EASTERN REGION TECHNICAL ATTACHMENT
NO. 91-5B
JUNE, 1991

THE INTERACTION OF JET STREAM DYNAMICS AND COLD AIR DAMMING IN A MID-ATLANTIC SNOW EVENT: VERTICAL MOTION FROM AN AGEOSTROPHIC PERSPECTIVE

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1. INTRODUCTION

On 27-28 December 1990, a winter storm occurred over much of the mid-Atlantic and southern New England states. A mixture of rain, freezing rain, and sleet fell from the Carolinas across southern and central Virginia, with snow occurring to the north from northern Virginia into Pennsylvania. Heaviest snowfall occurred in a swath across western Maryland and south-central Pennsylvania, where accumulations of up to 13 inches were measured (Figure 1).

This case clearly displayed characteristics of a cold air damming event (Richwien 1980), a phenomenon most common during the cool season months of March and December (Bell and Bosart 1988). In this situation, a wedge shaped ridge of high pressure, indicative of a low level cold air dome, was present between the east slopes of the Appalachian Mountains and the Atlantic Coast (Figure 2), where surface wind speed and direction departed significantly from geostrophy. There was also evidence of a mountain-parallel northeasterly jet as noted by Forbes et al. (1987). Forbes et al., as well as Uccellini and Kocin (1987), and Bell and Bosart (1988), described this cold dome as often being a critical factor in distinguishing a frozen or freezing precipitation event from a rain event, and that evaporative cooling could further intensify the cold dome, and the baroclinicity between the mountains and the coast. It should be noted that studies (e.g., Bell and Bosart 1988) have shown that the Regional Analysis and Forecast System (RAFS) has demonstrated significant improvement over previous models in simulating these cold air damming events.

The nature of the damming event, and its relationship to the upper jet stream will be explored from an ageostrophic perspective as suggested by Uccellini and Kocin (1987) and Uccellini et al. (1987). The interrelationship of these differing scales of motion will be briefly discussed, thereby establishing a crucial link between upper and lower tropospheric circulation patterns. In this way, the role of important secondary transverse ageostrophic circulations as a precipitation mechanism will be described. Techniques for the identification of these patterns in a real-time operational environment will be summarized.

2. UPPER JET INTERACTIONS

The majority of snowfall over Virginia and Maryland fell between 2200 UTC, 27 December, and 0600 UTC, 28 December. During this time, the surface temperature difference between Salisbury, MD (SBY), and Dulles International Airport, VA (IAD), increased from 6°F at 2100 UTC, to 15°F at 0500 UTC as the coast warmed and areas inland cooled. A subtle increase in the north-northeast surface winds was also noted. Coincident with the increase in thermal gradient and wind speed, was an increase in northeast-southwest enhanced (VIP2) radar precipitation bands across northern Virginia as observed from the Patuxent River, MD, radar site (not shown). This banding peaked in the 0000-0200 UTC time frame.

The 300 mb analyses are presented for: 1200 UTC, 27 December; 0000 UTC, 28 December; and 1200 UTC, 28 December, respectively (Figures 3a-c). From these charts, it appeared that the jet maximum slowly migrated from the mid-Mississippi and Ohio river valleys at 1200 UTC, 27 December, to the Atlantic seaboard by 1200 UTC, 28 December. At 0000 UTC, 28 December, the mid-Atlantic region was situated under the right entrance region of the jet, an area favorable for enhanced vertical motion through secondary transverse vertical circulations. While there were large data gaps in the analyses, we surmised that the mid-Atlantic region was, for a period, situated within the ascending branch of a direct circulation associated with the right entrance region of the jet. Precipitation had generally decreased in intensity by 1200 UTC, as the jet core passed over and to the south of Dulles Airport, with the area of interest becoming situated on the cyclonic side of the jet.

Studies by Uccellini and Johnson (1979), Uccellini and Kocin (1987), and Hakim and Uccellini (1991), have emphasized the role of jet stream dynamics in Eastern U.S. snowstorms. These papers provide a good review of jet streak dynamics, and establish the link between upper jet and the lower tropospheric thermal fields, and resultant geostrophic wind adjustments. Figure 4 illustrates the ageostrophic transverse circulation pattern associated with the right entrance region of a jet streak as it might have been oriented over the mid-Atlantic region at 0000 UTC, 28 December. This diagram depicts a direct circulation (warm air rising, cold air sinking) marked by rising motion on the anticyclonic side of the jet, since the ageostrophic component in the upper branch of the direct circulation is directed toward the cyclonic side of the jet. Mass continuity requires that the divergent patterns of the upper branch be compensated for by secondary ageostrophic circulations in the vertical and at lower levels.

