Observational Evidence of Slantwise Convective Adjustment

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(Manuscript received 20 November 1987, in final form 14 March 1988)

ABSTRACT

Attempts were made during two field experiments to fly instrumented aircraft along absolute momentum (M) surfaces as a means of accurately determining slantwise convective stability. The application of this technique appears to have been quite successful. We present the results of four such efforts conducted in the ascent regions of midlatitude cyclones observed during the New England Winter Storms and Genesis of Atlantic Lows Experiments. In three of the four cases the atmosphere was almost exactly neutral to slantwise ascent while being quite stable to vertical displacements. In the fourth case, the atmosphere departed from neutrality but was also substantially drier, evidently due to subsidence. We find excellent agreement between assessments of stability based on the M surface flights and on cross sections constructed from rawinsonde observations. On the basis of these results I hypothesize that slantwise convective neutrality is characteristic of the ascent regions of baroclinic cyclones and discuss the implications of this finding for the dynamics of baroclinic systems.

1. Introduction

The effects of phase changes of water on large- and meso-scale dynamical processes remains an outstanding problem in meteorology. The release of latent heat when water condenses is so large as to render the atmosphere statically neutral or unstable even while being substantially stable to unsaturated displacements. For this reason, small errors in the initial specification of water vapor content can lead to large errors in the numerical simulation of dynamical systems in which latent heat release is important; likewise, small inaccuracies in convective representations that specify total latent heat release (as opposed to the often small difference between condensation heating and adiabatic cooling) can lead to large inaccuracies with attendant misconceptions about the effects of latent heat release. For these reasons it is important to understand the spatial distributions of atmospheric moisture and the processes that determine such distributions.

In the baroclinic atmosphere, the stability to saturated displacements depends on the distribution of thermodynamic properties along surfaces containing the geostrophic vorticity vector (Eliassen and Kleinschmidt 1957; Bennetts and Hoskins 1979; Emanuel 1983a,b). If the vorticity due to local flow curvature is small compared to the Coriolis parameter (f), these surfaces are conveniently defined as surfaces of constant "absolute momentum" (M),[1] where

$$M \equiv v_g + fx, \tag{1}$$

where v_g is the geostrophic flow in the direction of the thermal wind and x is a coordinate in the direction of the temperature gradient. Emanuel (1983a,b) showed that the distribution of temperature and moisture along M surfaces determines the effective static stability of the baroclinic atmosphere in the same way as such soundings in the vertical direction can be used to assess stability of barotropic flows; in fact, the latter is a special case of the former. Bennetts and Hoskins (1979) and others have suggested that the release of conditional instability measured along M surfaces results in two-dimensional mesoscale bands aligned with the thermal wind, and there is mounting evidence (Bennetts and Sharp 1982; Emanuel 1983b; Parsons and Hobbs 1983; Seltzer et al. 1985; Wolfsberg et al. 1986) that "slantwise convection" actually occurs in the atmosphere. Moreover, the dynamics of quasi-balanced processes such as frontogenesis and baroclinic instability may be dramatically affected by condensation at or near the limit of neutral stability to slantwise convection (Thorpe and Emanuel 1985; Emanuel et al. 1987).

To date, all estimates of slantwise stability have relied on conventional rawinsonde observations. Emanuel (1983b) demonstrated a technique whereby two or

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[1] The quantity "M" was called "pseudo-angular momentum" by Emanuel (1983b).

more soundings are used to construct cross-sections of M and various thermodynamic variables which then allows interpolations of the thermodynamic quantities onto surfaces of constant M. These interpolated M surface soundings can then be used to assess stability in the usual fashion; in particular, one can evaluate the "slantwise convective available potential energy" (SCAPE), defined

$$\text{SCAPE} \equiv \int_M \frac{g}{\theta_{va}}(\theta_{vp} - \theta_{va})dz, \qquad (2)$$

where g is the acceleration of gravity, θ_{vp} is the virtual potential temperature of a reversibly displaced parcel and $\theta_{v\alpha}$ is that of the ambient air. Soundings presented by Emanuel (1983b) showed near neutrality to slantwise ascent, while vertical displacements were decidedly stable. But because M surfaces typically intersect only one or two rawinsonde sites, it might be argued that results such as these are sensitive to errors of interpolation. For this reason it is desirable to obtain measurements made directly along M surfaces. In the following section we describe a technique for doing so by flying instrumented aircraft along M surfaces. Four examples of flights of this kind are presented in section 3 and are compared with inferences based on standard and special rawinsonde measurements.

3. Aircraft soundings along *M* surfaces

The quantity M, defined by (1), depends on position and geostrophic velocity. As there is no simple way to calculate the latter on board an aircraft, it is approximated by the actual velocity v. To define x and v it is necessary to estimate the direction of the thermal wind. In each of the cases to be described this was done before the flight using the latest available analysis and 12-hour forecasts of the 1000–500 mb thickness. Once the thermal wind direction is specified, v, x and f can be calculated from the inertial navigation system of the aircraft. This in turn allows a direct estimate of M. In practice, this was done by entering the Cartesian quantities, u, v, x and y into a hand-held calculator, which was preprogrammed to display M in m s^{-1}. The aircraft scientist then requested alterations in the aircraft ascent or descent rate so as to keep M approximately constant. Note that it is not necessary to fly the aircraft exactly in the x direction since, by definition, variations of θ (or θ_e) and M in the y direction will be small. The descent or ascent rate of an aircraft flying in the direction of the temperature gradient will be determined by the airspeed and the slope of the M surface which, from (1) is $\eta_g/(\partial v_g/\partial z)$, where η_g is the vertical component of geostrophic absolute vorticity. In baroclinic air masses typical of those in which we conducted the experiments, $\eta_g \approx 10^{-4}$ s^{-1} and $\partial v_g/\partial z \approx 6 \times 10^{-3}$ s^{-1}, giving a slope of 1.6×10^{-2}. An aircraft flying at 100 m s^{-1} would therefore have to ascend or descend at about 1.6 m s^{-1} (300 ft min^{-1}). This is well within the ability of most research aircraft.

In the presence of a uniform geostrophic wind orthogonal to the thermal wind, the conserved quantity M must be modified slightly to account for advection, even though all the physical processes are invariant with respect to uniform translation. To the extent that the large-scale flow satisfies the geostrophic momentum approximation, differentiation of (1) shows that

$$\frac{dM}{dt} = \frac{dv_g}{dt} + fu = fu_g, \qquad (3)$$

where u_g is the component of geostrophic wind in the direction of the temperature gradient, and in the absence of radiation or turbulent heat fluxes

$$\frac{d\theta_e}{dt} = 0. \qquad (4)$$

If u_g is approximately constant in pressure and time during a particular aircraft sounding, it follows from (3) that the conserved quantity is $M - fu_g\tau$, where τ is the time from the beginning of the sounding. Therefore, we apply a correction $-fu_g\tau$ to the measured value of M, estimating u_g from analyses and numerical forecasts. In practice, this amounted to no more than 1 m s^{-1} over the full time of the sounding.

