23 February, it is likely that the circulations progressed eastward to the coast in the following 6 to 12 h as the upper-level jet streaks and associated trough-ridge pattern also progressed to the east. It is also possible that as the circulations progressed to the east, the lower branch of the direct circulation may have enhanced the advection of cool, dry air toward the region of precipitation from the preexisting mass of relatively cold, dry air established over the northeastern United States. This infusion of somewhat colder, drier air in the lower troposphere undoubtedly contributed to the formation of snow, rather than rain, across the Middle Atlantic states. Unfortunately, while the 0000 UTC 23 February radiosonde network could resolve the two-cell pattern only to the west of the East Coast, the 1200 UTC 23 February observations (not shown) indicated that the upper-level troughs and jet streaks had advanced too far to the east over the Atlantic Ocean to diagnose the dual circulation pattern over the East Coast. It is possible that upper-air observations at 0600 UTC 23 February would have been ideal for-identifying the circulation pattern along the East Coast, at a time when heavy snowfall was expanding rapidly across the Middle Atlantic region.

6) 1200 UTC 18 February 1979—the Presidents' Day Storm

In the previous cases, direct and indirect circulations were diagnosed in the entrance and exit regions of upper-level jet streaks embedded within confluent and diffluent flow regimes, respectively, as expected. As discussed by Shapiro and Kennedy (1981) for a jet streak marked by significant cyclonic curvature and by Uccellini et al. (1984) for an anticyclonic flow regime preceding the Presidents' Day storm, this simple relationship did not always exist in curved flow regimes.

Prior to the rapid development of the "Presidents' Day" cyclone on 19 February 1979, heavy snow developed across the Carolinas and the Tennessee Valley by 1200 UTC 18 February (Fig. 14). At 300 mb (Fig. 14a), the northeastern United States was located within the confluent entrance region of a jet streak, while the southeastern United States appeared to be within the exit region of a separate upper-level subtropical jet streak (STJ). An intense and bitterly cold surface anticyclone (1050 mb) was located beneath the entrance region of the jet streak over New England while a coastal front/inverted pressure trough was found off the southeast coast (Fig. 14b).

Unlike the other cases presented in this section, two cross sections are needed to represent the dual circulation pattern. A cross section constructed parallel to the East Coast (Fig. 14c) provided a clear representation of the direct circulation within the confluent entrance region of the polar jet located off the New England coast. However, the indirect circulation was not well represented by this cross section, especially with respect to the lack of an upper branch directed toward the anticyclonic side of the STJ. A separate cross section (Fig. 14d), constructed along a line from northern Illinois to a position off the Southeast Coast and described in detail by Uccellini et al. (1984), clearly depicted the indirect circulation associated with the STJ.

Even though the dual circulation pattern was not easily depicted on one cross-sectional plane, the transverse circulations for this case was similar to others in that they both appeared to contribute to the ascent, moisture, and