The importance of this configuration is illustrated in a case study by Dunn (1987), in which a band of heavy snow fell along the Front Range of Colorado. This snowfall displayed little relationship to local topography, but rather, was in close association with a jet streak. The majority of the snow occurred on the anticyclonic side of the jet, and decreased markedly as the jet core passed overhead. The snow ended soon after the area came under the cyclonic side of the jet core. This appears to correlate well with the sequence of events for the 27-28 December case.

3. LOW LEVEL ADJUSTMENTS

As mentioned earlier, a subtle but noticeable increase in north-northeast surface winds was observed through the evolution of the mid-Atlantic snow event. This increase in the surface winds was coincident with an increase in low-level baroclinicity, and the passage of the upper jet core. How were these events related, and what effect did they have on the development of precipitation? Assuming the normal distractions of a busy operational forecast environment would not prevent the recognition of these events in real-time, how could the forecaster apply this knowledge to the preparation of forecast products?

Cold air damming in the Eastern U.S. results when an air mass of high static stability is blocked by the Appalachian Mountains and becomes sloped in a manner as illustrated in (Figure 5; Schwerdtferger 1975). From the hydrostatic relationship, pressure in the vertical increases downward from level 2 to level 1 at faster rate at point B than at point A. This results in the pressure at point B being greater than at point A. Geostrophic adjustment processes result in a mountain-parallel low-level wind that is proportional to the horizontal temperature gradient, and accelerates as the horizontal temperature gradient increases.

When an upper jet streak is superimposed upon a low-level damming event, the transverse circulation in the right entrance region further contributes to low-level convergence, and an increase in baroclinicity between the mountains and the coast, since the lower branch of the circulation enhances cold advection toward the coast. This frontogenetic process also contributes to an acceleration of the mountain-parallel low-level wind and enhanced vertical motion. These processes likely enhanced the temperature gradient between the Appalachian mountains and the coast, forced the acceleration of the low-level wind, and ultimately, enhanced the precipitation on 27-28 December.

Ignored to this point has been the role of the 850 mb jet. As can be seen in Figure 6, the situation was characterized by strong warm advection, and considerable low-level convergence with 50 kt south-southwest flow advecting Gulf of Mexico and Atlantic moisture into the region. This resulted in considerable large-scale isentropic lift. Rather than a mechanism or driving force as it is often incorrectly described, however, the point to remember is that this too was a manifestation of the the upper jet stream, and its attendant divergent circulation patterns. As discussed by Homan and Uccellini (1987), attempts are often made to relate low-level forcing of vertical motion with warm advection as a separate entity. More correctly, as described by Homan and Uccellini, the warm air advection pattern represents a manifestation of the isentropic sloped response to upper- and mid-tropospheric divergence.

4. OPERATIONAL IMPLICATIONS

Points to remember in diagnosing jet streak snowstorms are:

- Pay close attention to the evolution of 200-300 mb jet stream and migratory jet streaks, particularly in situations where the conventional methods of assessing vertical motion (e.g., 500 mb PVA) appear to be inconclusive. Note the orientation of the jet with respect to the area of interest. The entrance region on the anticyclonic (right) side of a jet streak seems particularly conducive to jet stream snow events, but any jet in the proximity should be viewed as a possible precipitation enhancer. Moreover, Uccellini and Kocin (1987) have shown that the interaction of jet streaks in which the right entrance region of a jet becomes collocated with the left exit region of a second jet is a configuration that has been associated with major snowstorms along the East Coast.

- Until wind profilers are available, our ability to monitor jet stream evolution is limited by the coarse temporal and spatial resolution of the rawinsonde network. However, satellite imagery can be very helpful in supplementing upper air data and filling in the gaps. Animation of infrared imagery can reveal the development of the parallel banding of high level clouds that is often the signature of jet stream precipitation events. Additionally, water vapor imagery will often reveal migratory jet streaks in subtle, fast moving, and faintly enhanced dark bands.