4. Case studies

a. 15–16 November 1983

Our first attempt at an M-surface sounding was made in advance of a developing cyclone during the New England Winter Storms Experiment. The large-scale settings roughly 12 hours before and after the sounding are shown in Fig. 1. The short, heavy line near Brunswick, Maine (NHZ) shows the projection of the sounding on a level surface. At the time of the sounding, moderate warm advection was occurring in all of New England and the atmosphere was nearly saturated along the path of the sounding. Precipitation had reached southern New England at the time of the sounding, but had not reached the surface in the region of the sounding.

The M surface descent, directed by MIT graduate student Peter Neilley aboard the NCAR King Air, commenced at 420 mb at 0125 UTC on the 16th and terminated at 700 mb at 0211 UTC. The thermodynamic sounding is shown in Fig. 2. The numbers in parenthesis to the left of the sounding indicate the departure of M from its value at the beginning of the descent. Since the vertical change in M over the same distance was about 35 m s^{-1}, the sounding was quite close to being on an M surface, down to about 650 mb. The numbers in brackets to the right of the sounding show θ_e with respect to an ice process, while the dashed line is a pseudoadiabat corresponding to a wet-

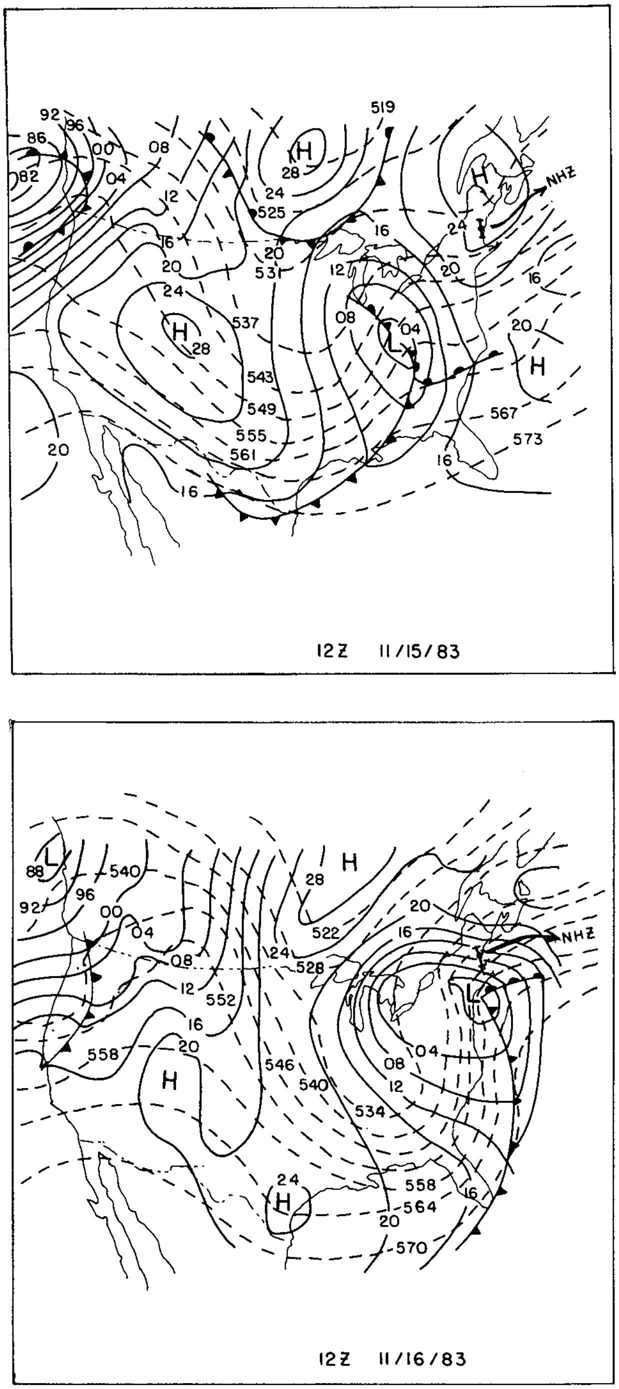

FIG. 1. (a) Surface pressure (mb) and 1000–500 mb thickness (dm) at 1200 UTC 15 November 1983. Heavy bar centered at Brunswick, Maine (NHZ) shows horizontal projection of M-surface sounding. (b) As in (a) but for 1200 UTC 16 November 1983.

bulb potential temperature (θ_w) of 14°C. The sounding is clearly very close to moist-neutral down to about 650 mb. The dash-dot line is a vertical temperature sounding made a short time earlier by the aircraft. In contrast with the M-surface sounding, the vertical profile is decidedly stable.

Cross sections showing M together with saturated equivalent potential temperature (θ_e^*) and θ_e are presented in Fig. 3 using 0000 UTC 16 November 1983 soundings from Caribou, Maine (CAR), Portland, Maine (PWM) and Chatham, Massachusetts (CHH). In constructing these cross sections we intentionally omitted data from the aircraft as a means of determining how well slantwise stability can be assessed from standard rawinsondes alone.

Figure 3 shows that the aircraft descent occurred within a narrow tongue of air of nearly neutral slantwise stability, projecting northward from a deep layer of neutrally stable air over Chatham. In view of the likely presence of frontogenetical forcing (Fig. 1), the tongue of air of low moist potential vorticity may have arisen as a consequence of the type of frontal circulation predicted by Emanuel (1985) and Thorpe and Emanuel (1985). In that work it was demonstrated that frontogenesis in the presence of small stability to slantwise moist convection results in a very narrow sloping updraft aligned with M surfaces. If such a circulation advected an initially smooth distribution of moist potential vorticity, a pattern similar to that shown in Fig. 3 could well result.

b. 26 January 1986

Several M-surface flights were conducted during the Genesis of Atlantic Lows Experiment (GALE). The

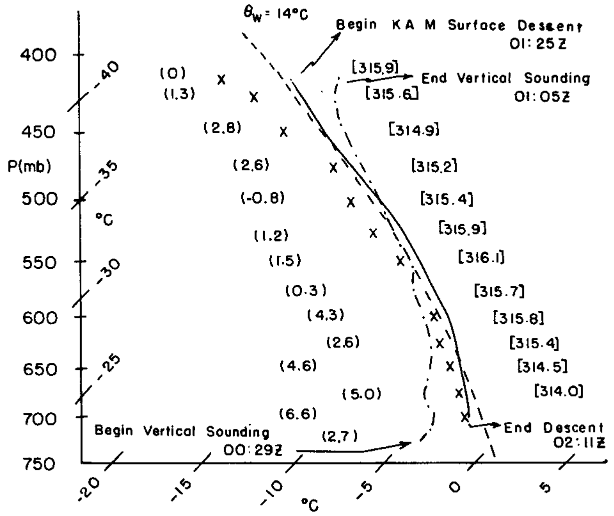

FIG. 2. Sounding along M-surface made by NCAR King Air between 0125 and 0211 UTC 16 November 1983. Solid line shows temperature while X's denote dewpoint. Numbers in parentheses at left are departures of M (m s^{-1}) from initial value; numbers in brackets at right are equivalent potential temperature (K) with respect to ice. Dash-dot line shows temperature sounding made by rapid ascent of aircraft near Brunswick, Maine between 0029 and 0105 UTC 16 November 1983.

