Chapter 6

Processes Contributing to the Rapid Development of Extratropical Cyclones

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6.1 Introduction: Historical Perspective

The study of extratropical cyclones has provided the basis for vigorous scientific debates within the meteorological community for at least the past 150 years. In her monograph entitled *The Thermal Theory of Cyclones: A History of Meteorological Thought in the Nineteenth Century,* Kutzbach (1979) documents the interest of the leading European and American meteorologists of the 19th and early 20th centuries in providing a description of the weather and airflow associated with cyclones and identifying the physical processes that contribute to their development. In the 19th century, the emergence of the so-called "thermal theory of cyclones" (see Fig. 6.1) was based, to a large degree, on the work of Espy, who believed that the decrease of surface pressure in storms is related primarily to the release of latent heat in the ascending air near the storm center. By the early 20th century, the theoretical work of Margules and V. Bjerknes and the observational studies by Dines (which indicated extratropical cyclones were cold core systems) led to a more dynamically based perspective on cyclogenesis. The energy conversions and low-level convergence associated with instabilities in regions marked by significant temperature gradients (especially in the lower troposphere) were recognized as important contributing factors in the development of extratropical storms.

The growing awareness of the importance of dynamical processes provided a basis for the polar front theory of cyclogenesis that was developed by the Bergen school in Norway (see, e.g., Bjerknes and Solberg 1922) and set the stage for vigorous discussions concerning the relative importance of dynamic and thermodynamic processes in extratropical storms. Kutzbach's (1979, pp. 125–128) discussion on the "controversial evidence" introduced through the synoptic studies of Hann and Loomis in the late 19th century, and Brunt's (1930) brief note on the origin of cyclones, in which he reviews the differences between the thermal (or "local heating") and dynamic (or

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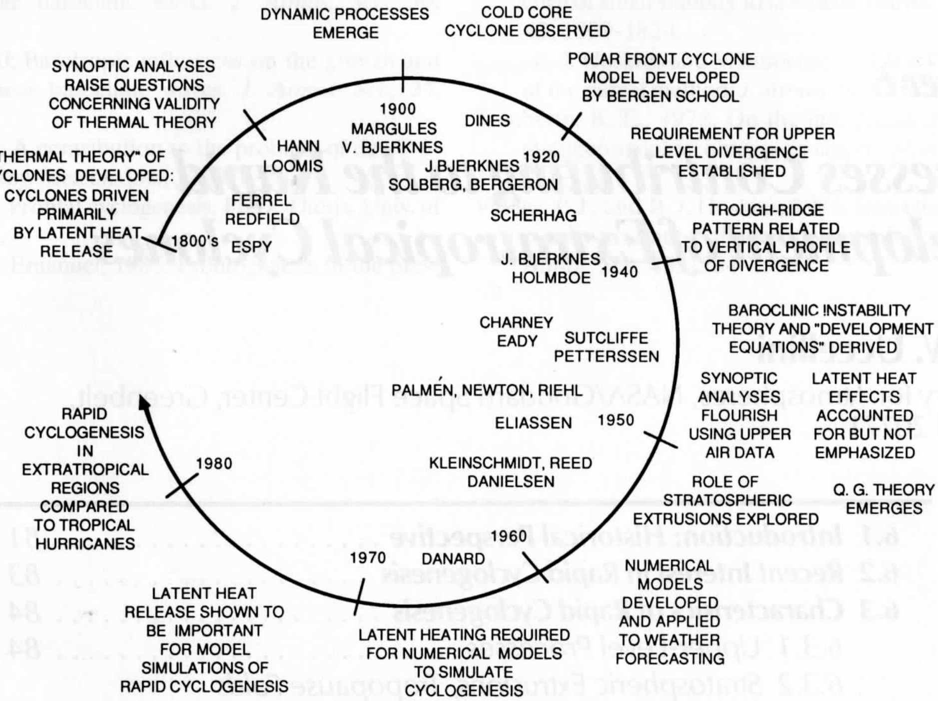

FIG. 6.1. Summary of major developments in the study of cyclogenesis from the 1800s to the present.

"polar front") theories, provide evidence of the early debates on the relative importance of various physical processes in rapid cyclogenesis. Brunt concludes that observational studies in the 1920s tended to support the concept that dynamic processes associated with low-level fronts and the existence of a strong upper-level current are important for the development of cyclones, while not ruling out the importance of boundary layer heating and latent heat release.

From the 1920s to the 1950s, rapid advances in the understanding of cyclogenesis occurred over a relatively short period of time (Fig. 6.1). Upper-level trough/ridge systems were shown to provide the divergence required to reduce the surface pressure, while low-level convergence contributed to the vorticity increase that marked the rapid spin-up of cyclones (see, e.g., Bjerknes and Holmboe 1944). By the end of this period, the jet stream was discovered, the role of stratospheric extrusions in cyclogenesis was elucidated, and baroclinic instability theory became firmly established as a basis for describing the energy conversions associated with cyclogenesis. Furthermore, synopticians began to focus on vorticity advection and thermal advection patterns as key factors in cyclogenesis, as reflected by Petterssen's (1956, p. 337) hypothesis that "cyclone development at sea level occurs when and where an area of appreciable vorticity advection in the upper troposphere becomes superimposed upon a slowly moving quasi-stationary front at sea level." Therefore, an almost complete transition had occurred in that cyclones were now increasingly related to dynamic processes associated with upper-level troughs and jets and low-level fronts rather than to thermodynamic processes associated with the release of latent heat.

Despite the emphasis on dynamics (especially with the emergence of baroclinic instability concepts in the late 1940s and early 1950s), synopticians continued to recognize the important role of diabatic processes in cyclogenesis. For example, the development equations derived by Sutcliffe (1947) and Petterssen (1956, p. 324) include a diabatic term that accounts for the effect that latent heat release has in offsetting the cooling associated with adiabatic ascent in a statically stable environment. In his *Compendium of Meteorology* article on extratropical cyclones, Palmén (1951) also discusses the importance of latent heat release in focusing the area of "principal ascent" in the precipitation region associated with cyclones. In separate diagnostic studies, Krishnamurti (1968) and Johnson and Downey (1976) emphasize the importance of latent heat release for its contribution to the rapid deepening of extratropical cyclones and the vertical extension of the vortex from the lower to middle troposphere.

The introduction of numerical weather prediction models in the 1950s based on the quasi-geostrophic framework, however, and their failure to simulate rapid cyclogenesis in many cases, set the stage for the reemergence of the concept that the impact of latent heat must be accounted for to describe and simulate cyclogenesis (Danard 1964). As discussed by Keyser and Uccellini (1987), the proliferation of model sensitivity studies from the 1960s to the present has had a major impact in focusing attention on the importance of latent heat release in the overall development of cyclones, perhaps contributing to an overemphasis of its importance at the expense of the dynamic processes. This trend has nearly brought us full circle to the position espoused by Espy in the 19th century (Fig. 6.1), with some recent work on rapid cyclogenesis drawing an analogy between extratropical cyclones and tropical hurricanes (e.g., Rasmussen 1979; Bosart 1981; Anthes et al. 1983; Gyakum 1983a,b). Nevertheless, current modeling systems and observations are far from perfect, and our understanding of the interaction among the various physical and dynamical processes is incomplete. Thus, the meteorological community still finds itself involved in a vigorous debate concerning the relative importance of latent heat release, boundary-layer processes and dynamical processes in the development of extratropical cyclones.

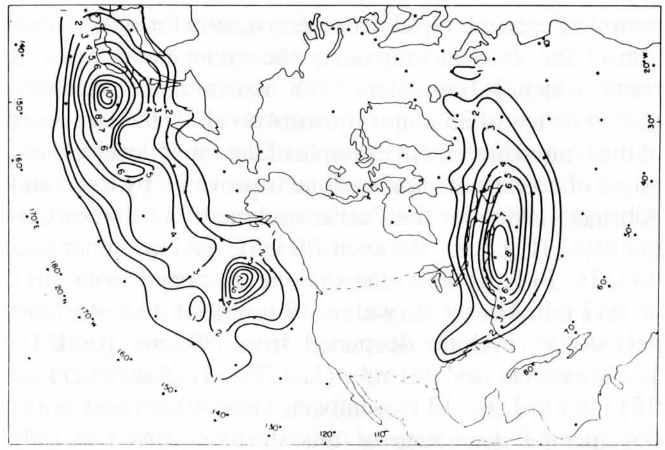

FIG. 6.2. Geographic distribution of maximum deepening positions for explosive cyclogenesis observed during 24-h periods from 1976 to 1982, smoothed over a 5° longitude by 5° latitude grid (Roebber 1984).

6.2 Recent Interest in Rapid Cyclogenesis

The recent interest in cyclogenesis has focused on cyclones that undergo a period of rapid development and are often marked by severe winds and heavy precipitation. In their study of "explosive" cyclogenesis in the Northern Hemisphere, Sanders and Gyakum (1980) found that the rapidly deepening storms occur primarily over the ocean above or just to the north of the warm ocean currents in the North Atlantic and North Pacific Oceans. This result is confirmed in follow-up studies by Roebber (1984; see Fig. 6.2), Rogers and Bosart (1986), and numerous case studies which include: analyses of the QE II storm in the North Atlantic (Anthes et al., 1983; Gyakum 1983a,b; Uccellini 1986); a study of a North Pacific cyclone which deepened 40 mb in a 12-hour period and attained a central pressure of 950 mb or less (Reed and Albright 1986; Kuo and Reed 1988); studies of cyclogenesis along the east coast of Australia (Holland et al. 1987; Leslie et al. 1987); a number of papers on major snowstorms along the east coast of the United States (e.g., Bosart 1981; Bosart and Lin 1984; Uccellini et al. 1984, 1985, 1987; Kocin et al. 1985; Sanders and Bosart 1985a,b; Bosart and Sanders 1986; Kocin and Uccellini 1990); and a growing number of studies on polar lows in the North Atlantic and Pacific Oceans (e.g., Rasmussen 1979; Sardie and Warner 1985; Shapiro et al. 1987; Businger and Reed 1989). There are always exceptions to the rule that rapid cyclogenesis occurs over the ocean or near a coastline. For example, several major cyclones occur over the central United States each winter that have deepening rates exceeding the criterion for explosive development. An example is the 25–26 January 1978 cyclone which deepened 40 mb in 24 hours over the east-central United States and southern Canada producing severe blizzard conditions over a large area as described by Burrows et al. (1979) and Salmon and Smith (1980).

In an extension of the Sanders and Gyakum study, Roebber (1984) presents a statistical analysis of the 24-hour deepening rates for a one-year sample of cyclones occurring in the Northern Hemisphere, and shows that the distribution is skewed toward the rapidly deepening storms (Fig. 6.3). Roebber chose a normal distribution approach to argue that two normal curves can be used to classify cyclogenesis in two categories; one being "common" or "ordinary" and the other "explosive." An important aspect of this distinction (and a major practical reason for the growing interest in studying rapid cyclogenesis) is that in many instances numerical models continue to have problems simulating cyclones that exhibit an explosive development phase. In recent papers by Anthes et al. (1983) and Kuo and Reed (1988) which describe numerical simulations of rapid cyclogenesis, even the best simulations had central pressures in the storm center that were 15 to 19 mb above those observed. The rapid cyclogenesis that produced destructive winds in southern England on 15 October 1987 (see Section 5.7) was also poorly predicted by the best operational models in Great Britain (Morris and Gadd 1988).

The storms that are characterized by the most rapid deepening rates are marked by decreasing pressure for a longer period of time compared to ordinary cyclones (Roebber 1984). As noted by Roebber, however, the

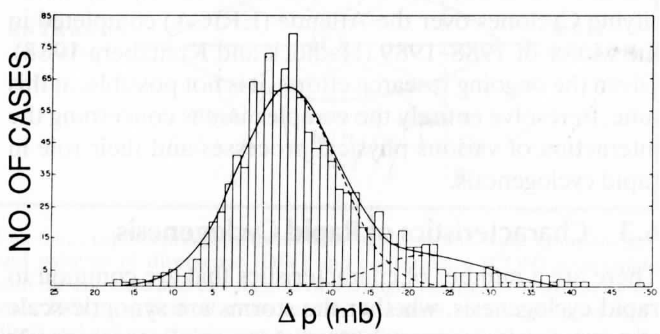

FIG. 6.3. Distribution of 24-h deepening rates for Northern Hemisphere cyclones observed for a 1-year period and adjusted for latitude dependence. The solid line indicates the sum of two normal curves; the dashed lines indicate the separate curves. The pressure difference (Δp) has been adjusted according to latitudinal position; negative deepening rates imply a net filling of the system during a 24-h period (Roebber 1984).

period of extreme rapid deepening occurs for only a fraction of the time encompassing the cyclogenetic event, a result which is consistent with Kocin and Uccellini's (1990) review of 23 major snowstorms along the east coast of the United States. An example of the rapid development phase of an extratropical cyclone is provided by Reed and Albright (1986) for the Pacific cyclone of 12–14 November 1981 (Fig. 6.4). Between 06 UTC 12 November and 03 UTC 14 November, the cyclone deepened from 1011 to 947 mb. However, within 12 hours of that 45-hour period, the cyclone deepened from 992 mb (06 UTC 13 November) to 981 mb (12 UTC 13 November) to 954 mb (18 UTC 13 November). Thus, 60 percent of the documented deepening of this storm occurred in only 26 percent of the time that deepening was observed.

The observations that many of these cyclones exhibit a short period of extreme rapid deepening lends support to the terminology of "explosive development" used by Sanders and Gyakum (1980) and Roebber (1984), among many others, in describing these storms. The separation of explosive and ordinary cyclogenesis by these authors, combined with the well-known fact that baroclinic instability theory yields development rates which are below those which are observed (e.g., Farrell 1984), have also led Roebber (1984, p. 1582) to suggest that "explosive cyclogenesis is produced by a mechanism or mechanisms that are distinct in some meaningful way from the baroclinic process" and that rapid cyclogenesis "develops differently from less intense storms." However, the observations might also suggest that these storms are a result of an interaction of various physical and dynamical processes that occurs over a relatively short period of time—an interaction that is common to some degree in all cyclones, but which might act more efficiently in the more intense storm systems.

These differing viewpoints have provided the scientific basis for field programs along the east coasts of Canada and the United States such as the Canadian Atlantic Storms Program (CASP) (Stewart et al. 1987), the Genesis of Atlantic Lows Experiment (GALE) conducted in 1986 (Dirks et al. 1988) and the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) completed in the winter of 1988–1989 (Hadlock and Kreitzberg 1988). Given the ongoing research efforts, it is not possible, at this time, to resolve entirely the complex issues concerning the interaction of various physical processes and their role in rapid cyclogenesis.