- Watch for subtle variations in low-level temperature, wind, moisture, and pressure fields. Intensifying surface temperature gradients accompany cold-air damming, signifying coastal frontogenesis. Increasing surface winds, along with moisture advection, are a response to changing temperature and wind fields. Falling surface pressure can signal the approach of mid- and upper-tropospheric troughs. These are all signals to events occurring on other scales and at other levels.

- Watch for changes in the character of radar echoes such as banding, rapid fluxuations in intensity, ang embedded convection.

- Be aware of the position, intensity, and trend of the surface through 850-, and 700 mb baroclinic zones. Jet stream dynamics superimposed upon a strong baroclinic zone is especially conducive to precipitation development.

5. CONCLUSION

This example indicates that a great deal can be inferred in regard to the synoptic and sub-synoptic scale circulation patterns associated with a mid-Atlantic snowstorm through a careful analysis of data from the current rawinsonde, surface, and radar networks. However, a correct assessment of these features in real-time, given the limitations of the current operational environment, is a difficult challenge. Nevertheless, there is value in applying these principles now, and there is a very real potential for tremendous benefits and advances in forecasting as these principles are applied to the vastly improved observational and diagnostic capability offered by new remote sensing technologies.

Two new technologies just now coming on line should help immensely with observing and diagnosing the evolution of cold air damming events and jet stream snowstorms. Experience with experimental research Doppler radars in Denver (Dunn 1988) has shown an increased ability to observe the nature of precipitation associated with winter snowstorms. Reflectivity displays have revealed with much greater detail, resolution, and sensitivity the structure and intensity of winter snowstorms. Previously, winter storms have been studied from a synoptic scale perspective, with little aid from weather radar, which is limited in its ability to resolve winter precipitation, low density snowfall in particular. With the aid of the WSR-88D system, winter storms can be approached with more attention to the mesoscale features. This will enable better delineation of snowfall amounts, especially in short-range forecasts, and should result in improved skill in anticipating the onset and termination of a snowfall event. Doppler velocity displays are also valuable in following the evolution of the low-level jet, especially since profilers are, as yet, limited in their ability to observe the vertical wind structure in the lowest 1 km. The details and height of the top of the cold air dome can also be revealed by Doppler velocity displays.

Finally, wind profilers should be especially useful in studying the evolution of jet stream level winds. These systems can easily reveal the approach and passage of jet streaks such as was likely present in the 27-28 December event.

References

Bell, B. D., and L. F. Bosart, 1988: Appalachian cold-air damming. Mon. Wea. Rev., 116, 137-161.

Dunn, L. B., 1987: Cold air damming by the Front Range of the Colorado Rockies and its relationship to locally heavy snows. Wea. Forecasting, 2, 177-189.

_____, 1988: Vertical motion evaluation of a Colorado snowstorm from a synoptician's perspective. Wea. Forecasting, 3, 261-272.

Forbes, G. S., R. A. Anthes, and D. W. Thomson, 1987: Synoptic and mesoscale aspects of an Appalachian ice storm associated with cold air damming. Mon. Wea. Rev., 115, 564-591.

Hakim, G. J., and L. W. Uccellini, 1991: Diagnosing coupled jet streak circulations for a northern Plains snow band from the operational Nested-Grid Model. Preprints, First International Symposium on Winter Storms, New Orleans, Amer. Meteor. Soc., 90-96.

Homan, J., and L. W. Uccellini, 1987: Winter forecast problems associated with light to moderate snow events in the mid-Atlantic states on 14 and 22 February 1986. Wea. Forecasting, 2, 206-228.

Richwien, B. A., 1980: The damming effect of the southern Appalachians. Nat. Wea. Digest, 5(1), 2-12.

Schwerdtfeger, W., 1975: The effect of the Antarctic Peninsula on the temperature regime of the Weddell Sea. Mon. Wea. Rev., 103, 45-51.

Uccellini, L. W., and P. J. Kocin, 1987: The interaction of jet streak circulations during heavy snow events along the east coast of the United States. Wea. Forecasting, 1, 289-308.

_____, R. A. Petersen, K. F. Brill, P. J. Kocin, and J. J. Tuccillo, 1987: Synergistic interactions between an upper-level jet streak and diabatic processes that influence the development of a low-level jet and a secondary coastal cyclone. Mon. Wea. Rev., 115, 2227-2261.