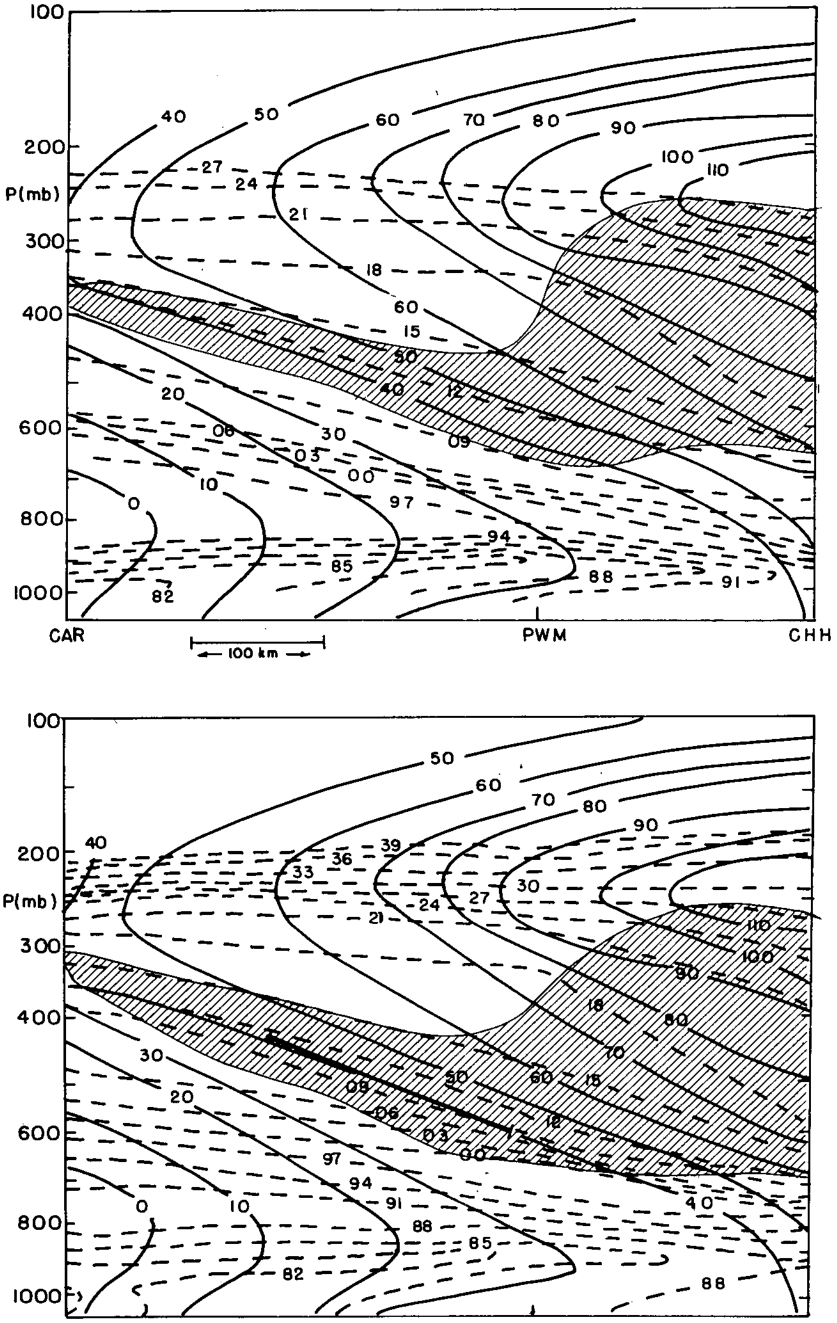

FIG. 3. (a) Cross section from Caribou, Maine (CAR) to Chatham, Massachusetts (CHH) constructed from rawinsonde observations at CAR, CHH and Portland, Maine (PWM) at 0000 UTC 16 November 1983. Solid lines denote absolute momentum (M; m s^{-1}) while dashed lines depict saturated equivalent potential temperature (θ_e^*; K, with first digit omitted). Values of θ_e^* greater than 327 K not shown. Hatching denotes regions where lapse rate along M surfaces is greater than or equal to the moist adiabatic rate. (b) As in Fig. 3a but showing equivalent potential temperature (θ_e; K, with first digit omitted). Heavy bar descending through 500 mb between CAR and PWM shows partial path of M-surface aircraft sounding.

first of these began at about 550 mb over Fayetteville, North Carolina at 1543 UTC 26 January and descended to about 50 m over the Atlantic southeast of Wilmington, North Carolina at 1630 UTC. The synoptic environments about 4 hours before and 8 hours after the flight are shown in Fig. 4. A strong baroclinic

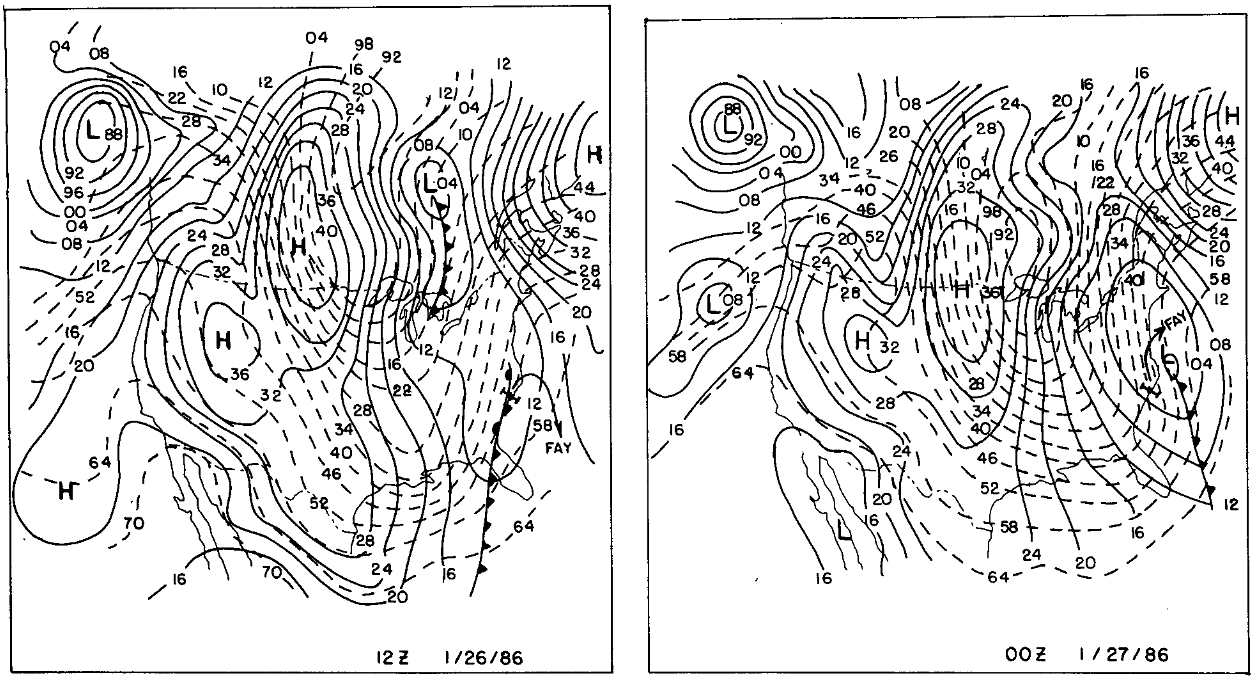

FIG. 4. As in Fig. 1 but for 1200 UTC 26 January 1986 (a) and 0000 UTC 27 January 1985 (b). Heavy bar through Fayetteville, North Carolina (FAY) shows path of M-surface aircraft sounding.