6.3 Characteristics of Rapid Cyclogenesis

There are a number of characteristics that are common to rapid cyclogenesis, whether the storms are synoptic-scale systems (such as coastal storms) or smaller, mesoscale systems (such as polar lows). The common characteristics along with associated dynamical and physical processes are described in this section (see also Section 3.3.4). While these processes are treated separately in order to identify their possible contributions to the developing storm systems, the interaction among these various processes appears to be the critical factor for rapid cyclogenesis, an issue which is addressed in Section 6.4.

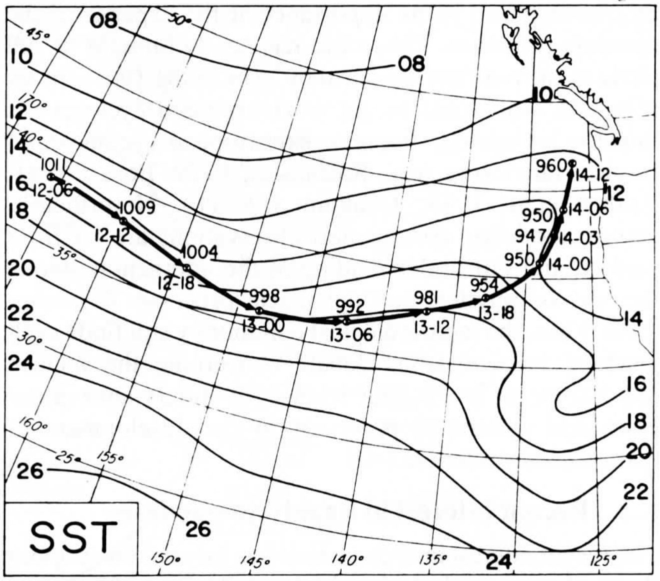

FIG. 6.4. Storm track for an intense oceanic cyclone. The 6-h positions and corresponding central pressures are marked for the period from 06 UTC 12 November to 12 UTC 14 November. Light solid lines are sea-surface temperature (°C) (Reed and Albright 1986).

6.3.1 Upper-Level Processes

The study of upper-level conditions required for cyclogenesis dominated synoptic meteorological research during the first half of the 20th century in association with the introduction of techniques to monitor and measure atmospheric winds, temperature and moisture above the earth's surface. As described by Palmén and Newton (1969, Chap. 5), a basic principle which emerged during this period (largely due to the concepts promoted by Margules, Dines and Scherhag) is that the development of cyclonic disturbances at sea level requires upper-level divergence, so as to yield a net reduction of mass and a decrease in the sea-level pressure in a region where the low-level wind field is generally convergent. Bjerknes and Holmboe (1944) relate the vertical distribution of divergence required to sustain cyclogenesis to the presence of an upper-level trough-ridge pattern, with divergence aloft, convergence near the earth's surface and a level of nondivergence in the middle troposphere located downstream of the trough axis (Fig. 6.5a). The recognition that upper-level divergence is required for surface cyclogenesis has also been linked with an associated requirement for the existence of "longitudinal" or along-stream ageostrophic wind components that result from cyclonic or anticyclonic curvature (Sutcliffe 1939; Bjerknes and Holmboe 1944; Bjerknes 1951). Subgeostrophic flow at the base of a trough and supergeostrophic flow at the ridge crest are associated with the divergence (convergence) downstream (upstream) of the trough axis (Fig. 6.5a).

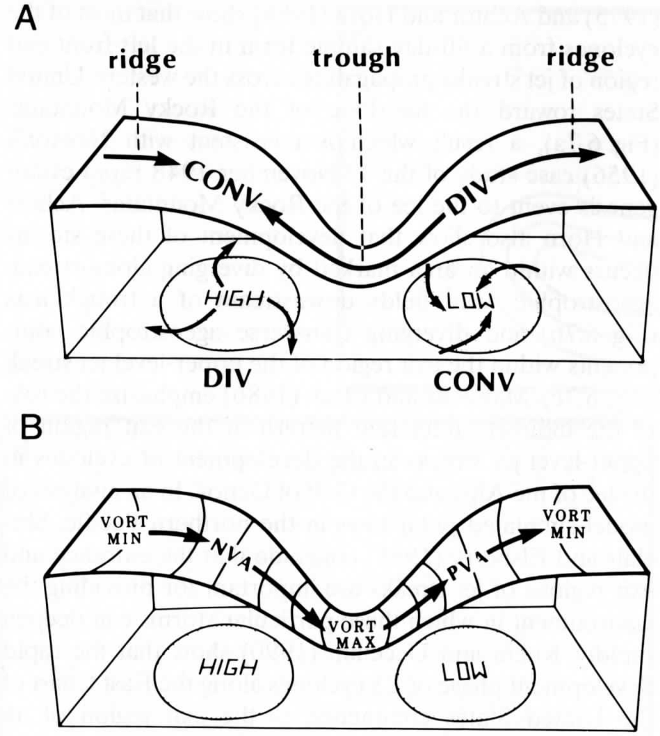

FIG. 6.5. (a) Schematic relating the along-stream ageostrophic wind at upper levels to patterns of divergence associated with an upper-level wave and surface high- and low-pressure couplets (based on Bjerknes and Holmboe 1944). (b) Schematic of maximum (cyclonic) and minimum (anticyclonic) relative vorticity centers and advections (NVA = negative or anticyclonic vorticity advection; PVA = positive or cyclonic vorticity advection) associated with an idealized upper-level wave (Kocin and Uccellini 1990).

Given the problem of diagnosing divergence aloft and the associated ageostrophic wind field, 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. Within this framework, the divergence in the upper levels is approximated by the vorticity advection fields (Fig. 6.5b), with cyclonic or positive vorticity advection (PVA) associated with the divergence required for surface cyclogenesis (see also Palmén and Newton 1969, pp. 318–319). Furthermore, as derived by Sutcliffe, the advection of absolute vorticity by thermal wind (typically at 500 mb) has been shown to be highly correlated with surface cyclogenesis, a relationship which provided a basis for the synoptic analyses and forecast procedures used before the advent and acceptance of numerical models. Recent climatological studies of rapid cyclogenesis confirm that the development of these storms commences as the trough/ridge system and its associated region of PVA propagate to within 500 km upstream of the cyclogenetic region (Sanders and Gyakum 1980; Sanders 1986, 1987).

In addition to the contribution of the longitudinal or along-stream ageostrophic components to divergence within trough/ridge patterns, Bjerknes (1951) and Reiter (1963, pp. 339–342) discuss the likely contribution of "transverse" (or cross-stream) ageostrophic components, and associated divergence patterns, in the entrance and exit regions of jet streaks to surface cyclones and anticyclones. As described by Namias and Clapp (1949), Bjerknes (1951) and Murray and Daniels (1953), the entrance region of an *idealized* jet streak (with a maximum wind speed greater than the propagation rate of the jet) is marked by a transverse ageostrophic component directed toward the cyclonic-shear side of the jet (Fig. 6.6a). 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 defined by the vertical ascent on the anticyclonic (or warm) and descent on the cyclonic (or cold) sides of the jet (Fig. 6.6b), a pattern that is consistent with vorticity advection concepts described by Riehl et al. (1952) and illustrated in Fig. 6.6c. Conversely, in the exit region, the ageostrophic components in the upper tropo-

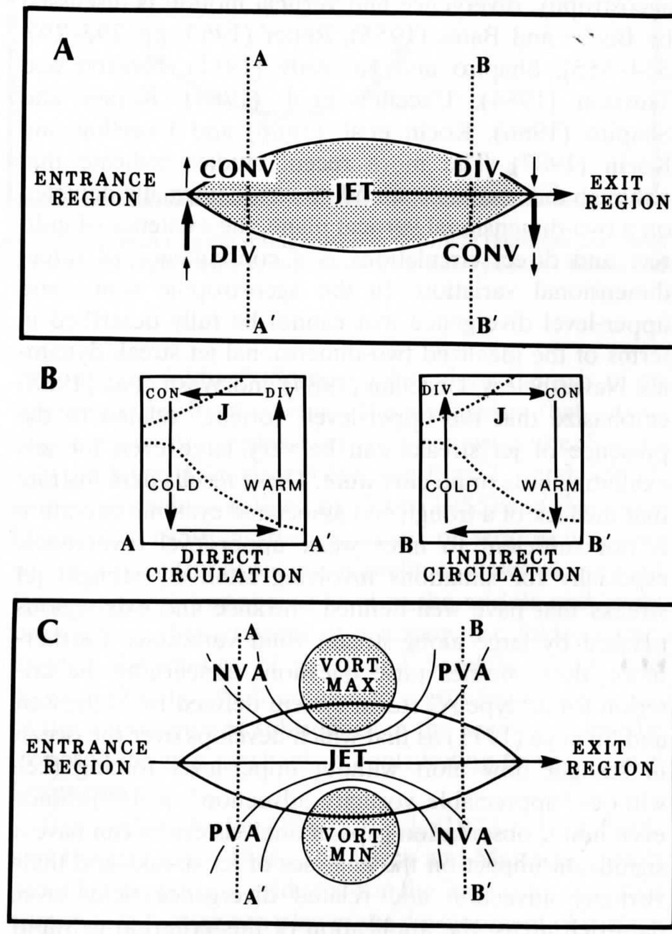

FIG. 6.6. (a) Schematic of transverse ageostrophic wind components and patterns of divergence (DIV) and convergence (CON) associated with the entrance and exit regions of a straight jet streak (based on Bjerknes 1951). (b) Vertical cross sections illustrate vertical motions and direct and indirect circulations in the entrance region (line A-A′) and exit region (line B-B′) of a jet streak. Cross sections include two representative isentropes (dotted), upper-level jet (J) location, upper-level divergence and horizontal ageostrophic wind components within the plane of each cross section. (c) Schematic of maximum and minimum relative vorticity centers, and associated PVA and NVA patterns, associated with a straight jet streak (after Riehl et al. 1952). Schematic is from Kocin and Uccellini (1990).

sphere are directed toward the anticyclonic-shear side of the jet (Fig. 6.6a), representing the upper branch of an indirect transverse circulation pattern (Fig. 6.6b) that converts kinetic energy to available potential energy as parcels decelerate upon exiting the jet. (See example in Fig. 12.18.) In conjunction with this circulation pattern is ascent (descent) on the cyclonic or cold (anticyclonic or warm) side of the jet, which again is in agreement with the vorticity advection patterns (Fig. 6.6c). As discussed by Uccellini and Johnson (1979), an important factor that determines the magnitude of the horizontal ageostrophic components of the transverse circulation and the associated vertical motion pattern is the along-stream variation of the wind speed in the exit and entrance region of the jet and not necessarily the magnitude of wind maximum in the jet core.

The influence of curvature effects in masking or distorting the contribution of jet streaks to upper-level ageostrophy, divergence and vertical motion is discussed by Beebe and Bates (1955), Reiter (1963, pp. 293–297, 354–355), Shapiro and Kennedy (1981), Newton and Trevisan (1984), Uccellini et al. (1984), Keyser and Shapiro (1986), Kocin et al. (1986) and Uccellini and Kocin (1987). The 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 the idealized two-dimensional jet streak dynamics. Nevertheless, Uccellini (1984) and Wash et al. (1988) emphasize that the upper-level "forcing" related to the presence of jet streaks can be very large even for jets exhibiting little or no curvature. These results demonstrate that the lack of a trough and associated cyclonic curvature is not sufficient to infer weak upper-level divergence, especially for situations involving relatively straight jet streaks that have well-defined entrance and exit regions marked by large along-stream wind variations. Furthermore, these studies raise questions concerning the criterion for a "type A" storm system defined by Petterssen and Smebye (1971) as that which develops over the ocean in straight flow aloft without upper-level forcing (i.e., without "appreciable vorticity advection," p. 459). Since even minor observation gaps or analysis errors can have a significant impact on the analyses of jet streaks and their vorticity advection and related divergence fields over data-rich areas, the application of this criterion to rapid cyclogenesis in the data-void regions over the oceans should be discouraged.

Despite the complications related to curvature effects, and also to the influence of latent heat in enhancing the ascent patterns associated with jet streaks (Cahir 1971; Uccellini et al. 1987), there is growing recognition that jet-streak-induced circulations play a role in rapid cyclogenesis. For example, in climatological studies of cyclogenesis 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 toward the lee-slope of the Rocky Mountains (Fig. 6.7a), a result which is consistent with Newton's (1956) case study of the 17 November 1948 rapid cyclogenesis event to the lee of the Rocky Mountains. Achtor and Horn also show that development of these storms occurs within an area marked by diverging along-stream ageostrophic wind fields downstream of a trough axis (Fig. 6.7b) and diverging transverse ageostrophic components within the exit region of the upper-level jet streak (Fig. 6.7c). 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. In an analysis of model-simulated polar lows 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 deepen rapidly. Kocin and Uccellini (1990) show that the rapid development phase of 23 cyclones along the East Coast of the United States commence as the exit region of an upper-level jet becomes collocated with the region marked by increasing diffluence in the geopotential height field immediately downstream of the trough axis. In a companion paper published earlier, Uccellini and Kocin (1987) conclude that the transverse ageostrophic components associated with jet streaks aloft appear to combine with the longitudinal components associated with the trough-ridge pattern to enhance and focus the upper-level divergence required for rapid cyclogenesis, a process that was originally envisioned by Bjerknes (1951).

6.3.2 Stratospheric Extrusions, Tropopause Folds and Related Potential Vorticity Contribution to Surface Cyclogenesis

Upper-level trough/ridge patterns and jet streaks not only provide the divergence aloft needed for deepening surface cyclones, but also contribute to the intensity of upper-level fronts and related distribution of potential vorticity which can, in turn, have a significant impact on the spin-up of these storms through the descent and horizontal advection of stratospheric air toward the cyclogenetic region. Attempts have been made to link the extrusion of stratospheric air into the upper and middle troposphere to cyclogenesis through the principle of conservation of isentropic potential vorticity (IPV), where IPV $= -(\zeta_\theta + f)\partial\theta/\partial p$. As stratospheric air descends into the troposphere, the air mass is stretched and the static stability ($-\partial\theta/\partial p$) decreases significantly. Consequently, the absolute vorticity ($\zeta_\theta + f$) increases with respect to parcel trajectories as long as the stratospheric values of IPV are preserved.