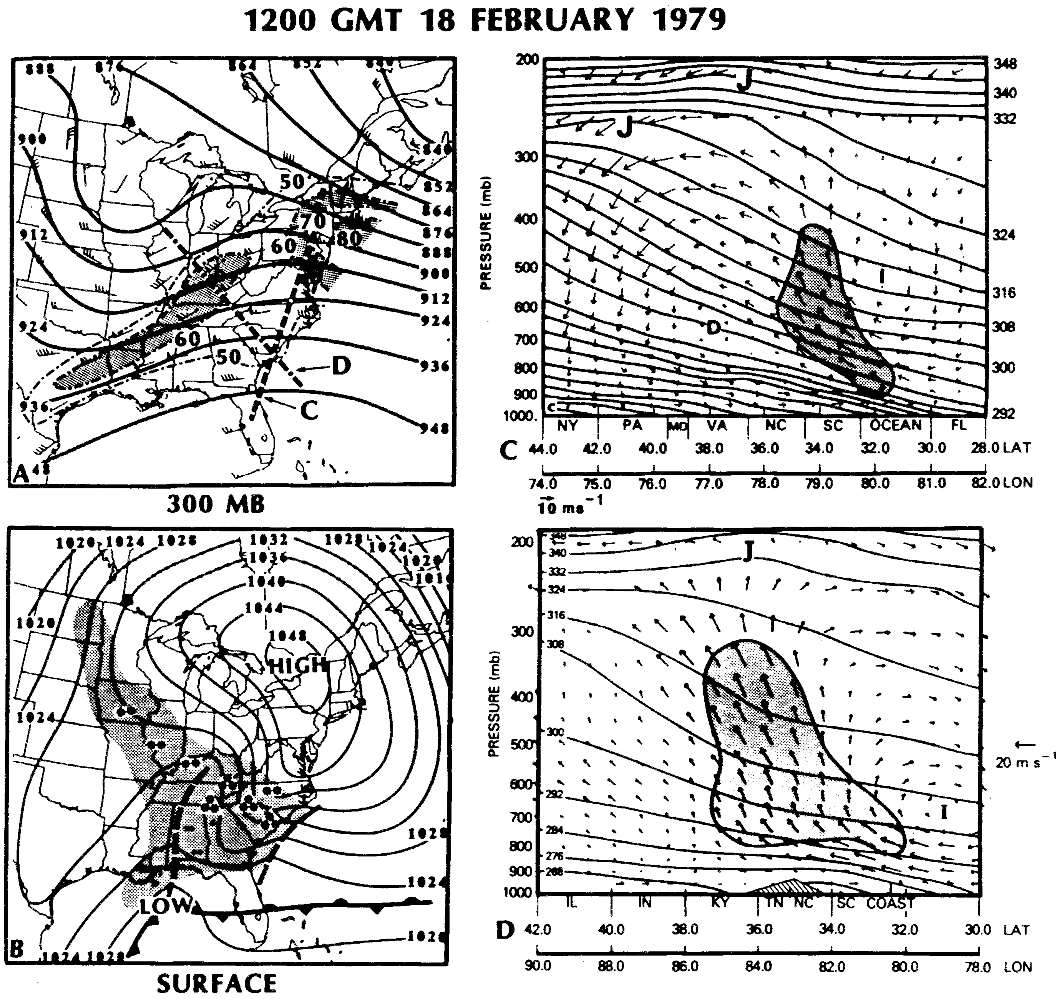

FIG. 14. (a) The 300-mb geopotential height and wind analyses, (b) surface frontal and isobaric analyses, (c) and (d) vector representation of vertical motions and geostrophic wind components at 1200 UTC 18 February 1979 within cross-sectional planes shown in a. See Fig. 9 caption for details.

thermal advections necessary for heavy snowfall along the East Coast. However, unlike the other cases, the circulations were diagnosed in a regime that differed somewhat from the scenario presented in Fig. 1. Both direct and indirect circulations appeared to be displaced to the anticyclonic-shear sides of the upper-level jets. More importantly, the detailed isentropic analysis of this case by Uccellini et al. (1984) showed that the jet located over Tennessee at the 300-mb level (Fig. 14a) actually represented an accelerating flow that was ascending through the 300-mb level over the Tennessee Valley toward the STJ core located at the 200-mb level and centered over southern Virginia at this time. Therefore, the indirect circulation diagnosed along the Southeast Coast was not located in the diffluent exit region of an upper-level jet at the base of a trough nearing the East Coast as in the other cases. In this case, the indirect circulation was actually located near the core of an anticyclonically curved STJ, with maximum wind speeds located near the crest of an upper-level ridge at 200 mb. This case illustrates the advantages of using isentropic analyses over isobaric analyses in defining the actual position of upper-level jets. Furthermore, it appears that the dual circulation pattern can evolve in flow regimes which deviate from the conceptual model based on straight-jet dynamics.

c. *Problems encountered in diagnosing jet streak circulation patterns*

The large number of cases presented in this section provides supporting evidence that the transverse circulation patterns associated with two distinct jet streak systems span the entire troposphere and are a consistent signal in these selected cases. This observation strongly suggests that the interaction of the separate jet streak systems likely is a common feature for snowstorms that affect the East Coast.