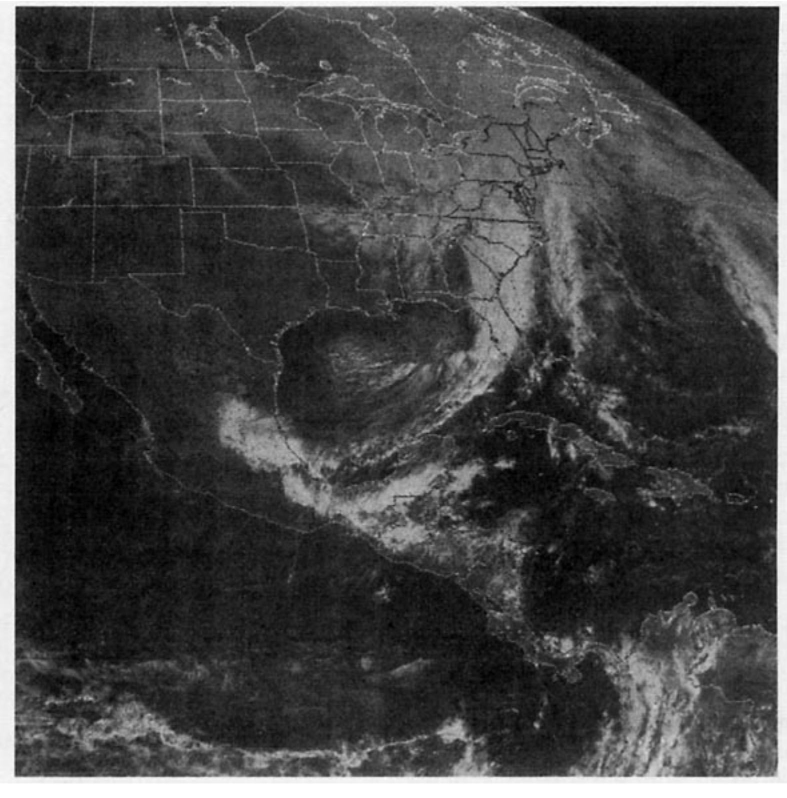

FIG. 5. Geostationary Operational Environmental Satellite (GOES) visible imagery from 1631 UTC 26 January 1986.

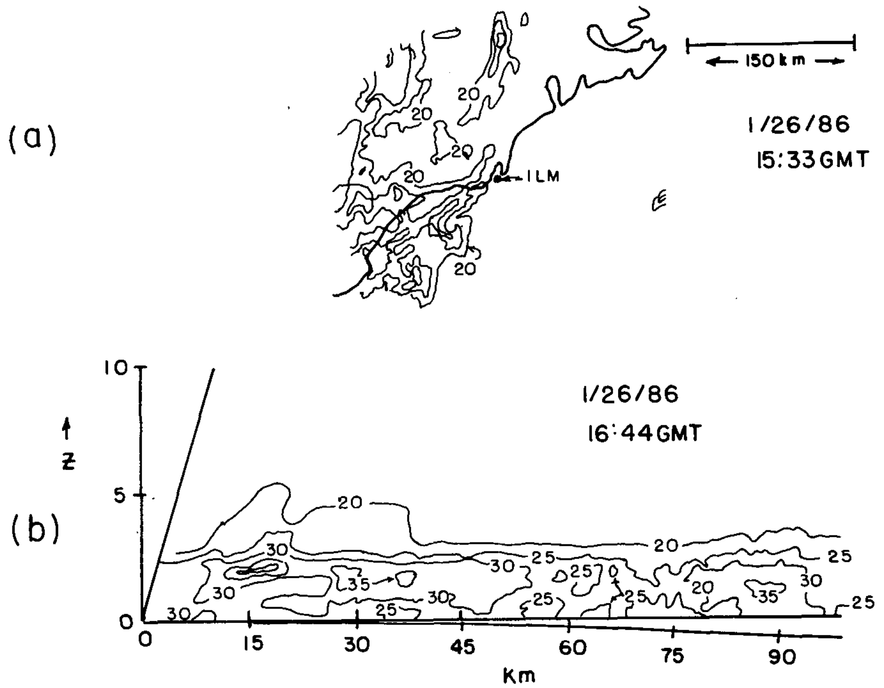

FIG. 6. (a) Horizontal scan of radar reflectivity (dbZ) from the MIT 5-cm radar located at Wilmington, North Carolina (ILM) at 1533 UTC 26 January 1986. Scan is at an elevation angle of 0 degrees. Carolina coastline shown by bold line. (b) Range–height cross-section of radar reflectivity (dbZ) at azimuth of 300 deg from the MIT radar at 1644 UTC 26 January 1986. Height is in km.

zone with an analyzed weak stationary front was aligned southwest–northeast through the mid-Atlantic states, with light precipitation occurring in the vicinity of the M-surface flight. On board the NCAR King Air, the author noted stratiform clouds with some clear areas between cloud decks and occasional moderate snow down to about 800 mb. Weak frontogenetical forcing was probably present at the time of the M-surface sounding.

The GOES visible imagery at the time the sounding ended (Fig. 5) shows what appears to be a frontal cloud band extending along the U.S. eastern seaboard, and an offshore prefrontal squall line. A PPI from the MIT 5-cm Doppler radar located near Wilmington, North Carolina (Fig. 6a) shows more or less randomly distributed moderate reflectivity shortly before the time of the sounding, while an RHI taken about an hour later (Fig. 6b) indicates fairly uniform returns below about 3 km. There are only weak indications of along-shear (SW–NE) alignment of the radar echoes in Fig. 6a.