Kleinschmidt (1950) was apparently the first to relate the advection of a stratospheric reservoir of high IPV

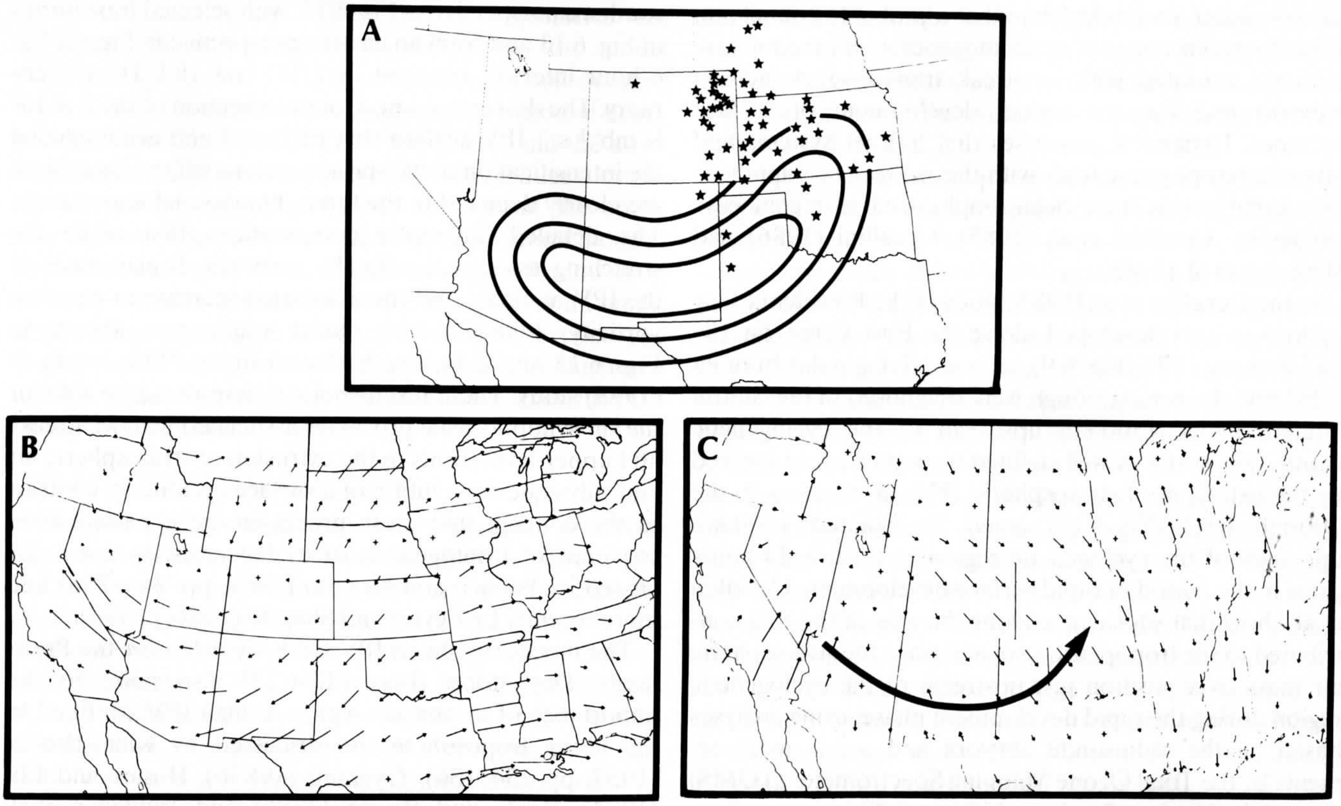

FIG. 6.7. (a) Mean 300-mb isotach field superimposed on sites of cyclogenesis for cases during the spring season in Colorado (Hovanec and Horn 1975). (b) Longitudinal and (c) transverse ageostrophic components derived for a subsample of the spring season Colorado cyclones (Achtor and Horn 1986).

associated with a low tropopause to cyclogenesis, going so far as to state that the stratospheric reservoir "is essentially the producing mass of the cyclones" (Kleinschmidt 1957, p. 125). This emphasis on the stratosphere by Kleinschmidt reflects a long-term interest of German meteorologists in studying the association between warm-air advection above the tropopause and surface cyclogenesis, dating back to Wagner's work in the early part of the century (see Kutzbach 1979, p. 184). A recent review article by Hoskins et al. (1985) discusses the impact of stratospheric IPV anomalies on surface cyclogenesis (see Section 5.4). Through an "invertibility principle" expressed by Kleinschmidt (1950), Hoskins et al. show that a positive IPV anomaly that extends downward from the stratosphere into the middle troposphere provides an optimal situation for enhancing the IPV advection in the middle to upper troposphere, which acts to induce a cyclonic circulation that extends throughout the entire troposphere to the earth's surface (Fig. 6.8a).

Kleinschmidt (1957) also explores the means by which a stratospheric air mass is detached from the main reservoir and is subsequently displaced equatorward, hypothesizing that a disturbance associated with the jet stream is likely responsible for the equatorward displacement of the stratospheric air mass and its descent toward the middle troposphere during the period of cyclogenesis. It now appears that the transverse circulations associated with "tropopause folding" (Section 3.3.2) along the axis of an upper-level jet/front system is the mechanism that acts to displace the stratospheric air down toward the 500 to 700 mb layer (Danielsen 1968; see Figs. 3.8 and 3.9). A tropopause fold is defined by Reed (1955) and Reed and Danielsen (1959) as the extrusion of stratospheric air within upper-tropospheric baroclinic zones downward from a normal tropopause level to the middle and lower troposphere. The concept of a tropopause fold complemented the studies of Reed and Sanders (1953) and Newton (1954), which pointed to a growing appreciation of the importance of subsidence in the upper and middle troposphere as a mechanism contributing to upper-level frontogenesis.

The work of Staley (1960), Bleck (1973, 1974), Boyle and Bosart (1983, 1986) and Bleck and Mattocks (1984) provides supporting evidence for the important role that tropopause folding can play in the development of surface cyclones. Staley discusses cyclogenesis in terms of a simultaneous strengthening of the vortex and tropopause folding. Bleck's analysis of numerical simulations of several cyclones, and Boyle and Bosart's case studies of an East Coast cyclone, also emphasize the simultaneous extrusion of stratospheric air into the middle and lower troposphere and surface cyclogenesis.

While the dominant theme has been to relate the *simultaneous development* of the tropopause fold and cyclogenesis, other studies indicate that a probable connection exists between upper-level frontogenesis and tropopause folding associated with jet-streak transverse circulation patterns and the subsequent development of surface cyclones. Dynamical processes that link jet systems and attending tropopause folds with the *subsequent* rapid surface cyclogenesis have been emphasized in recent case studies by Uccellini et al. (1985), Uccellini (1986) and Whitaker et al. (1988).

In the Uccellini et al. (1985) study of the Presidents' Day cyclone, which developed along the East Coast on 18–19 February 1979 (Fig. 6.9), an intensifying polar front jet (PFJ) and deepening trough were diagnosed in the central United States, 1500 km upstream of the cyclogenetic region (Fig. 6.10). A well-defined tropopause fold marked by the extrusion of stratospheric IPV values down to the 700-mb level (Fig. 6.11) could be isolated 1500 km upstream of the cyclogenetic region and 12 to 24 hours prior to the period of rapid surface development. Uccellini et al. show that subsidence along the axis of the PFJ contributed to the tropopause fold, and trace the stratospheric air mass to a position just upstream of the cyclogenetic region during the rapid development phase, using analyses based on the radiosonde network and ozone measurements by the Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus-7 polar-orbiting satellite.

Because of the data-void region off the East Coast, Whitaker et al. (1988) use a model-based diagnostic study of the same cyclone to analyze the stratospheric extrusion in the central United States and its subsequent eastward displacement toward the coastal region where rapid cyclogenesis occurred. A three-dimensional perspective of the model-simulated stratospheric extrusion and eastward displacement of this air mass was generated on the University of Wisconsin McIDAS system and is shown from a southern perspective in Fig. 6.12, with selected trajectories in Fig. 6.13 and from an eastern perspective in Fig. 6.14 at 6-hour intervals between 00 UTC and 18 UTC 19 February. The descent and horizontal advection of the 2×10^5 K mb^{-1} s^{-1} IPV surface that preceded and accompanied the intensification of the surface cyclone off the East Coast are clearly depicted in the three-dimensional illustrations. The detailed diagnostic computations that relate the stretching associated with the eastward displacement of the IPV anomaly and the associated increase in absolute vorticity, following the parcel trajectories shown in Figs. 6.13 and 6.14, can be found in the Whitaker et al. (1988) study. These results point to a more active role for the subsynoptic-scale processes associated with jet streaks and upper-level fronts in the extrusion of stratospheric air and subsequent evolution of a surface cyclone, in contrast to the concept that these processes are a passive consequence of frontogenesis or cyclogenesis, an issue discussed by Palmén and Newton (1969, pp. 256–258) and more recently by Keyser and Shapiro (1986, p. 493).

The model-simulated IPV fields depicted for the Presidents' Day storm (Figs. 6.12–6.14) also point to the importance of a separate region of high IPV confined to the lower troposphere. As discussed by Kleinschmidt (1957, pp. 134–136), Gyakum (1983b), Bosart and Lin (1984), Boyle and Bosart (1986) and Whitaker et al. (1988), diabatic processes (primarily associated with the vertical and horizontal distribution of latent heat release within a low-level baroclinic zone) contribute to the development of low-level IPV anomalies. The low-level trajectories in Figs. 6.13 and 6.14 that (1) approach the Presidents' Day storm from the east and wrap around the center, and (2) approach the storm center from the south and rise rapidly before turning anticyclonically, pass through the low-level 2×10^5 K mb^{-1} s^{-1} IPV surface

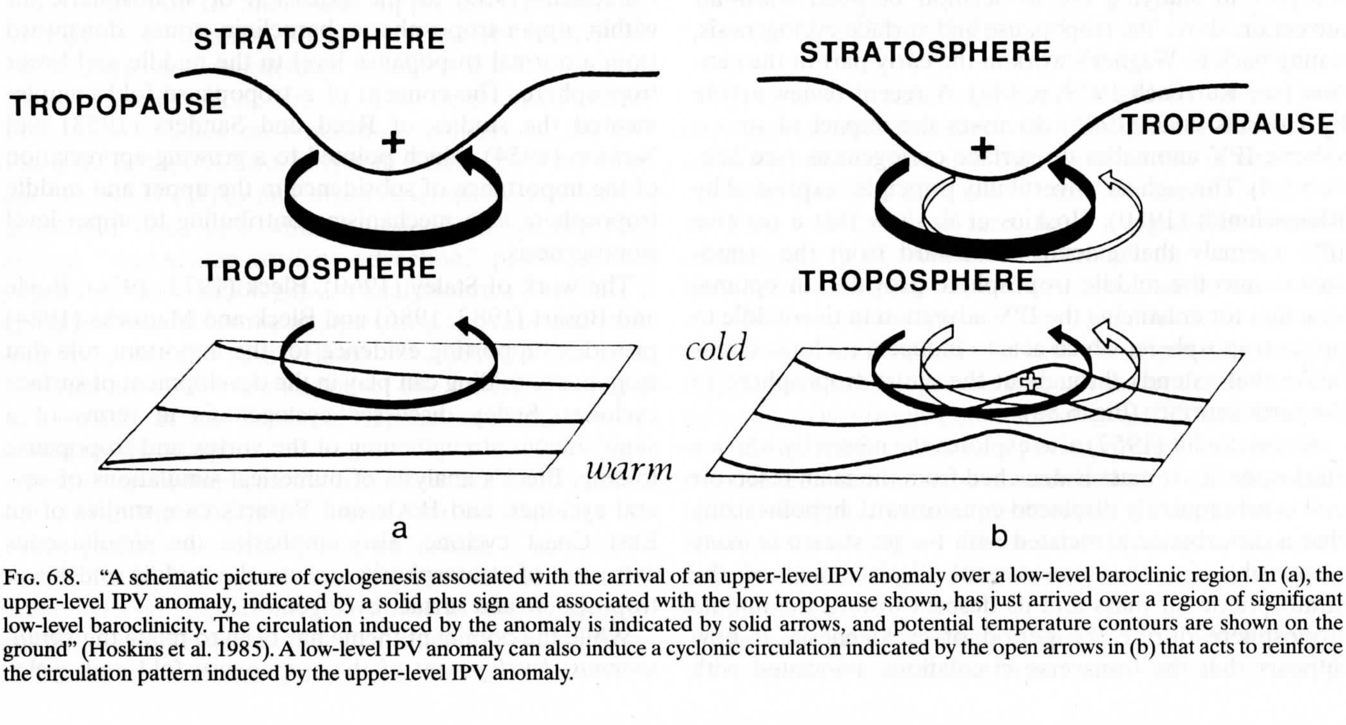

FIG. 6.8. "A schematic picture of cyclogenesis associated with the arrival of an upper-level IPV anomaly over a low-level baroclinic region. In (a), the upper-level IPV anomaly, indicated by a solid plus sign and associated with the low tropopause shown, has just arrived over a region of significant low-level baroclinicity. The circulation induced by the anomaly is indicated by solid arrows, and potential temperature contours are shown on the ground" (Hoskins et al. 1985). A low-level IPV anomaly can also induce a cyclonic circulation indicated by the open arrows in (b) that acts to reinforce the circulation pattern induced by the upper-level IPV anomaly.

along the East Coast. These parcel trajectories are influenced by the latent heat simulated by the model (Whitaker et al. 1988) and illustrate the nonconservative aspects of the low-level IPV maximum in a region of heavy precipitation. The low-level IPV maximum, and the associated thermal advection pattern, will also induce a cyclonic circulation extending upward throughout the entire troposphere (Fig. 6.8b) and add to the circulation induced by the upper-level IPV maximum, as long as the low-level anomaly remains downwind of the upper-level anomaly, maintaining a positive feedback between the two. The model results described by Whitaker et al. and illustrated in Figs. 6.12–6.14 basically confirm this hypothesis for the Presidents' Day cyclone.

6.3.3 Low-Level Processes

The previous discussion on the cyclogenetic processes as viewed from an IPV perspective provides a basis for linking upper- and lower-tropospheric processes in the evolution of a rapidly developing storm. This perspective is similar to the "type B" cyclogenesis described by Petterssen and Smebye (1971), which relates surface cyclogenesis to the superposition of cyclonic absolute vorticity advection ahead of an upper-level trough over a low-level baroclinic zone and associated thermal advection pattern as depicted in Fig. 6.8b. Both perspectives account for not only the upper-tropospheric processes associated with troughs and jet streaks but also the influence of low-level baroclinic zones in the evolution of these storms (see also Farrell 1984, 1985).