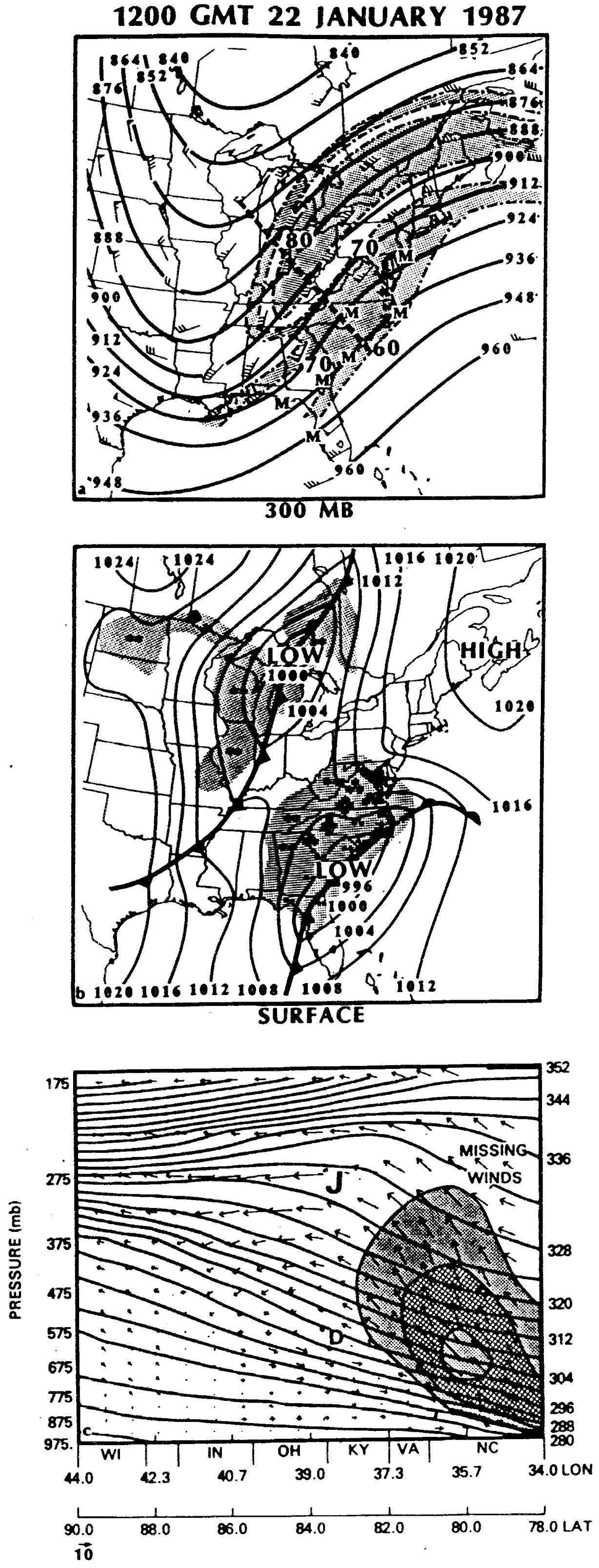

FIG. 15. As in Fig. 9 except for 1200 UTC 22 January 1987. Hatched shading and interior dotted shading represent ascent in excess of -10 μb s^{-1} and -15 μb s^{-1}, respectively.

These examples also indicate that the transverse circulations are easy to identify by applying the Petersen (1986) isentropic analysis package to the operational radiosonde data, even as far back as 1960 when it was believed that such circulations might not be identifiable because of data limitations.