As in the previous case the M-surface sounding (Fig. 7) is nearly moist-neutral while a vertical sounding taken at about the midpoint of the M-surface flight shows marked stability. Close inspection of Fig. 7 also shows that there is some correlation between departures of the temperature sounding from the $\theta_w = 13°C$ moist adiabat and departures of M from its initial value, as would be expected in a baroclinic atmosphere. The

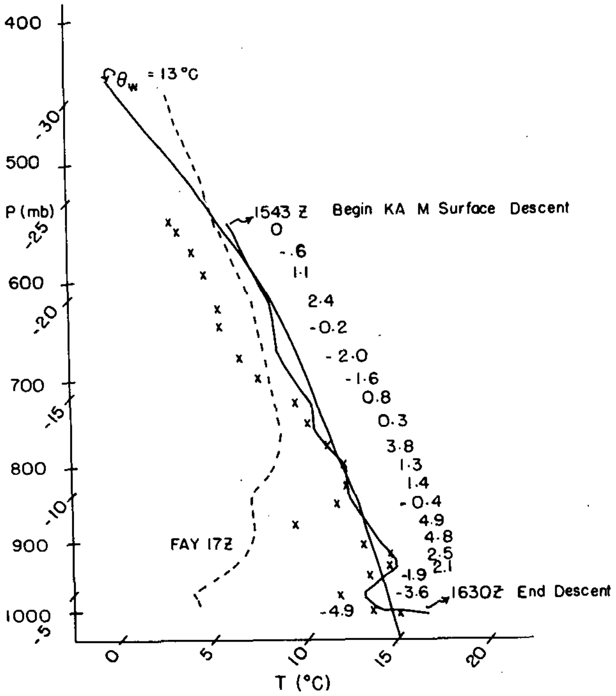

FIG. 7. M-surface sounding by NCAR King Air between 1543 and 1630 UTC 26 January 1986. Solid line shows temperature while X's denote dewpoint. Numbers to right show departures of M (m s^{-1}) from initial value. Dashed line is temperature from the 1700 UTC CLASS sounding at Fayetteville, North Carolina (FAY).

superadiabatic lapse rate near 1000 mb is due to a segment of level flight toward warmer air within the boundary layer. The difference between the upright and M-surface stability indicated by Fig. 7 is truly remarkable and serves to further illustrate the atmosphere's preference for slantwise (as opposed to vertical) neutrality.

Horizontal cross sections of M, θ_e^* and θ_e made from 1500 UTC special National Weather Service (NWS) soundings and GALE Cross-Chain Loran Atmospheric Sounding Systems (CLASS) are shown in Figs. 8a and 8b. The location of these soundings is illustrated in Fig. 9. Once again, a large region of moist adiabatic lapse rates along M surfaces is evident (Fig. 8a), consistent with the direct aircraft sounding shown in Fig. 7. Note that this condition takes the form of inertial neutrality in the upper troposphere between Greensboro and Wilmington, as evidenced by the nearly vanishing horizontal gradient of M. Elsewhere, the atmosphere is both inertially and conditionally stable even though large regions are slantwise neutral.

The cross section of M and θ_e (Fig. 8b) exhibits a

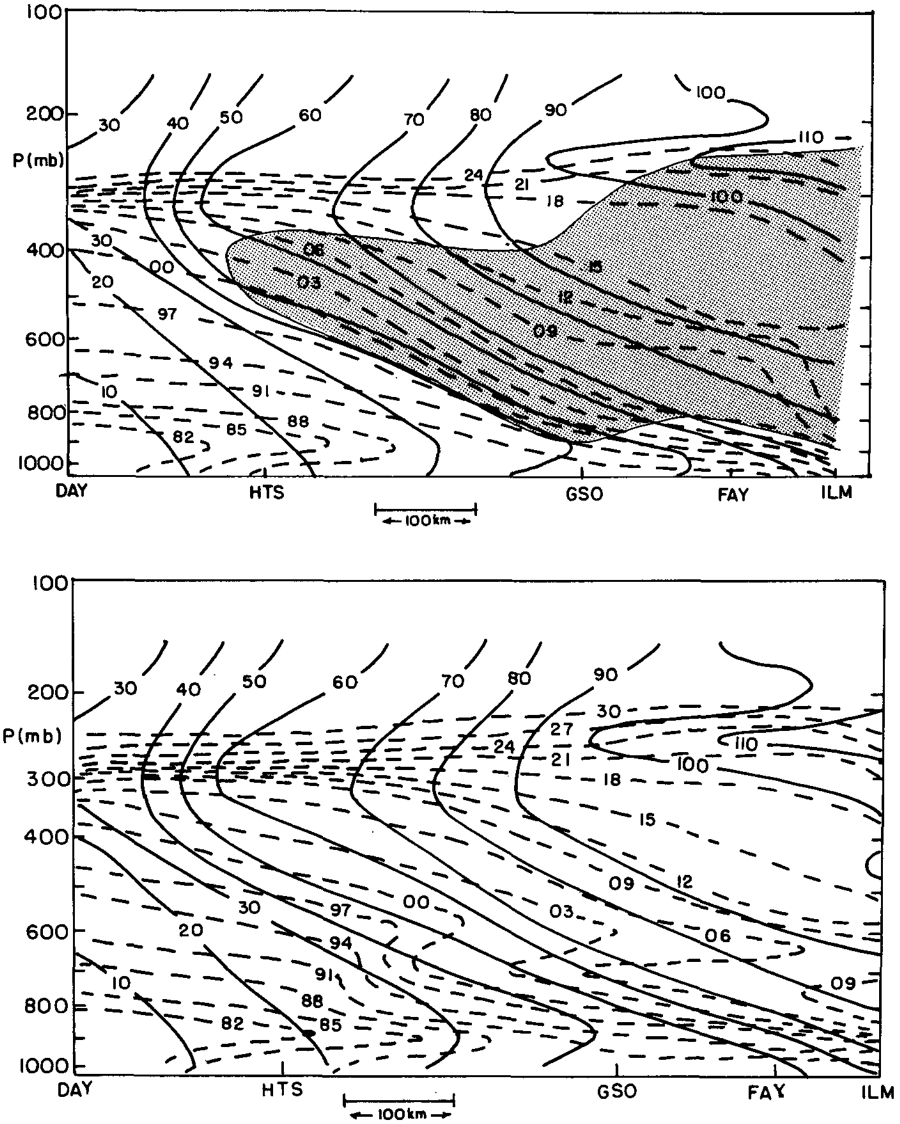

FIG. 8. (a) Cross section from Dayton, Ohio (DAY) to Wilmington, North Carolina (ILM) constructed from National Weather Service and CLASS sondings made at DAY, Huntington, West Virginia (HTS), Greensboro, North Carolina (GSO), Fayetteville, North Carolina (FAY) and ILM at 1500 UTC 26 January 1986. Solid lines denote M (m s^{-1}) while dashed lines show θ_e^* (K; first digit omitted and values above 324 K not contoured). Stippling denotes regions where lapse rate along M-surfaces is greater than or equal to moist adiabatic rate. (b) As in (a) but showing θ_e (K) and M (m s^{-1}). Values of θ_e above 330 K not contoured.