At least four low-level processes appear to influence the deepening rates of extratropical cyclones: (1) the thermal advection pattern in the lower troposphere in conjunction with the presence of low-level baroclinic zones and strong low-level winds; (2) sensible and latent heat fluxes in the boundary layer (especially over the ocean) that act to fuel these systems; (3) the decrease of the static stability in the lower troposphere related, in part, to the boundary-layer heating noted above; and (4) mountain ranges.

Charney (1947) not only recognized the importance of Bjerknes and Holmboe's (1944) paper relating upper-level trough/ridge patterns to surface cyclogenesis, but also noted that many such features are observed without surface cyclogenesis. Charney (1947) and Eady (1949) introduced the concept of baroclinic instability, which defined preferred wavelengths for an atmospheric instability that is likely to produce surface cyclogenesis, and attempted to distinguish between those troughs which induce surface development and those that do not. As discussed by Eliassen (1956), even though the baroclinic instability

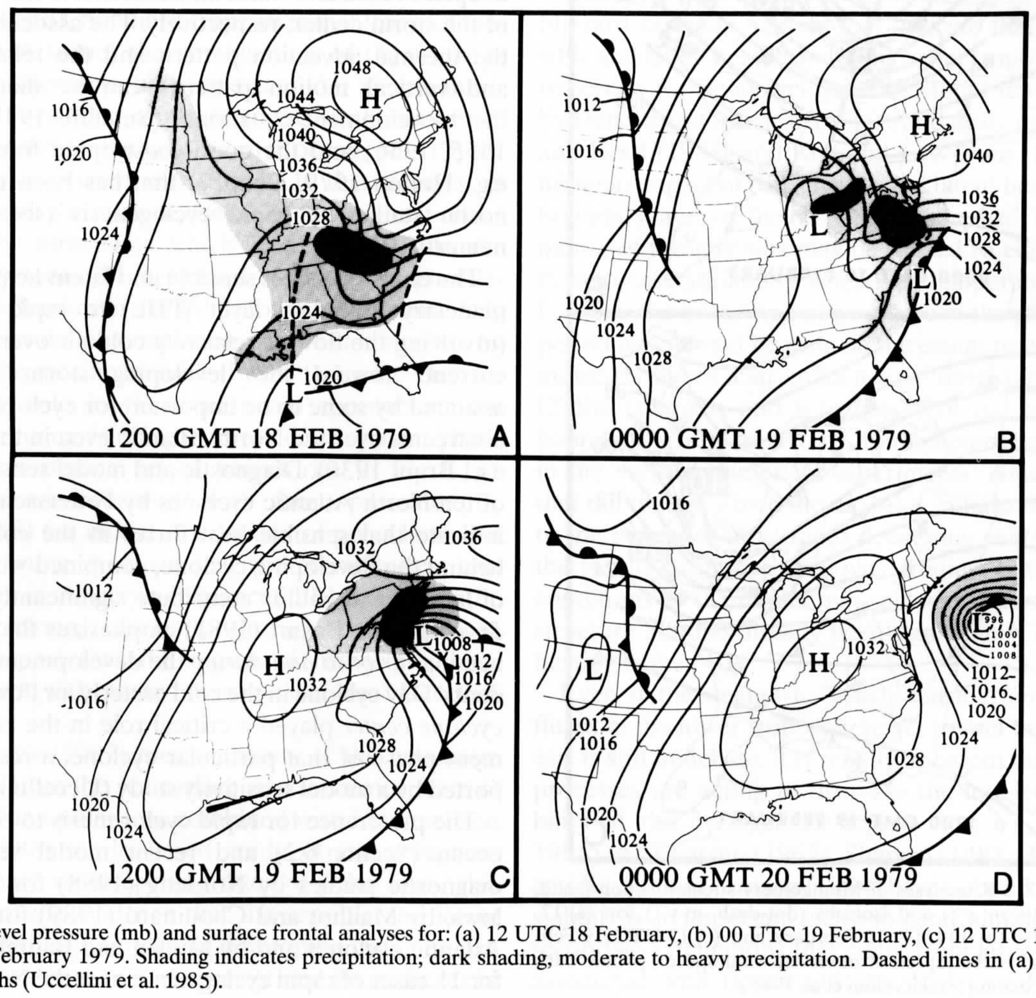

FIG. 6.9. Sea-level pressure (mb) and surface frontal analyses for: (a) 12 UTC 18 February, (b) 00 UTC 19 February, (c) 12 UTC 19 February and (d) 00 UTC 20 February 1979. Shading indicates precipitation; dark shading, moderate to heavy precipitation. Dashed lines in (a) denote inverted and coastal troughs (Uccellini et al. 1985).

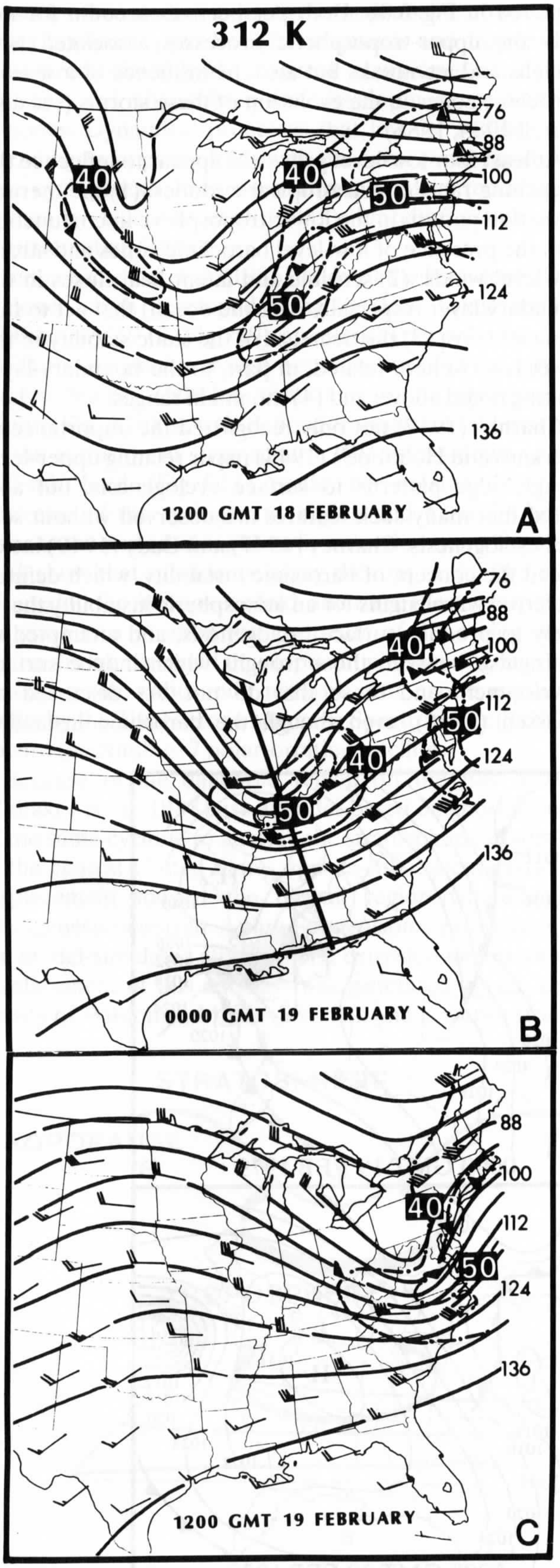

Fig. 6.10. The 312 K analyses of Montgomery streamfunction (solid, $124 = 3.124 \times 10^5$ m^2 s^{-2}) and isotachs (dot-dash, m s^{-1}) for: (a) 12 UTC 18 February, (b) 00 UTC 19 February and (c) 12 UTC 19 February 1979. Wind barbs represent observed wind speeds (whole barb 10 m s^{-1}, half barb 5 m s^{-1}) (Uccellini et al. 1985).

theories introduced by Charney and Eady do not properly account for the initial amplitude of observed trough/ridge patterns that precede cyclogenesis, these theories point to the low-level thermal structure and associated temperature advection patterns as important factors in the total evolution of cyclones. More recent theoretical work by Farrell (1984, 1985) indicates that, when treated as an initial value problem and accounting for the nonmodal aspects, baroclinic instability theory can account for a more rapid initial development when an upper-level perturbation is properly superimposed over a low-level thermal advection pattern.

As discussed as far back as Bjerknes and Solberg (1922), cyclogenesis is usually marked by a thermal field in the lower troposphere that evolves into an "S" shape pattern during the period of most rapid development. This pattern typifies the wide variety of cyclones ranging from the larger-scale storms along the east coast of the United States (Kocin and Uccellini 1990) to the meso-α-scale polar lows observed in the North Atlantic Ocean (see, e.g., Fig. 13 in Shapiro et al. 1987). This S-shaped isotherm pattern, combined with low-level winds ranging up to 40 m s^{-1} in many cases (usually taking the form of a low-level jet (LLJ)) and directed at a significant angle to the isotherms (Fig. 6.15), yields a favorable pattern for the Laplacian of the thermal advection and the well-known couplet of cold and warm air advection to the west and east of the storm center, respectively. The association between the thermal advection pattern and the relative vorticity and vertical motion patterns can be diagnosed from the "development equations" (Sutcliffe 1947; Petterssen 1955, 1956) and the quasi-geostrophic framework (see, e.g., Holton 1979, Chap. 7) that has been used in diagnostic studies of rapid cyclogenesis (see, e.g., Krishnamurti 1968).

The contribution of sensible and latent heat fluxes in the planetary boundary layer (PBL) to rapid cyclogenesis (involving the flow of relatively cold air over warm ocean currents toward the developing storm system) was assumed by some to be important for cyclogenesis in cold airstreams over the North Atlantic even in the 1920s (see, e.g., Brunt 1930). Diagnostic and model sensitivity studies of ten North Atlantic cyclones by Petterssen et al. (1962) indicate that sensible heat fluxes in the cold air stream behind the developing cyclone, combined with the release of latent heat, could "contribute significantly" to cyclone development. Bosart (1981) emphasizes that the sensible heating *prior to and during* the development of the Presidents' Day cyclone in the cold easterly air flow *ahead of the cyclone center* played a critical role in the rapid development phase of that particular cyclone, a result later supported by a model sensitivity study (Uccellini et al. 1987).

The preference for rapid cyclogenesis to occur over the ocean (Section 6.2) and recent model sensitivity and diagnostic studies by Nordeng (1988) for several polar lows, by Mailhot and Chouinard (1989) for three North Atlantic cyclones and by Mullen and Baumhefner (1988) for 11 cases of rapid cyclogenesis over the North Pacific all

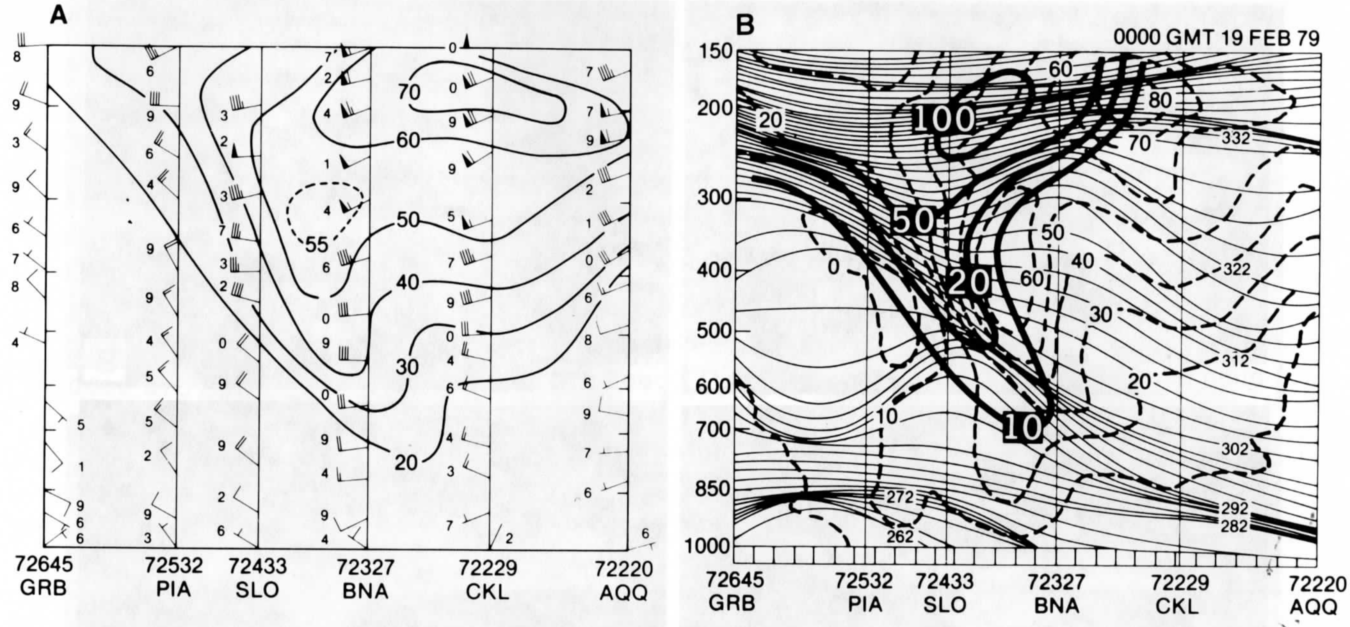

FIG. 6.11. Vertical cross section from Green Bay, Wisconsin to Apalachicola, Florida, along heavy line in Fig. 6.10b, at 00 UTC 19 February 1979. (a) Isotach analysis for total wind speed (m s^{-1}); wind barbs plotted as in Fig. 6.10 with last digit of observed speed. (b) Isentropes (solid, K), geostrophic wind speed normal to plane of cross section (dashed, m s^{-1}) and potential vorticity (dark solid, 10 = 10×10^{-6} K mb^{-1} s^{-1}) (Uccellini et al. 1985).

indicate that the rate of cyclogenesis is enhanced by the sensible and latent heat fluxes within the ocean-influenced PBL. Mailhot and Chouinard emphasize that (for cyclones in the North Atlantic) the combination of (1) the large temperature differences between the colder air streaming off the North American continent to the north and east of the cyclone and the relatively warmer ocean, plus (2) the strong winds associated with the LLJs that develop in conjunction with the cyclone, yields large total heat fluxes that affect the airstreams which feed directly into the developing cyclones. Model-based trajectory diagnostics provided by Whitaker et al. (1988) for the Presidents' Day storm show that the potential temperature can increase by 1 K h^{-1} and the specific humidity by 0.5 to 1 g kg^{-1} h^{-1} for parcels in the cold low-level airstream approaching the cyclone from the east during its rapid development phase (i.e., the yellow-orange set of trajectories in Fig. 6.13). These results are consistent with those presented by Nordeng (1988) for model simulations of polar lows and provide supporting evidence that the sensible heat and moisture fluxes in the ocean-influenced PBL act to fuel the developing cyclone, especially through the enhanced moisture transport into the region of heavy precipitation associated with these storms (see also Uccellini et al. 1984).