Despite the apparent ease in illustrating the interactions of the dual circulation pattern for a significant number of heavy snow events, there are several factors that limit the ability to depict the circulation pattern. Since the operational radiosonde observations are made only once every 12 h, it is often difficult to select a time that captures the presence of both direct and indirect circulations over the fairly narrow coastal region which borders the data-void Atlantic Ocean, as suggested by the analysis for the 23 February 1987 storm. In particular, it is often impossible to diagnose fully the indirect circulation, since the exit region of the upper-level jet associated with the trough approaching the East Coast frequently passes east of the coastline during the cyclogenetic period. As such, various components of the circulation, especially the sinking branch, are likely to be found over the Atlantic Ocean where they are difficult to diagnose. Conversely, it is fairly easy to diagnose the horizontal and vertical components of the direct circulation associated with the jet over the northeastern United States or southeastern Canada since the entrance region of that jet is typically observed over data-rich land areas for 24 h or greater. To counter difficulties in identifying the indirect circulation, it becomes necessary to perform analyses at times prior to the passage of the jet streak exit region across the coastline. Thus, most of the analyses shown in Figs. 9-14 are made early in the evolution of each storm and prior to the development of heaviest snowfall along the coast in some cases.

As indicated for the Presidents' Day cyclone in section 3b, part 6, the choice of one relatively straight cross section to identify the interaction of the transverse circulations about two separate jet systems that are, in most cases, not parallel to each other is another complication that can limit the straightforward application of the diagnostic approach used in this paper. However, since it is rare for the two upper-level jets to be oriented at a large angle to each other, the choice of one cross section is usually sufficient to depict an interaction of the two circulations, although either circulation alone may be depicted in a clearer fashion by use of other cross sections oriented perpendicular to the axis of the individual jet streaks.

A final obstacle to identifying the interactions of direct and indirect circulations during a heavy snow event along the East Coast is the numerous missing wind reports which are prevalent in severe weather events. For example, an excellent opportunity for depiction of the two-cell circulation patterns appeared to occur during the heavy snowstorm of 22 January 1987. At 1200 UTC 22 January, an upper-level jet streak over southern Georgia (Fig. 15a) at 300 mb appears to be immediately upwind of a developing surface cyclone and outbreak of heavy snowfall across the Carolinas and Virginia (Fig. 15b). However, a closer inspection of the 300-mb chart shows that upper-level wind observations are missing at seven radiosonde sites along the East Coast, presenting an obvious impediment to the adequate representation of the upper-level wind structure. As such, the inadequate representation of the winds over this region may have resulted in the inability to diagnose an indirect circulation over the southeastern United States at this time. While one of numerous cross sections constructed over the eastern United States (Fig. 15c) clearly shows a direct transverse circulation in the entrance region of an 85 m s^{-1} jet extending from the Ohio Valley to northern Maine, no indirect circulation could be diagnosed since an upper horizontal branch and a sinking component could not be resolved. The problem of missing wind reports at upper levels was pronounced in other cases as well, especially in regions where high wind speeds associated with jet streaks were expected. The missing wind reports that plagued this study serve as a reminder of the inadequacies of the operational observing system in measuring wind speeds in potentially severe weather situations.

Despite these problems, this and other studies (i.e., Kocin and Uccellini, 1985a,b) point to key signatures that can be easily identified on operational weather charts to detect regions where upper-level jets are having an impact on a significant weather event. For example, the presence of an upper-level trough and associated jet streaks approaching the East Coast from the west is conducive for the development of a surface low-pressure system or surface front in the exit region of the jet streak, downwind of the trough axis. A separate jet streak associated within a region of upper-level confluence upwind of a trough located in the northeastern United States or southeastern Canada is also important for providing the advection of colder air toward the south that may keep the precipitation in the form of snow, rather than rain, along the coast. In many instances, such confluent regions will be associated with anticyclones of Canadian or polar origin, which can provide a source of cold air at the low levels needed for snowfall along the coast. Thus, the schematic in Fig. 1 provides a simple framework from which researchers and forecasters alike can recognize weather patterns from both the operational charts and numerical model guidance which are indicative of jet-streak-related processes that help to establish conditions conducive for heavy snowfall along the East Coast.

Summary

An examination of eight heavy snow events along the East Coast of the United States has shown that the transverse ageostrophic flow and vertical motion patterns associated with upper-level jet streaks can be identified by applying Petersen's (1986) objective analysis scheme to the operational radiosonde data network. The analyses of these cases also indicate that a particular configuration of two separate jet streaks can give rise to two interactive, transverse-ageostrophic circulations: 1) a direct circulation located within the confluent entrance region of a jet streak over the northeastern United States or southeastern Canada; and 2) an indirect circulation in the diffluent exit region of a jet streak associated with a trough in the southeastern United States. The interaction of the two circulations contributes to conditions suitable for heavy snowfall along the East Coast.