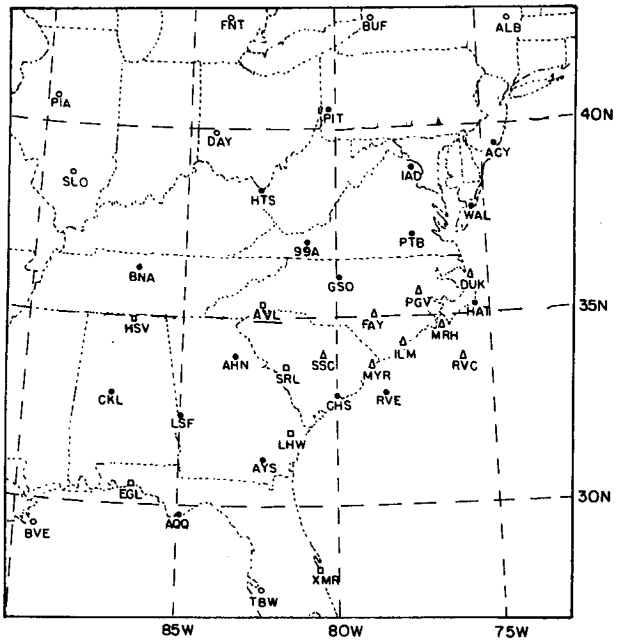

FIG. 9. Inner and Regional GALE rawinsonde network. Open circles are surrounding National Weather Service (NWS) sites, closed circles are NWS sites in the regional area. Squares denote GMD sites while triangles are CLASS locations. The locations of the research vessels Cape Hatteras (RVC) and Endeavor (RVE) are also shown.

tongue of relatively dry air sloping upward from about 800 mb over Wilmington to 700 mb over Greensboro. Above the tongue, the atmosphere is *potentially* unstable to upright and slantwise convection; presumably, slight lifting of the atmosphere would result in unstable slantwise convection. It is apparent that as this air mass rises through the frontal region, slantwise convection acts so rapidly to eliminate instability that very little if any instability is evident (Figs. 7 and 8a) at a given time. Nonetheless, Fig. 8b suggests that circulations associated with frontal lifting will contain slantwise convection.

c. 10 February 1986

Two more *M*-surface aircraft soundings were conducted on this date by MIT graduate students Peter Neilley and John Nielsen on board the NCAR Electra. The first commenced at 1718 UTC at about 520 mb over north central North Carolina and terminated at 1809 UTC near sea level over the coastal waters southeast of Myrtle Beach, South Carolina. The second followed nearly the reverse course, although somewhat farther inland, beginning at 900 mb at 2221 UTC and ending at 520 mb at 2301 UTC.

The surface maps and 1000–500 mb thickness patterns at 1200 UTC 10 February and 0000 UTC 11 February 1986 are shown in Fig. 10, together with the approximate location of the two *M*-surface soundings. Once again, the soundings were made in the ascent region ahead of a weak wave depression. There is, however, some evidence from detailed surface analyses (not shown) that a very small wave depression passed

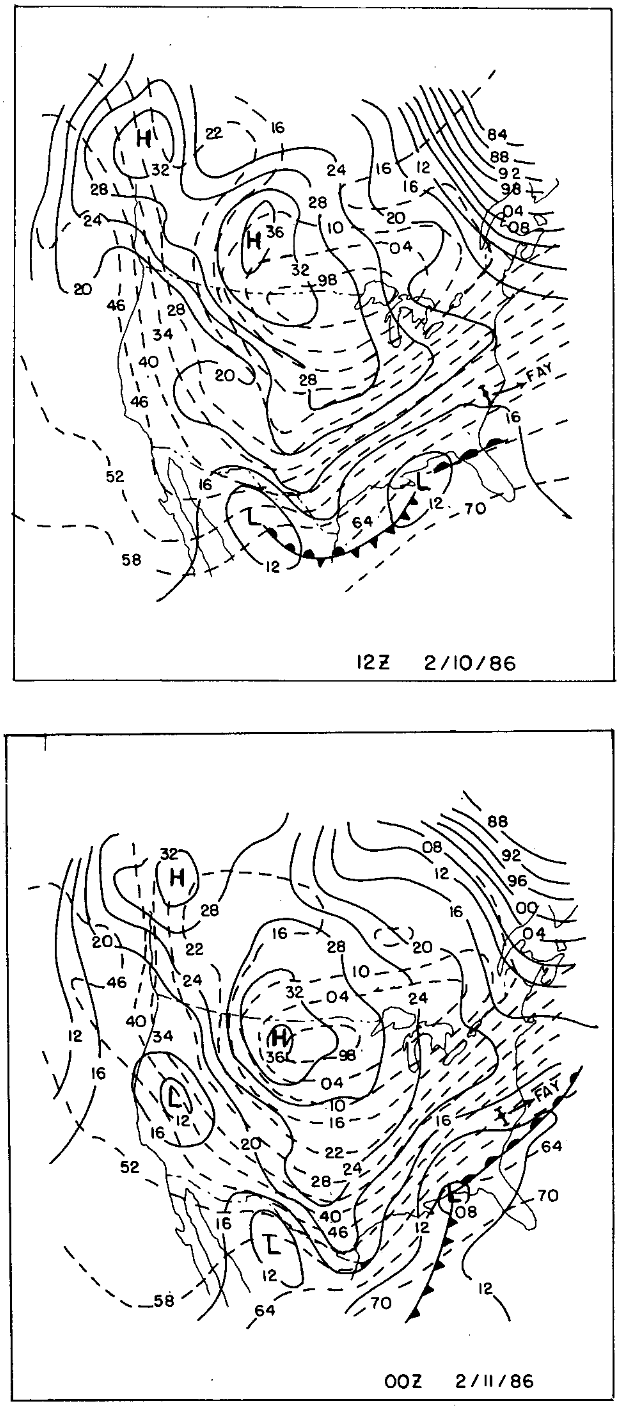

FIG. 10. As in Fig. 1 but for 1200 UTC 10 February 1986 (a) and 0000 UTC 11 February 1986 (b). Heavy bars through Fayetteville, North Carolina (FAY) show locations of *M*-surface descent (a) and ascent (b).

southeast of the Carolinas sometime between the two sounding times.

The GOES satellite imagery taken 45 minutes before the beginning of the first sounding is shown in Fig. 11. A large cloud mass covers the southeastern states (except for Florida) and prominent striations aligned with the thermal wind are discernable. The national radar summary for 1735 UTC 10 February (Fig. 12a) shows several east–west elongated regions of precipitation in the southeastern states including a prominent band in the region of the first sounding. By 2335 UTC (Fig. 12b), however, precipitation had temporarily ended over central North and South Carolina where the second sounding was made.

The two M-surface soundings are shown in Fig. 13 together with nearby CLASS soundings. (The first M-surface sounding suffers missing data between 710 and 850 mb. Also note the apparently supersaturated conditions between 850 and 900 mb. This results from artificially low temperatures recorded by a dry-bulb thermometer that has been wetted and/or artificially high values of dewpoint resulting from wetting of the hygrometer.) The earlier sounding resembles the two other cases discussed: it is saturated and very close to moist-neutral. The flight scientists were successful in keeping the aircraft very close to the M surface it started on. Once again, the M-surface sounding is far closer to neutrality than the vertical sounding. The second sounding (Fig. 13b) shows considerable drying and warming, consistent with the radar summary and the expectation of weak subsidence to the rear of the aforementioned wave disturbance. This is particularly true above 700 mb. (The "superadiabatic" lapse rate near 690 mb is due to a nearly horizontal segment of the aircraft track which the flight scientists undertook in an attempt to regain the original M surface.)

Cross sections from Petersburg, Virginia to Charleston, South Carolina showing M, θ_e^* and θ_e at 1800 UTC 10 February are displayed in Fig. 14, together with the projected flight path of the first Electra flight. Once again, the M–θ_e^* section shows a large region of moist adiabatic lapse rates along M surfaces and near-inertial neutrality in the upper troposphere. Vertical lapse rates are quite stable, however, except near Charleston where they are close to neutral. The M–θ_e section (Fig. 14b) exhibits some potential slantwise instability in the low and middle troposphere between Myrtle Beach and Fayetteville.