Shapiro et al.'s (1987) measurements of the maximum total heat flux from the sea surface into the atmosphere of 1000 W m^{-2} for a polar low, combined with Emanuel and Rotunno's (1988) model-based study of the influences these fluxes have on deepening rates of polar lows, also provide supporting evidence that the sensible and latent heat fluxes contribute to rapidly developing cyclones. Yet the issue of the direct role of sensible and latent fluxes in rapid cyclogenesis is not entirely resolved. Cases of major storms over land masses (such as the 25–26 January 1978 blizzard noted in Section 6.2) indicate that perhaps sensible and latent heat fluxes in the lower troposphere are not necessary for rapid cyclogenesis. Model sensitivity studies by Danard and Ellenton (1980), and more recently by Kuo and Reed (1988) and Kuo and Low-Nam (1989), show a minimal impact of the sensible and latent heat fluxes in the boundary layer on the rate of cyclogenesis. The contrasting nature of these results may be related to either (1) a large case-to-case variability where the temperature difference between the ocean and atmosphere in the precyclogenetic period has a direct bearing on the extent to which heat and moisture fluxes can influence a developing storm, or (2) the strengths and weaknesses of the various model boundary-layer parameterization schemes being employed in the various numerical experiments. Another factor is that the time at which the model is initialized with respect to the period of most rapid deepening can also influence the results of model sensitivity studies, in that the initial conditions of the model may include a thermal and wind structure that has already been significantly influenced by heating in the PBL.

Even if the degree to which sensible and latent heat fluxes in the lower troposphere act to fuel rapid cyclogenesis is still in debate, it is readily apparent that these same processes are acting to decrease the low-level static stability in the cyclogenetic region (see, e.g., Smith et al. 1988). As Eliassen (1962), Shapiro (1981), Bosart (1981) and Keyser and Carlson (1984) have pointed out, the static stability is an important factor in determining the nature of secondary circulations that result from large-scale forcing associated with fronts and jets. Staley and Gall (1977)

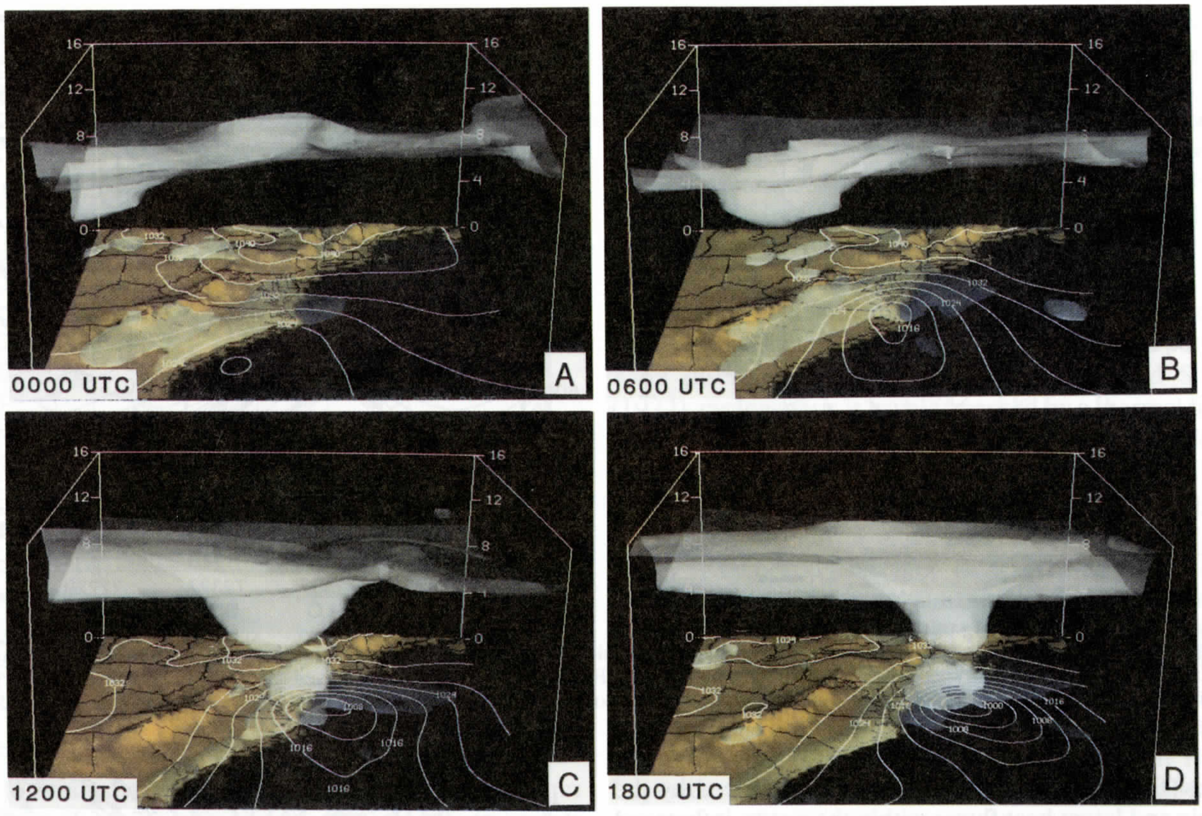

FIG. 6.12. Three-dimensional perspectives, as viewed from the south, of the 2×10^{-5} K mb^{-1} s^{-1} IPV surface, and sea-level pressure isobar pattern (mb) derived from the numerical simulation of the Presidents' Day cyclone of Whitaker et al. (1988) for (a) 00 UTC, (b) 06 UTC, (c) 12 UTC and (d) 18 UTC 19 February 1979. The three-dimensional perspectives were derived by William Hibbard using the University of Wisconsin, Space Science and Engineering Center, three-dimensional McIDAS system.

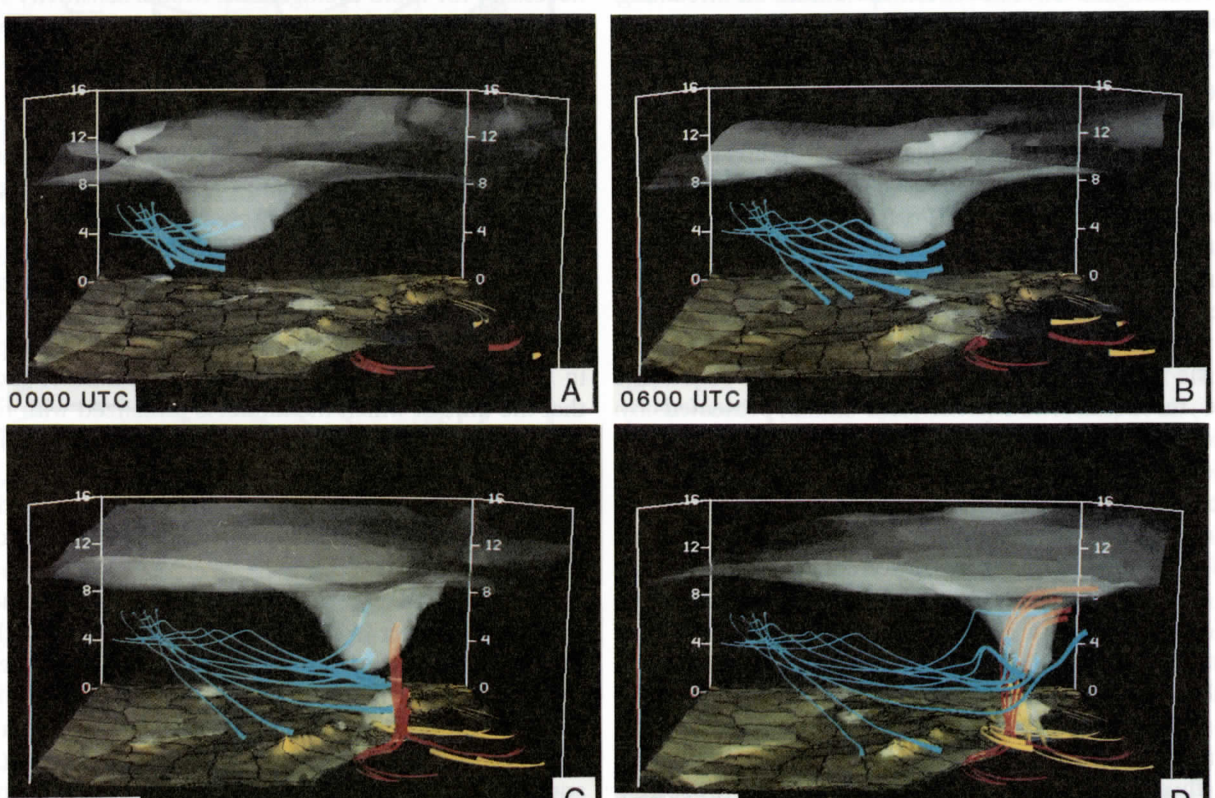

FIG. 6.13. Three-dimensional potential vorticity perspective as in Fig. 6.12, but with sea-level pressure analyses removed and trajectories included, derived from 15-min model output as described by Whitaker et al. (1988). Blue trajectories originate within stratospheric extrusion west and north of the cyclone; yellow and red trajectories originate in the low levels within the ocean-influenced planetary boundary layer.

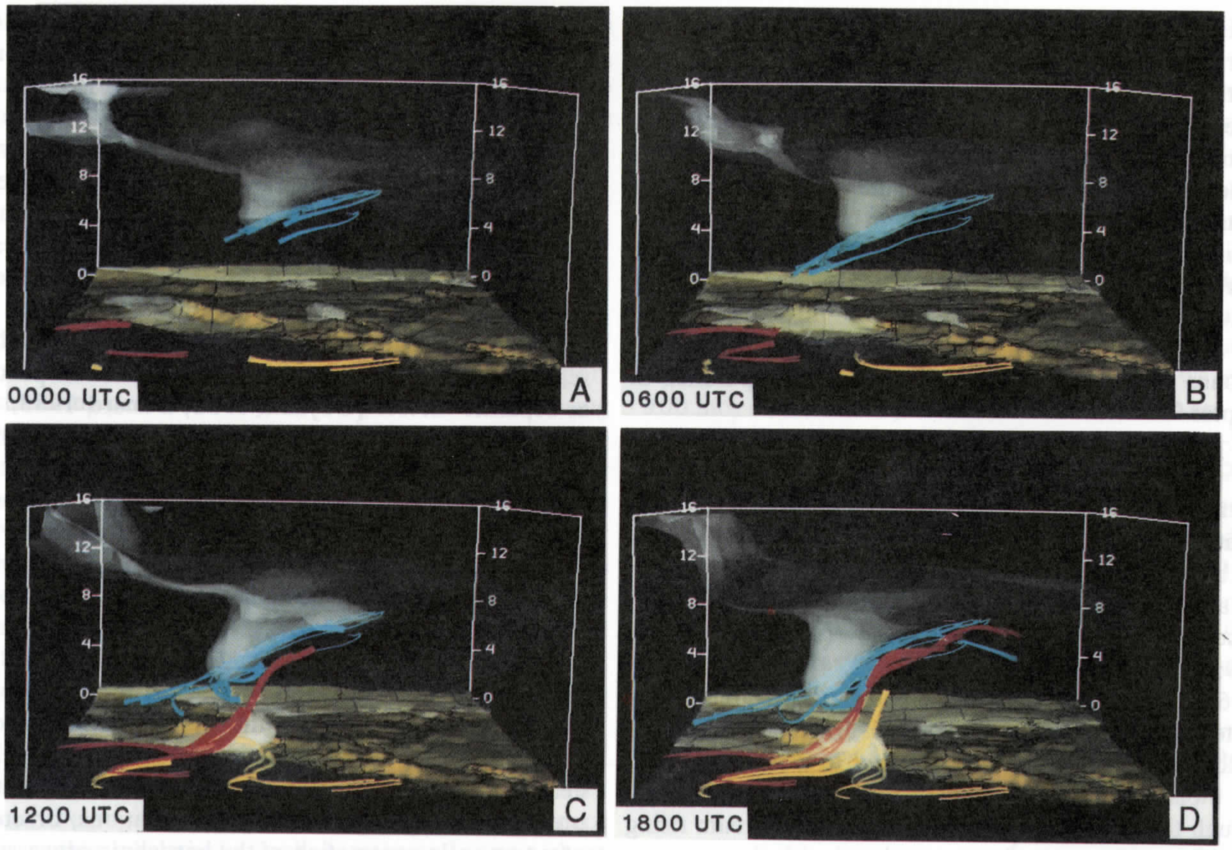

FIG. 6.14. Three-dimensional, model-generated potential vorticity perspective and trajectories as in Figs. 6.12 and 6.13, but as viewed from an eastern perspective, illustrating the slope nature of both the potential vorticity surface and the trajectories approaching the storm from the south.

conclude that the baroclinic growth rates are very sensitive to decreased static stability in the lower troposphere, again pointing to the important influence of PBL heating on rapid cyclogenesis. Wash et al. (1988) use model-based data sets to show that sensible heating of the atmosphere over the warmer ocean surface reduces the static stability prior to and during rapid cyclogenesis over the Pacific Ocean. They note that the decreased static stability effectively reduces the braking tendency of vertical motion on cyclogenesis, such that low-level convergence and upper-level divergence can more readily increase in magnitude during the rapid development phase of the storm. The increased sensible and latent heat fluxes also tend to decrease the symmetric stability (Sections 5.2.1, 5.6.1, 9.6), a process that tends to render the atmospheric conditionally unstable to "slantwise convection" (Emanuel 1983). Kuo and Reed (1988) use a model simulation of the November 1981 North Pacific cyclone (Fig. 6.4) to diagnose that the rapid sloped-ascent (and associated low-level convergence and increasing absolute vorticity) was focused within a region in which the model atmosphere has been affected by sensible and latent heat fluxes (and other processes as well), and which was marked by neutral (to slightly unstable) symmetric stability.