The configuration of jet streaks and their associated vertical circulations links the upper-level troughs and jet streaks to the orientations of the surface cyclones and anticyclones, temperature advection patterns, moisture transport, and the vertical motion pattern needed to produce the heavy snowfall, as illustrated in the schematic in Fig. 16. The schematic shows the following: 1) A well-defined upper-level trough is located over the Ohio and Tennessee valleys with a jet streak at the base of the trough entering a diffluent region downward of the trough axis. A surface low-pressure system develops downstream of the trough axis and within the exit region of the jet streak where upper-level divergence (cyclonic vorticity advection) related to both features favors surface cyclonic development. 2) Another upper-level trough is centered over southeastern Canada with a jet streak embedded in a confluent zone across New England. A cold surface high-pressure system is usually found beneath the confluent entrance region of the jet streak. 3) Indirect and direct transverse circulations that span the entire troposphere are located in the exit and entrance regions of the southern and northern jet streaks, respectively. 4) The rising branches of the transverse vertical circulations in the exit and entrance regions of the two jet streaks appear to merge, contributing to a widespread region of ascent that produces clouds and precipitation between the diffluent exit region downwind of the trough nearing the East Coast and the confluent entrance region located over the northeastern United States. 5) The advection of Canadian air southward in the lower branch of the direct circulation across the northeastern United States maintains cold lower-tropospheric temperatures needed for snowfall along the East Coast. It appears that in many cases the lower branch of this circulation pattern is enhanced by the ageostrophic flow associated with cold-air damming east of the Appalachian Mountains. 6) The northward advection of warm, moist

FIG. 16. Three-dimensional schematic of jet-related circulation patterns during East Coast snowstorms. The transverse circulations are associated with diffluent exit and confluent entrance regions of jet streaks embedded, respectively, at the base of troughs moving across the Ohio and Tennessee valleys and across southeastern Canada. Surface low and high pressure systems, isobars, and frontal positions are also indicated.

air in the lower branch of the indirect circulation across the southeastern United States ascends over colder air to the north of the surface low. Kocin and Uccellini (1985a,b) have found that an easterly or southeasterly low-level jet streak typically develops beneath the diffluent exit region of the upper-level jet or, as shown from diagnostic results presented in this paper, within the lower branch of the indirect circulation. The development of the LLJ within the lower branch of an indirect circulation has been shown to increase significantly the moisture transport into the region of heavy snowfall for the Presidents' Day storm (Uccellini et al., 1984) and also contribute to the decreasing sea level pressure that marked the secondary cyclogenesis along the coast for that case (Uccellini et al., 1987). 7) The combination of the differential vertical motions in the middle troposphere and the interactions of the lower branches of the direct and indirect circulations appear to be highly frontogenetic [as computed by Sanders and Bosart (1985a) for the February 1983 case], increasing the thermal gradients in the middle to lower troposphere during cyclogenesis.

This study demonstrates that transverse ageostrophic components associated with jet streaks aloft combine with the longitudinal components associated with trough-ridge systems to provide for the upper-level divergence that is conducive to surface cyclogenesis as envisioned by Bjerknes (1951). Additional studies need to demonstrate the wider applicability of this scenario, and, especially, to discriminate between cases of heavy snow versus cases in which either the storms do not develop or the precipitation is predominantly rainfall along the coast and further inland. These studies are needed to determine the existence or relative strength of either transverse circulation and the time and location of these interactions. Future studies must also take into account how these circulations evolve in flow regimes that deviate from the simple models and how boundary-layer processes act to modify the lower branches. The effects of boundary-layer processes are especially important in these heavy snow situations since cold-air damming and coastal frontogenesis occur east of the Appalachians for a large percentage of these cases. These types of case studies, augmented by numerical model simulations, would be extremely useful to help resolve how the scale-interactive processes contribute to East Coast storms that bring heavy snowfall to the coastal metropolitan areas.

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