5. Conclusions

The attempts made to fly various instrumented aircraft along surfaces of constant absolute momentum (M) proved successful. In three of the four flights the soundings were remarkably close to neutral to moist ascent, while the remaining sounding departed from this condition, but was substantially undersaturated. Vertical soundings taken near the mid-points of the aircraft soundings generally show pronounced stability. Cross sections made from rawinsonde data demonstrate that the slantwise stability can be marginally assessed from rawinsondes with spatial resolution typical of the eastern U.S., but is well resolved by experimental networks with spacing less than 100 km, as was the case during GALE. The three cases for which cross sections were constructed show large regions of near neutrality to slantwise ascent and smaller regions of

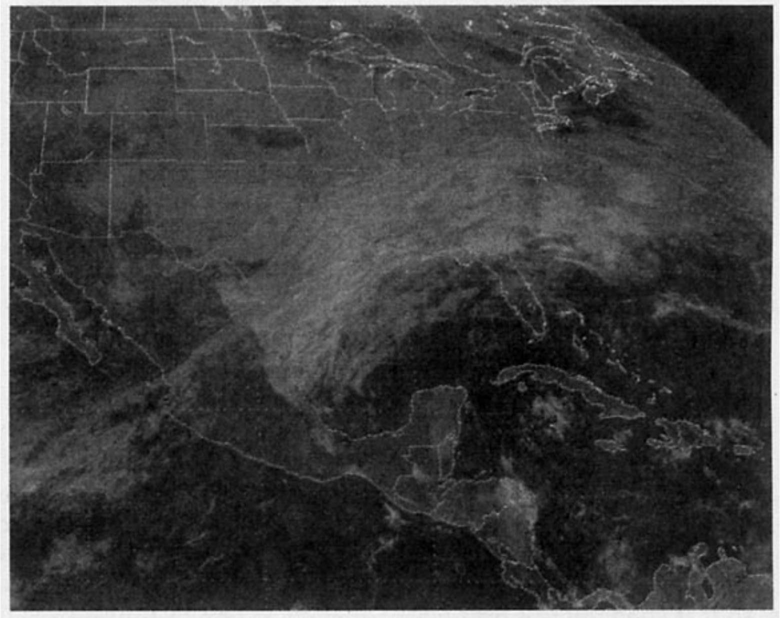

FIG. 11. As in Fig. 5 but for 1631 UTC 10 February 1986.

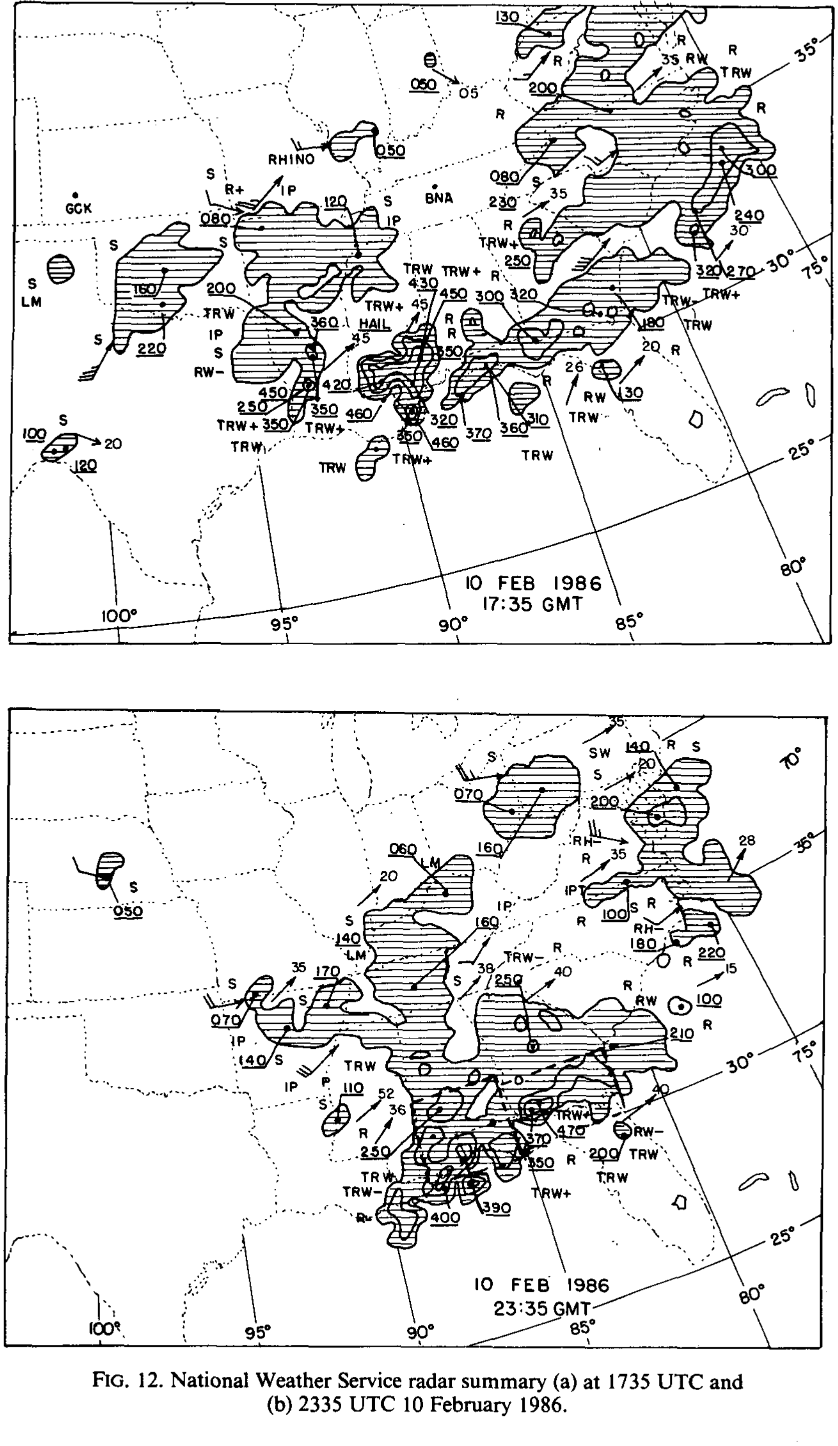

FIG. 12. National Weather Service radar summary (a) at 1735 UTC and (b) 2335 UTC 10 February 1986.

potential slantwise instability that would be realized were the air mass bodily lifted.

The implication of these analyses is that slantwise convective adjustment occurs on time scales that are small compared to the time scale of baroclinic processes such as frontogenesis, so that conditions of near neutrality are often observed. The co-existence of slantwise conditional neutrality and *potential* instability (θ_e decreasing upward along M surfaces) suggests that slantwise moist convection serves to continuously neutralize instability generated by large-scale ascent, so that large-scale systems may be thought of, to a first approximation, as passing through a sequence of neutral equilibrium states.