Finally, although the emphasis in this chapter has been on rapid cyclogenesis which occurs over the ocean, orographical features play an important role in enhancing cyclogenesis in some areas. For example, case studies and numerical experiments demonstrate that the Alps exert a significant modifying influence on large-scale flow patterns and jet-streak circulation patterns that contribute to rapid cyclogenesis in the Ligurian Sea just to the west of Italy (Buzzi and Tibaldi 1978; Bleck and Mattocks 1984; Mattocks and Bleck 1986). As discussed by Newton (1956)

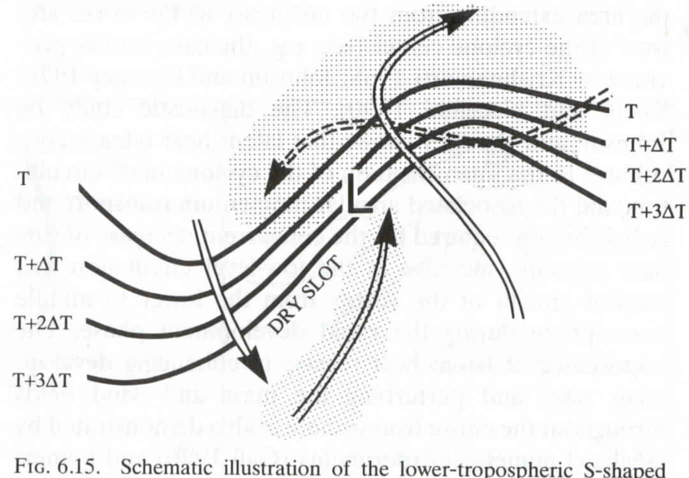

FIG. 6.15. Schematic illustration of the lower-tropospheric S-shaped isotherm pattern and asymmetric cloud distribution associated with rapid cyclogenesis. The "dry slot" indicates region where stratospheric air approaches cyclone. Areas of strong low-level wind maxima or low-level jets which act to enhance thermal advection pattern also indicated with arrows.

and Hovanec and Horn (1975), the Rocky Mountains also contribute to cyclogenesis through vortex tube stretching and the subsequent concentration of absolute vorticity to the lee of the mountains. The Appalachian Mountains play a significant role in influencing the low-level thermal fields (principally by the "damming" of the cold air along the coastal plain) which, along with coastal frontogenesis, provides a low-level baroclinic zone in the Carolinas which contributes to coastal cyclogenesis (see, e.g., Baker 1970; Richwien 1980; Bosart 1981; Stauffer and Warner 1987; Bell and Bosart 1988). The influence of orography on cyclones is covered by Tibaldi, Buzzi and Speranza in Chapter 7.

6.3.4 Latent Heat Release

Perhaps the most common feature of rapidly-developing extratropical cyclones is that these storms are characterized by an asymmetric distribution of clouds, precipitation and an associated vertical motion pattern with respect to the center of the developing surface low (see, e.g., Bjerknes 1919; Palmén and Newton 1969, p. 284). As depicted in Fig. 6.15, an extensive area of clouds and precipitation is located on the poleward side of the surface low. The area of clouds and precipitation is related to a relatively cold and moist easterly flow that is ascending and moving through the storm system, and to a warm airstream rising rapidly over the warm front associated with these storms (see Fig. 6.13). A clear dry slot extends from the west of the surface low toward the equatorward side, which is related to the descending stratospheric airstream discussed in the previous section (see Figs. 6.13 and 6.14). These "dry," "cold" and "warm" "conveyor belts" are described in detail by Carlson (1980), Young et al. (1987) and Browning, who presents a general review of airflow in cyclones in Chapter 8.

In all of the case studies reviewed for this paper, the onset of most rapid deepening of the surface cyclone coincides with the development of heavy precipitation in the area extending from the northeast to the north and west of the cyclone center (see, e.g., the case studies provided by Krishnamurti 1968; Johnson and Downey 1976; Kocin and Uccellini 1990). The diagnostic study by Johnson and Downey shows that latent heat release contributes to the intensification of the cyclone mass circulation and the associated angular momentum transport and redistribution required for the concurrent decrease of surface pressure, increase in the low-level circulation and vertical growth of the vortex from the lower to middle troposphere during the rapid development phase. The importance of latent heat release in enhancing development rates and perturbing the mass and wind fields throughout the entire troposphere is also demonstrated by idealized numerical experiments (Gall 1976) and numerous model sensitivity studies, most notably those of Danard (1964) and Chang et al. (1982). Model-based energy diagnostic studies, performed for wet and dry simulations of several cyclones in the central United States, demonstrate that latent heat release provides an important energy source for these storms (Robertson and Smith 1983; Kenney and Smith 1983; Chang et al. 1984; Dare and Smith 1984).

Yet questions remain concerning the relative importance of latent heat release, which is difficult to assess given the interaction of this physical process with the boundary-layer and free-atmospheric processes discussed earlier. Several studies have pointed out the difficulty of treating sensible heat and moisture fluxes in the boundary layer and their subsequent influence on convective (subgrid-scale) or stable (grid-resolvable) precipitation processes as separate factors (Ooyama 1982; Danard 1983, 1986; Emanuel and Rotunno 1989). Latent heat release also can have a direct and immediate impact on the structure and dynamics of the upper-level trough/ridge systems and jet streaks which then act to enhance cyclogenesis, a point recently emphasized by Chang et al. (1982), Uccellini et al. (1987), Manobianco (1989) and discussed in Section 6.4. Latent heat release can focus the dynamic processes and associated vertical motion pattern on a smaller scale (Emanuel 1985), which may then act to enhance the baroclinic processes that affect the development rate of the storm system. A question that arises is whether the latent heat is directly responsible for the decrease in sea-level pressure through hydrostatic considerations, or contributes to a scale contraction of the baroclinic processes that is essential for the mesoscale dynamic processes that enhance deepening rates, or both. Given this range, it may not be possible to assign a specific percentage to a separate physical process while attempting to determine its relative impact on development rates of cyclones.

The role of convection in enhancing cyclogenesis also remains unresolved. Hypotheses have been presented that convective cells near the storm center play an active role in contributing to and even initiating rapid cyclogenesis (Tracton 1973; Bosart 1981; Gyakum 1983b). However, the evidence presented to support these hypotheses is still inconclusive. Model sensitivity studies using actual data (Danard 1986; Leslie et al. 1987); theoretical studies using axisymmetric models (Shutts et al. 1988); and linear CISK models (Økland 1987), demonstrate significant sensitivity of simulated surface low-pressure systems to latent heat release associated with convection. Other studies show little or no impact related to the inclusion of convective parameterization schemes in numerical model systems (see, e.g., Mullen and Baumhefner 1988; Reed et al. 1988; Mailhot and Chouinard 1989).

As noted for the boundary layer issues, these diverging results may point to model deficiencies, case-to-case variability, or both. In either event, the impact of convection on rapid cyclogenesis has not been clearly demonstrated, nor has the means by which convection may actually decrease the sea-level pressure over a large domain for an extended period of time been shown in a convincing manner. Indeed, even in the CISK-type papers that relate convection to cyclone development, there is a disagreement as to whether heating associated with the convection decreases the surface pressure (e.g., Rasmussen 1979; Danard 1983) or the warming related to compensating subsidence acts to decrease the surface pressure (Sardie and Warner 1985).

6.4 Feedback Between Diabatic and Dynamical Processes During Rapid Cyclogenesis

The various physical processes discussed in Section 6.3 and their potential for complex nonlinear interactions on the mesoscale (both space and time) have set the stage for the most recent debates concerning their relative importance during periods of rapid cyclogenesis. An increasing number of model-based sensitivity studies (see Sections 11.6 and 12.3.2) and diagnostic analyses of major cyclone events indicates that the individual dynamic and diabatic processes should be looked upon as necessary for rapid cyclogenesis, but not sufficient to produce these storm systems when acting alone. That is, the rapid development phase of extratropical cyclones is dependent not on the individual contribution of these physical processes, but on nonlinear synergistic interactions among them (see also Section 12.3.2g).

The problem in assessing the relative contributions of various physical processes to rapid cyclogenesis revolves around the rapid feedback that occurs among the processes within a relatively small domain and over a short period of time. For example, if sensible heat fluxes east or northeast of a surface low act to increase the temperature gradients (as shown in Figs. 6.16a,b), the developing low is affected by not only the increases of heat and moisture in the PBL but also the baroclinic processes associated with the increased temperature gradients and the resultant thermal advection pattern. The feedback does not stop there. A more intense low-level baroclinic zone depicted in Fig. 6.16b could be expected to contribute to stronger low-level wind speeds that could further enhance the warm-air advection pattern and deepening rate of the storm (Fig. 6.16c).

The increase of wind speed depicted in Fig. 6.16c is related to two factors: 1) an isallobaric contribution due to the change of the pressure gradient force associated with the deepening cyclone and 2) the vertical parcel displacement in a region where the pressure gradient force changes with height. As shown in Fig. 6.17, the vertical parcel displacement east and northeast of a developing surface cyclone (enhanced by the sensible and latent heat fluxes and latent heat release) can lead to a situation in which the parcel passes from one level, marked by a closed circulation (e.g., 850 mb) in which the parcel is in a relatively balanced state, to a level marked by an open wave (e.g., 700 mb) in which the parcel is now directed toward lower geopotential heights and accelerates rapidly. Model-based trajectory results described by Uccellini et al. (1987) and Whitaker et al. (1988) illustrate that this process operates over a very short period of time (2 to 4 hours) and contributes to ageostrophic wind speeds approaching 50 m s^{-1} and subsequent rapid parcel acceleration. Their results confirm Durst and Sutcliffe's (1938), Godson's (1950) and Newton and Palmén's (1963, p. 115) discussions on the

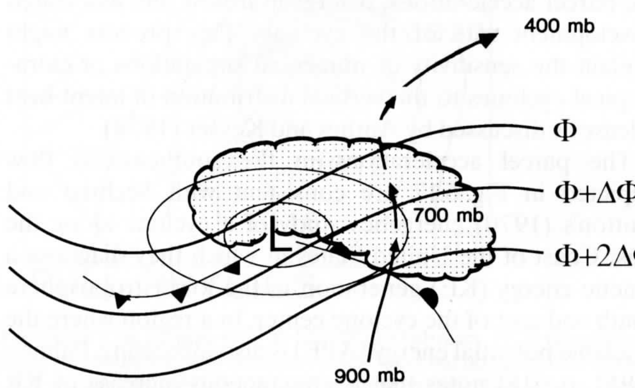

FIG. 6.17. Schematic illustration of the vertical displacement of a parcel trajectory approaching the cyclone from the south-southeast and passing through the area of precipitation associated with the cyclone and crossing the geopotential contours at the 700-mb level (marked by an open wave) at a significant angle.

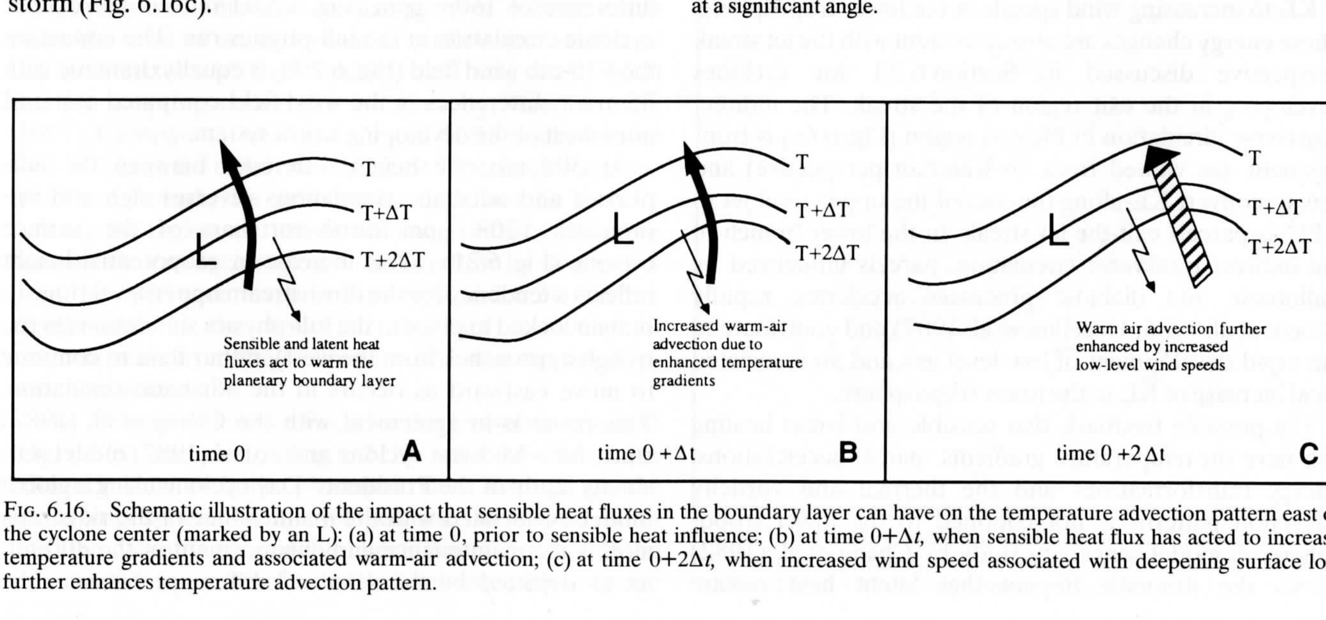

FIG. 6.16. Schematic illustration of the impact that sensible heat fluxes in the boundary layer can have on the temperature advection pattern east of the cyclone center (marked by an L): (a) at time 0, prior to sensible heat influence; (b) at time 0+Δt, when sensible heat flux has acted to increase temperature gradients and associated warm-air advection; (c) at time 0+2Δt, when increased wind speed associated with deepening surface low further enhances temperature advection pattern.

association between organized vertical motion patterns and the horizontal wind acceleration.

The acceleration of the east to southeasterly flow through the precipitation region near the 700- to 600-mb layer (Fig. 6.17) is generally located beneath the more southwesterly flow aloft associated with the upper-level trough/ridge system. Whitaker et al. (1988) show that, for the model simulation of the Presidents' Day cyclone, the transition layer between the accelerating southeasterly and southwesterly flow regimes marked the region in which the mass divergence increased to a maximum during the rapid development phase of that storm. These results indicate that the deepening rates of extratropical storms are related to a complex interaction between thermodynamic and dynamic processes, which is dependent on the spatial configuration of the pressure gradient force and the horizontal and vertical distributions of latent heat release (Fig. 6.16). From the perspective presented in Fig. 6.17, the release of latent heat poleward and east of a developing cyclone, within the transition layer between a closed circulation pattern in the lower troposphere and an open wave aloft, would be especially important for enhancing the parcel accelerations, divergent airflow and associated development rate of the cyclone. This process might explain the sensitivity of numerical simulations of extratropical cyclones to the vertical distribution of latent heat release as discussed by Anthes and Keyser (1979).