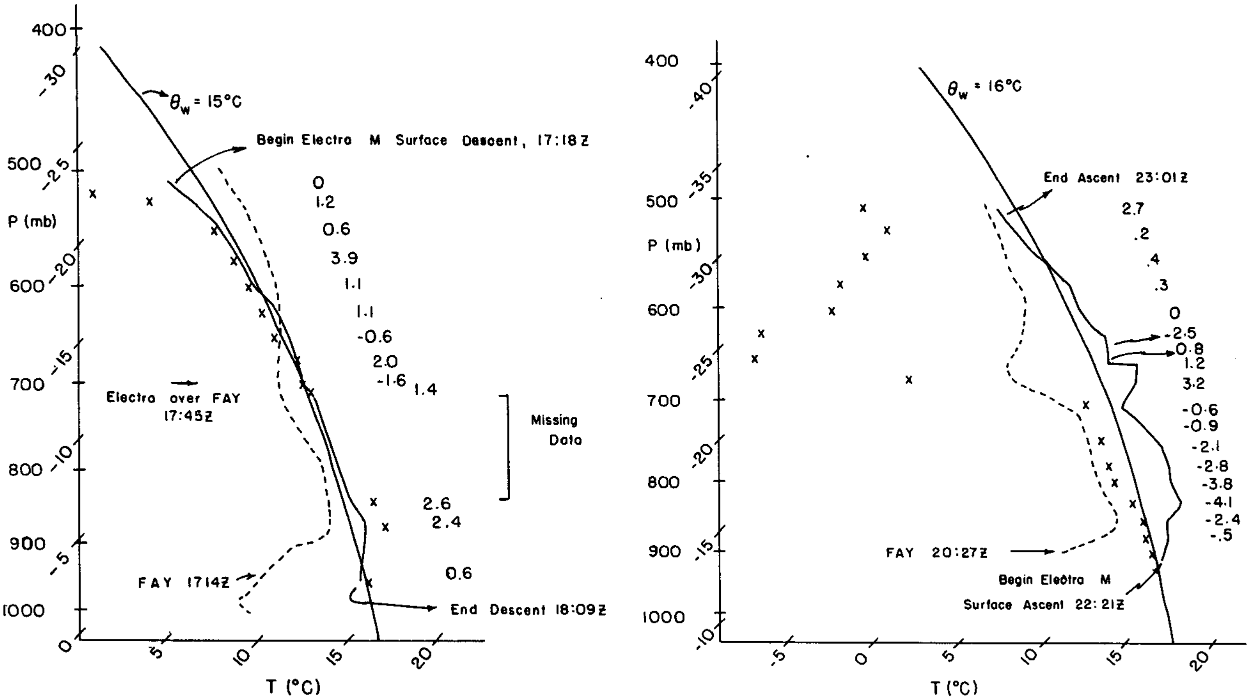

FIG. 13. As in Fig. 7 but for 10 February 1986 descent sounding (a) and ascent sounding (b). Times of soundings are shown on figures; FAY represents CLASS soundings at Fayetteville, North Carolina at indicated times.

Recent work by Thorpe and Emanuel (1985) and Emanuel et al. (1987) demonstrates that baroclinic circulations in atmospheres that are neutral to slantwise moist ascent (but stable to descent) differ in several remarkable ways from their classical dry counterparts. In the first place, the ascent regions of frontal zones and baroclinic cyclones become very small in scale compared to the descent regions and assume the form

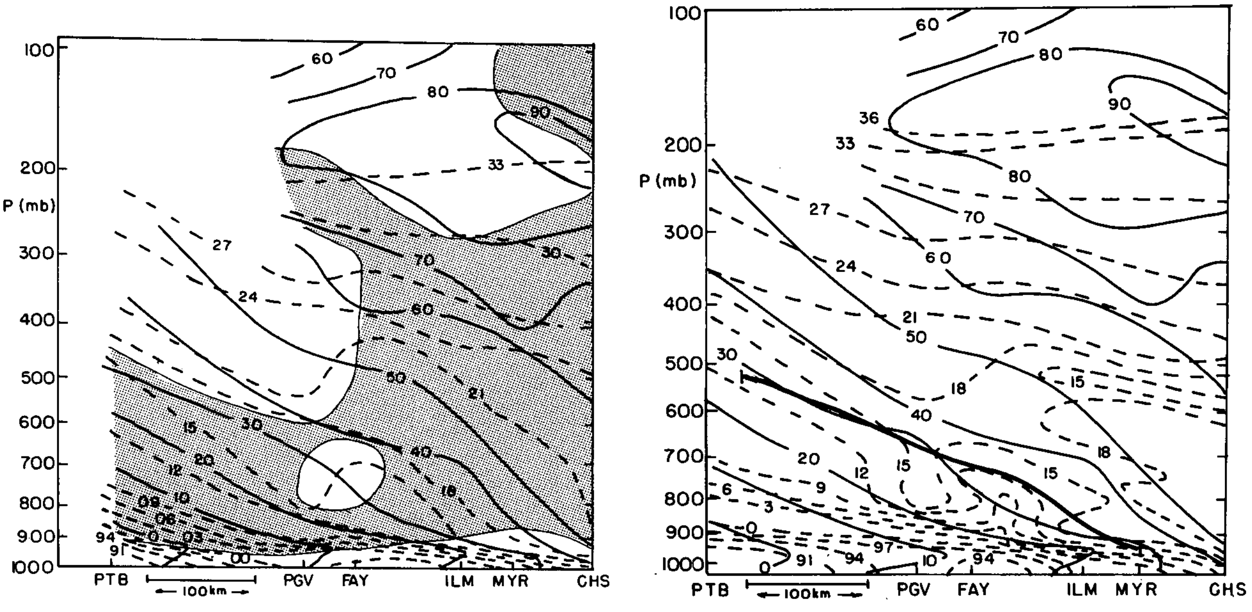

FIG. 14. As in Fig. 8 but for 1800 UTC 10 February 1986. See Fig. 9 for location of sounding sites. Data above 200 mb is missing at PTB. Heavy bar in (b) shows track of first *M*-surface aircraft sounding.

of thin, sloping sheets or "conveyor belts" of ascending air. Furthermore, the growth rate of cyclones in an Eady model with imposed moist slantwise neutrality can be more than twice those of dry Eady modes.

These results, taken together, suggest several avenues of future research. First, more attempts to measure the slantwise stability of baroclinic ascent regions should be made using standard rawinsonde observations and data from field experiments. If the prevalence of slantwise neutral states can be firmly established, the whole question of the effects of latent heat release on baroclinic systems can be put in a much simpler and empirically correct conceptual framework; namely, the effective stability for saturated ascent is zero. It then remains to reach a theoretical understanding of the effects this has on baroclinic processes and to find ways of representing or explicitly simulating slantwise convective adjustment in large-scale experimental and operational numerical models.

Acknowledgments. The research reported herein was made possible by the generous assistance of Dr. Richard Passarelli, who directed the New England Winter Storms Experiment, and by the directors of the GALE project. The author also wishes to thank Peter Neilley and John Nielsen, who conducted several of the *M*-surface aircraft soundings. The assistance of Joel Sloman and Isabelle Kole in preparing the manuscript is gratefully acknowledged. This research was funded by the National Science Foundation under Grant ATM-8513935.

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