The parcel accelerations in the southeasterly flow depicted in Fig. 6.17 are consistent with Sechrist and Dutton's (1970) energetics study of a cyclone along the East Coast of the United States in which they diagnose a kinetic energy (KE) generation in the lower troposphere south and east of the cyclone center, in a region where the available potential energy (APE) is also increasing. Palmén (1951, p. 618) notes that a simultaneous increase of KE and APE accompanies the initial period of cyclogenesis, wherein the increase of APE is related to frontogenesis within the middle and upper troposphere and the increase in KE to increasing wind speeds in the lower troposphere. These energy changes are also consistent with the jet streak perspective discussed in Section 6.3.1 for cyclones developing in the exit region of the streak. The indirect transverse circulation in the exit region (Fig. 6.6a) is frontogenetic (as viewed from an Eulerian perspective) and acts to convert KE along the axis of the upper-level jet to APE as parcels exit the jet streak. In the lower branch of the indirect transverse circulation, parcels influenced by isallobaric and diabatic processes accelerate rapidly (Kocin et al. 1986; Uccellini et al. 1987) and contribute to the rapid development of low-level jets and an associated local increase of KE in the lower troposphere.

The possible feedback that sensible and latent heating can have on temperature gradients, parcel accelerations, energy transformations and the thermal and vorticity advection patterns is not confined to the lower troposphere. A model sensitivity study by Chang et al. (1982) shows the dramatic impact that latent heat release can have upon the temperature, geopotential height and wind fields throughout the entire troposphere. Similar results are obtained for a series of numerical simulations conducted for the Presidents' Day cyclone, which are presented below.

Three 24-hour model simulations, initialized at 12 UTC 18 February, were run to illustrate the sensitivity of the full-physics numerical simulation of the Presidents' Day cyclone (used to depict the IPV fields in Figs. 6.12–6.14) to the incorporation of boundary-layer physics and latent heat release. The 58-km grid, 32-level σ-coordinate numerical model, the initialization procedure and the full-physics simulation are described by Whitaker et al. (1988). The other three model runs include an adiabatic simulation, a simulation that includes the effect of latent heat release but no boundary-layer fluxes, and a simulation with the boundary-layer fluxes included but not the effects of latent heat release, following the experimental design described by Uccellini et al. (1987).

The sea-level pressure (SLP) maps derived from the four simulations are shown in Fig. 6.18. The adiabatic simulation produces only a weak inverted trough (Fig. 6.18a). Including either latent heat release (Fig. 6.18b) or boundary-layer fluxes (Fig. 6.18c) produces only a modest impact on the deepening rate. There is, however, a major impact on the simulated cyclone when both the boundary-layer fluxes and latent heat release are included (Fig. 6.18d). The 32-mb difference between the full-physics simulation and the adiabatic simulation (Fig. 6.19) illustrates the dramatic influence that the diabatic processes can exert upon an extratropical storm, when these processes are acting in a synergistic mode with the upper-level trough/ridge pattern and jet streaks, as described for the initial development phase of this storm by Uccellini et al. (1987).

The difference in the circulation pattern between the full-physics and adiabatic simulations extends throughout the entire troposphere. At 850 mb, the geopotential height difference of 160+ gpm (Fig. 6.20a) reflects the deeper cyclonic circulation in the full-physics run. The impact on the 850-mb wind field (Fig. 6.20b) is equally dramatic with 35 m s^{-1} differences in the wind field computed east and northwest of the developing storm system.

At 300 mb, the height difference between the full-physics and adiabatic simulations reverses sign and approaches 120+ gpm north-northeast of the surface cyclone (Fig. 6.21a). This increase in geopotential height reflects a tendency for the downstream upper-level ridge to remain locked in place in the full-physics simulation (as the trough approaches from the west), rather than to continue to move eastward as occurs in the adiabatic simulation. This result is in agreement with the Chang et al. (1982) study for a Midwest cyclone and Atlas' (1987) model sensitivity study of the Presidents' Day cyclone using a global model. Associated with the maintenance of the ridge axis aloft is the maintenance and enhancement of the 300-mb jet as depicted by the 40 m s^{-1} difference between the

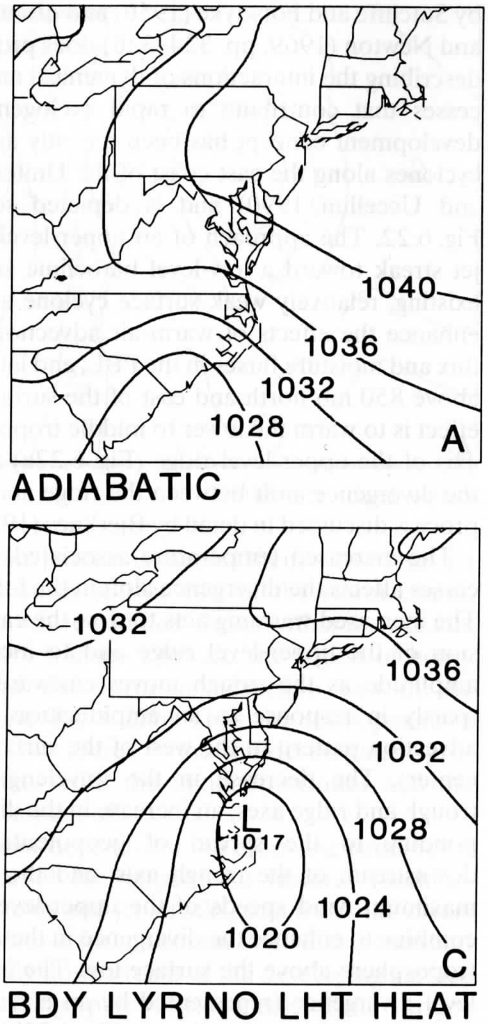

FIG. 6.18. Sea-level pressure analyses from 24-h model simulations of the Presidents' Day cyclone valid at 12 UTC 19 February 1979: (a) adiabatic simulation; (b) simulation with latent heat included but no boundary-layer fluxes; (c) simulation with boundary-layer fluxes but no latent heat release; and (d) full-physics simulation. Total precipitation greater than 2.0 cm for full-physics run indicated by light shading; greater than 4.0 cm, darker shading. See also Fig. 12.14.

full-physics and adiabatic simulations (Fig. 6.21b), which takes the form of an anticyclonic "outflow jet" similar to that isolated for a Midwest cyclone by Chang et al. (1982) and for a spring convective complex by Maddox et al. (1981). Comparison of Figs. 6.21 and 6.19 reveals that the area of maximum difference in the SLP between the adiabatic and full-physics simulations does not lie directly beneath the region marked by enhanced ridging aloft, but beneath the entrance region of this outflow jet. It appears from the difference maps in Figs. 6.19 and 6.21 that the acceleration of the flow into this jet is acting to evacuate mass from the column located over the developing storm system.

The 300-mb difference fields for the geopotential height (Fig. 6.21a) and wind (Fig. 6.21b) attest to the major influence that diabatic processes have throughout the entire troposphere during cyclogenesis. There is no doubt that the latent and sensible heat fluxes are acting to enhance the upper-level ridge and subsequently increase

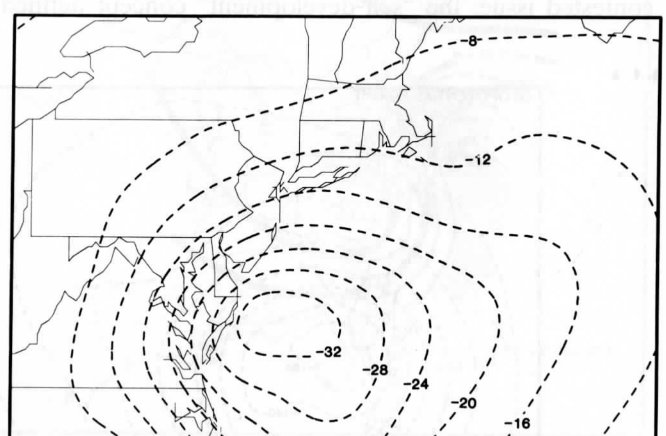

FIG. 6.19. Difference in the sea-level pressure (mb) between the 24-h full-physics and adiabatic model simulations of the Presidents' Day storm valid at 12 UTC 19 February as shown in Fig. 6.18.

the wind speeds aloft for this case. It appears from this experiment, however, that attempts to place the upper-level ridge directly above the developing surface low or directly above the region of maximum precipitation (Rasmussen 1979; Danard 1983) are not appropriate to describe the impact that latent heat release has on the upper-level height and wind fields during extratropical cyclogenesis. The region of maximum precipitation and latent heat release (Fig. 6.18d) and largest SLP difference between the adiabatic and full-physics run (Fig. 6.19) is 350 km upstream of the region marked by the largest positive geopotential height differences at 300 mb (Fig. 6.21a). The ridging aloft is located directly over the region where the 850-mb warm-air advection pattern is enhanced due to the increased wind speeds and cyclonic circulation pattern in the low levels (Fig. 6.20). These characteristics in the 300- and 850-mb difference fields indicate that the enhanced warm-air advection pattern in the lower troposphere is also an important factor in maintaining and enhancing the upper-level ridge and associated upper-level jet northeast of the surface low. The asymmetry in the difference fields between the adiabatic and full-physics simulations and associated downwind displacement of enhanced ridging aloft from the center of the surface low is in agreement with Palmén's (1951, pp. 610–611) discussion on the asymmetric nature of extratropical cyclones. Palmén emphasized that this factor is critical for describing the vertical distribution of vorticity and divergence required for the simultaneous decrease in the SLP and convergent cyclonic air flow in the lower troposphere, and the divergent anticyclonic air flow in the middle troposphere immediately downstream of the low-pressure center.

6.4.1 Sutcliffe's Self-Development Concept

While the problem of defining necessary conditions that are applicable to all rapidly developing cyclones remains a contested issue, the "self-development" concept defined by Sutcliffe and Forsdyke (1950) and discussed by Palmén and Newton (1969, pp. 324–326) does provide a basis for describing the interactions of dynamical and diabatic processes that contribute to rapid cyclogenesis. The self-development concept has been recently applied to major cyclones along the east coast of the United States (Kocin and Uccellini 1990) and is depicted schematically in Fig. 6.22. The approach of an upper-level trough and/or jet streak toward a low-level baroclinic zone and a pre-existing, relatively weak surface cyclone act to focus and enhance the effects of warm-air advection, sensible heat flux and moisture fluxes in the PBL, and latent heat release above 850 mb north and east of the surface low. The net effect is to warm the lower to middle troposphere near the axis of the upper-level ridge (Fig. 6.22a) and to increase the divergence aloft between the ridge and trough axes, a process discussed in detail by Bjerknes (1951, p. 599).

The increased temperature associated with these processes affects the divergence aloft in the following manner. The increased warming acts to slow the eastward progression of the upper-level ridge and to increase the ridge amplitude as the trough moves eastward and amplifies (partly in response to an amplification in the cold-air advection pattern to the west of the surface low-pressure center). The decrease in the wavelength between the trough and ridge axes, an increase in the diffluence corresponding to the spread of geopotential height lines downstream of the trough axis, and the increase in the maximum wind speeds of the upper-level jet streaks all combine to enhance the divergence in the middle to upper troposphere above the surface low. The increased upper-level divergence (represented by an enhancement of the cyclonic vorticity advection in Fig. 6.22b) acts to deepen the cyclone even further.

As the surface low deepens, the lower-tropospheric wind field surrounding the storm increases in intensity, especially to the north and east of the low, where the contribution of isallobaric effects and vertical motions to the

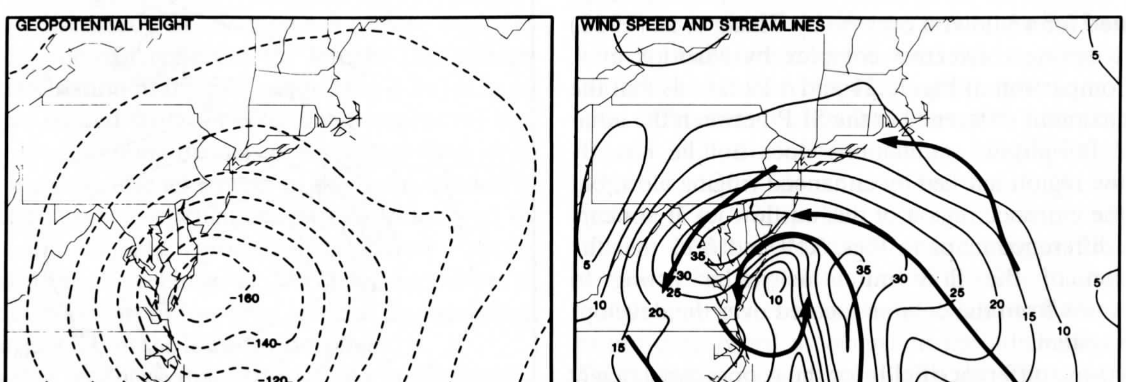

FIG. 6.20. (a) Difference in the 850-mb geopotential height field (gpm) and (b) isotachs (m s^{-1}) and streamlines of the wind field difference between the 24-h full-physics and adiabatic model simulations of the Presidents' Day storm valid at 12 UTC 19 February.

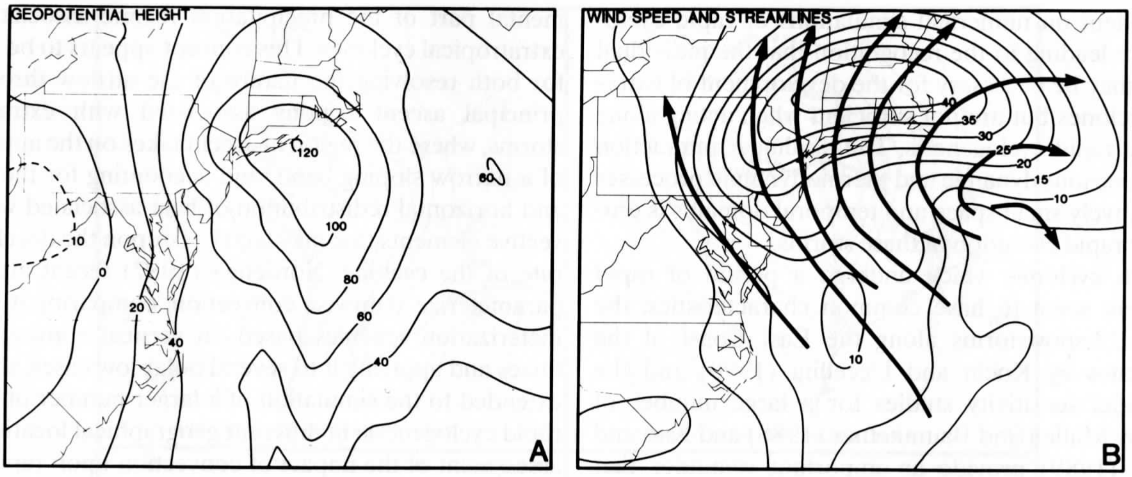

FIG. 6.21. Same as Fig. 6.20, but for the 300-mb level.

acceleration of air parcels is large. Often, a low-level jet develops to the north and/or east of the storm center, enhancing the moisture and heat fluxes within the oceanic PBL, the moisture transport toward the region of heavy precipitation and the warm-air advection east of the developing cyclone (Fig. 6.22b). Thus, the development of the LLJ further contributes to the self-development process that continues until the cyclone occludes and the heating is effectively cut off.

Self-development depends on the following conditions: (1) the existence of the upper-level features (such as trough/ridge systems and jet streaks) that focus the divergence aloft, conducive for maximum mass divergence and ascent immediately downstream of the developing surface low; and (2) warming (poleward and east of the surface low) due to diabatic processes and an enhanced thermal advection pattern associated with a lower-tropospheric baroclinic zone and strong low-level winds. The concept accounts for not only the adiabatic quasi-geostrophic framework that has been applied to cyclogenesis (Holton 1979, Chap. 7) but also the various interactions among the dynamic and diabatic processes discussed earlier. The asymmetric character of extratropical cyclones depicted in Fig. 6.15 and emphasized by Palmén (1951), and the convergence of the distinctly different airstreams illustrated in Figs. 6.13 and 6.14 and described by Carlson (1980), are also accounted for. As such, Sutcliffe's self-development concept represents a basis upon which the contribution of the various physical processes to rapid cyclogenesis can be described.

6.5 Summary and Issues

The study of extratropical cyclogenesis has been a focus of active meteorological research for at least the past 150 years, marked by alternating emphasis on the thermodynamic and dynamic processes that contribute to these systems. Upper-level trough/ridge systems, jet streaks, low-level fronts and jets, latent heat release, sensible and latent heat fluxes in the planetary boundary layer, sea surface temperatures and (in some areas) mountain ranges have been shown to be important factors in cyclogenesis. However, recent diagnostic analyses (based to a

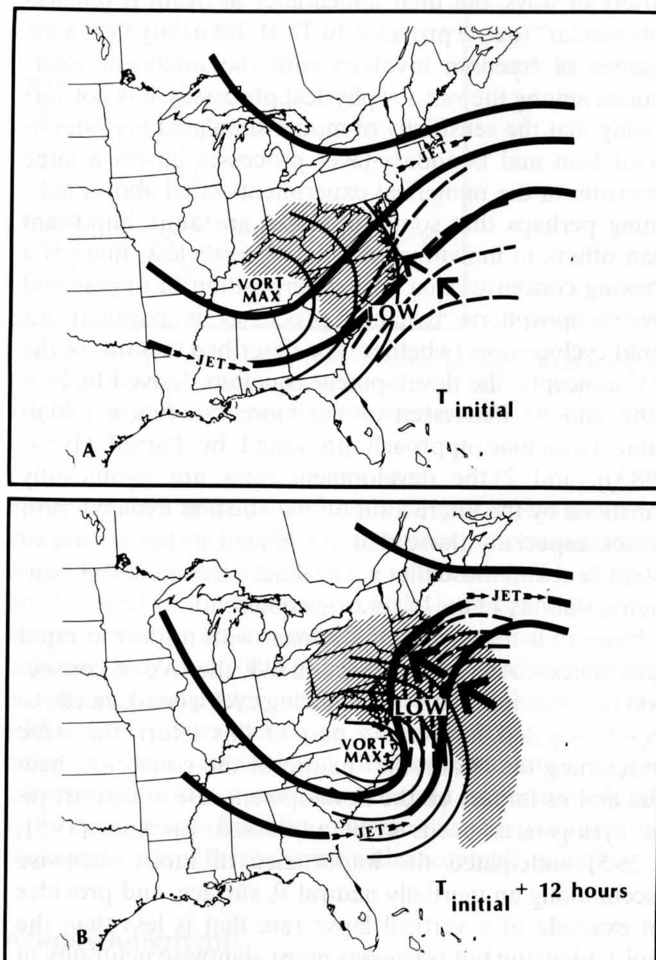

FIG. 6.22. Schematic illustration of the self-development concept postulated by Sutcliffe and Forsdyke (1950), illustrating how the temperature advections, sensible heat and moisture fluxes in the PBL, and latent heat release associated with cyclogenesis, enhance the amplitude and decrease the wavelength of the upper-level trough/ridge system which contributes to an increase in upper-level divergence (increased PVA) that further enhances cyclogenesis (Kocin and Uccellini 1990).

growing extent on numerical simulations of rapid cyclogenesis) are leading to the recognition that the individual processes may be necessary for the development of extratropical cyclones but are not sufficient when acting alone to produce rapid cyclogenesis. The nonlinear interaction among the various dynamic and thermodynamic processes within relatively small space and temporal domains is crucial for the rapid evolution of these storms.

Although cyclones which undergo a period of rapid development seem to have common characteristics, the review of 23 snowstorms along the East Coast of the United States by Kocin and Uccellini (1990) and the recent model sensitivity studies for a large number of cyclones by Mullen and Baumhefner (1988) and Kuo and Low-Nam (1989) provide an important reminder that cyclones display remarkable case-to-case variability, especially during the initial development phase. This issue was often discussed by S. Petterssen during his visits to the University of Wisconsin–Madison in the early 1970s, where he stated: "Extratropical cyclones are born in a variety of ways, but their appearance at death is remarkably similar" (quote provided by D. R. Johnson). Given the degrees of freedom involved with the nonlinear interactions among the various physical processes, it is not surprising that the sensitivity of model-simulated cyclones to latent heat and boundary-layer processes covers a large spectrum in the numerical experiments cited above, indicating perhaps that some processes are more important than others in individual storms. Nevertheless, there is a growing consensus that 1) a superposition of upper- and lower-tropospheric dynamic processes is required for rapid cyclogenesis (whether it be described in terms of the IPV concepts, the development equation derived by Sutcliffe and by Petterssen or the more theoretical initial-value baroclinic approach presented by Farrell (1984, 1985)); and 2) the development rates are significantly enhanced by the interaction of diabatic and dynamic processes, especially those that are related to the release of latent heat and those that act to reduce the static and symmetric stability of the lower troposphere.

Numerous research topics remain with respect to rapid cyclogenesis. As noted in Section 6.3, the role of convection in either initiating or enhancing cyclogenesis needs to be investigated further. As part of this effort, the issue concerning the "slantwise" nature of the convective heat flux and its impact on the development rate of extratropical cyclogenesis needs to be addressed. Bjerknes (1951, p. 595) anticipated the importance of moist slantwise ascent along an inertially neutral θ_e surface, and provides an example of a vertical lapse rate that is less than the moist adiabatic but possesses moist slantwise neutrality in the precipitation region ahead of a developing cyclone. Emanuel (1983, 1988) provides additional examples where the atmosphere is conditionally stable for vertical convection but neutral for parcel displacement along a slanted surface of constant absolute momentum, and supporting evidence that the slantwise convection is a fundamental part of the precipitation regime associated with extratropical cyclones. This concept appears to be relevant for both resolving the nature of the airflow through the principal ascent regions associated with extratropical storms, where the region of ascent takes on the appearance of a narrow sloping band, and accounting for the vertical and horizontal redistribution of heat associated with convective elements that may feed back upon the development rate of the cyclone. Nordeng's (1987) recent attempt to parameterize slantwise convection, comparing it to parameterization schemes based on vertical convective heat fluxes and applying it to several polar low cases, should be extended to the simulation of a larger number of cases of rapid cyclogenesis in different geographical locations. The assessment of the impact of convection upon rapid cyclogenesis should also involve the study concerning the extent to which boundary-layer heat and moisture fluxes merely precondition the cyclone environment, or actively fuel the convective systems and enhance development rates.

Another issue concerns the growing evidence that mesoscale flow regimes that are not properly described by either quasi-geostrophic and geostrophic momentum concepts or the balance equation, and thus appear to be unbalanced in nature, may be an important factor in cyclogenesis. A diagnostic case study of the Presidents' Day storm (Uccellini et al. 1984) indicates that the precyclogenetic environment was marked by a region in which the Rossby number approaches unity and the divergence tendency following air parcels exceeds 10^{-9} s^{-2} (indications that balance constraints are not being met). In the model simulations of this case, ageostrophic wind components approaching 40 to 50 m s^{-1} were diagnosed in the lower to middle troposphere (Uccellini et al. 1987; Whitaker et al. 1988). These large ageostrophic wind speeds occur near regions of heavy precipitation, latent heat release, and vertical ascent and precede the rapid accelerations that mark the development of low-level jets and rapid decrease of SLP.

Another indication of the unbalanced nature of these storms is the increasing number of observational studies that have documented the existence of large-amplitude gravity-inertia waves before and during cyclogenetic events (Uccellini 1975; Bosart and Sanders 1986; Uccellini and Koch 1987; Bosart and Seimon 1988). The recent 15 December 1987 blizzard in the central United States described by Schneider (1990) was associated with a rapidly developing cyclone (Figs. 6.23a,b) and a superimposed, large-amplitude (~12 mb) gravity wave (Figs. 6.23c,d). The barograph traces from north and west of the cyclone reveal that 10-mb pressure falls occurred during a 10-minute period with the passage of the gravity-inertia wave. The gravity-inertia wave could be clearly identified at individual stations, given the strong, gusty east to northeast winds at the wave trough (as expected from gravity wave considerations), in contrast to the weaker, slowly rotating winds near the storm center, as illustrated by the pressure trace from Chicago O'Hare Airport (where

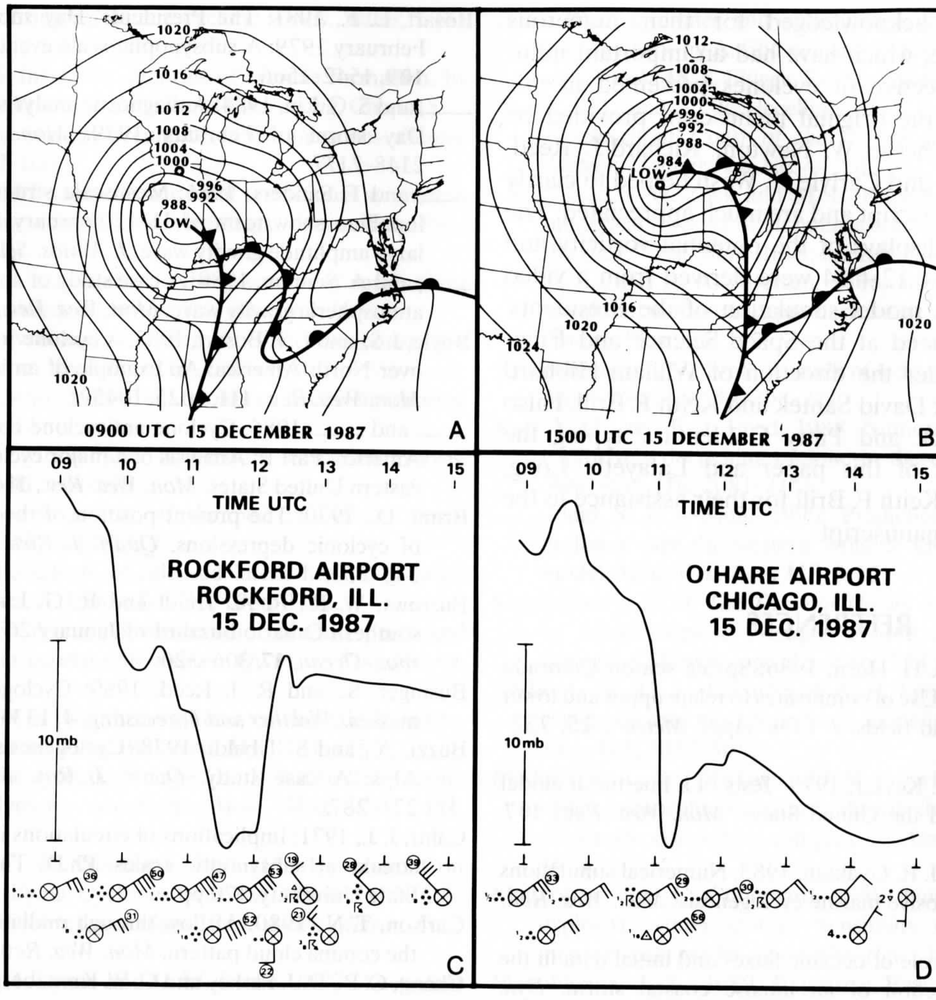

FIG. 6.23. Sea-level pressure (mb) and surface front analyses for (a) 09 UTC and (b) 15 UTC 15 December 1987. Pressure traces and hourly surface observations for (c) Rockford, Illinois and (d) Chicago O'Hare International Airport; locations indicated by circles in (a) and (b), respectively. Surface observations include wind direction and speed, gusts (kn) encircled, visibility (miles) and weather (symbols standard). (Figure derived from Schneider 1990.)

the SLP was lower during the gravity wave passage near 11 UTC than during the passage of the low center between 14 and 15 UTC (Fig. 6.23d)). The important issue is not only the effect this wave had on the weather (heavy snow plus strong gusty winds created "white-out" conditions during the wave passage (Figs. 6.23c,d)) but also the fact that the wave passed through the storm center (from south to north) during the rapid cyclogenetic period, when the central pressure of the cyclone decreased 5 to 7 mb in 1 hour (Schneider 1990). If this type of mesoscale adjustment is representative of other explosively developing storms, it would indicate that rapid cyclogenesis represents a mixed mode of dynamic processes that cannot be totally resolved through the use of the hydrostatic, quasi-geostrophic theory or other approaches based on larger-scale, balanced-flow considerations.

Resolving these issues and advancing our understanding of the nonlinear interactions among the numerous physical processes that contribute to rapid cyclogenesis requires improved models and enhanced data sets. Palmén (1951) ended his *Compendium* article on cyclones by calling for upper-air data with 2- to 3-hour temporal resolution to resolve the means by which the various processes contribute to cyclogenesis. This call is often repeated, seldom heeded and is still relevant to today's research requirements. Indeed, recent model-based diagnostic studies indicate that hourly data is necessary for studying certain aspects of rapid cyclogenesis. Future research efforts that address the issues discussed above and are based on enhanced data sets and well-designed numerical model experiments will not only advance our understanding of rapid cyclogenesis but also enhance our ability to predict the occurrence of these storms with acceptable reliability.

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