_____, and D. R. Johnson, 1979: The coupling of upper and lower-tropospheric jet streaks and implications for the development of severe convective storms. Mon. Wea. Rev., 107, 682-703.

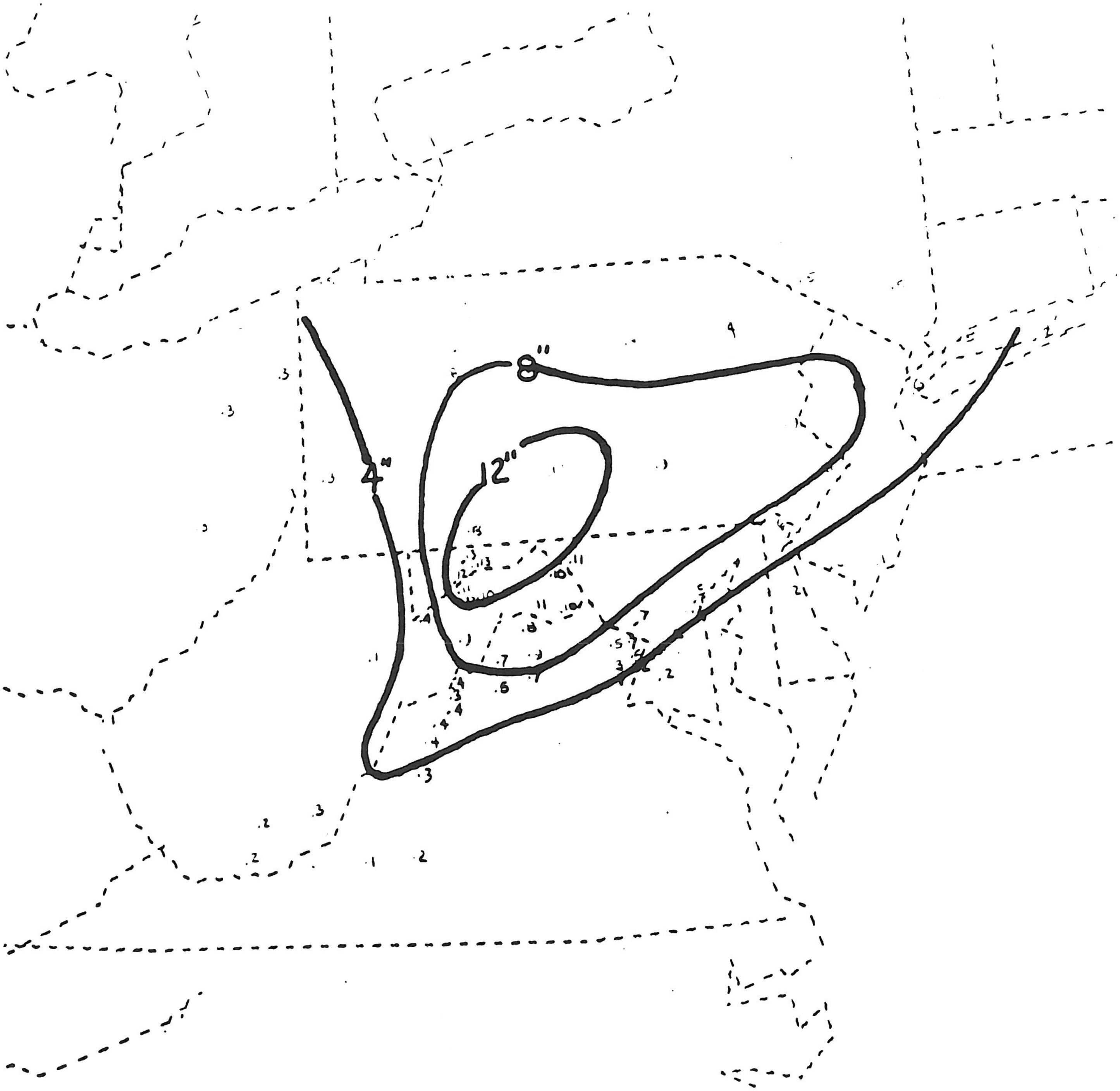

Figure 1. Snow depth for 1200 UTC, 28 December 1990.

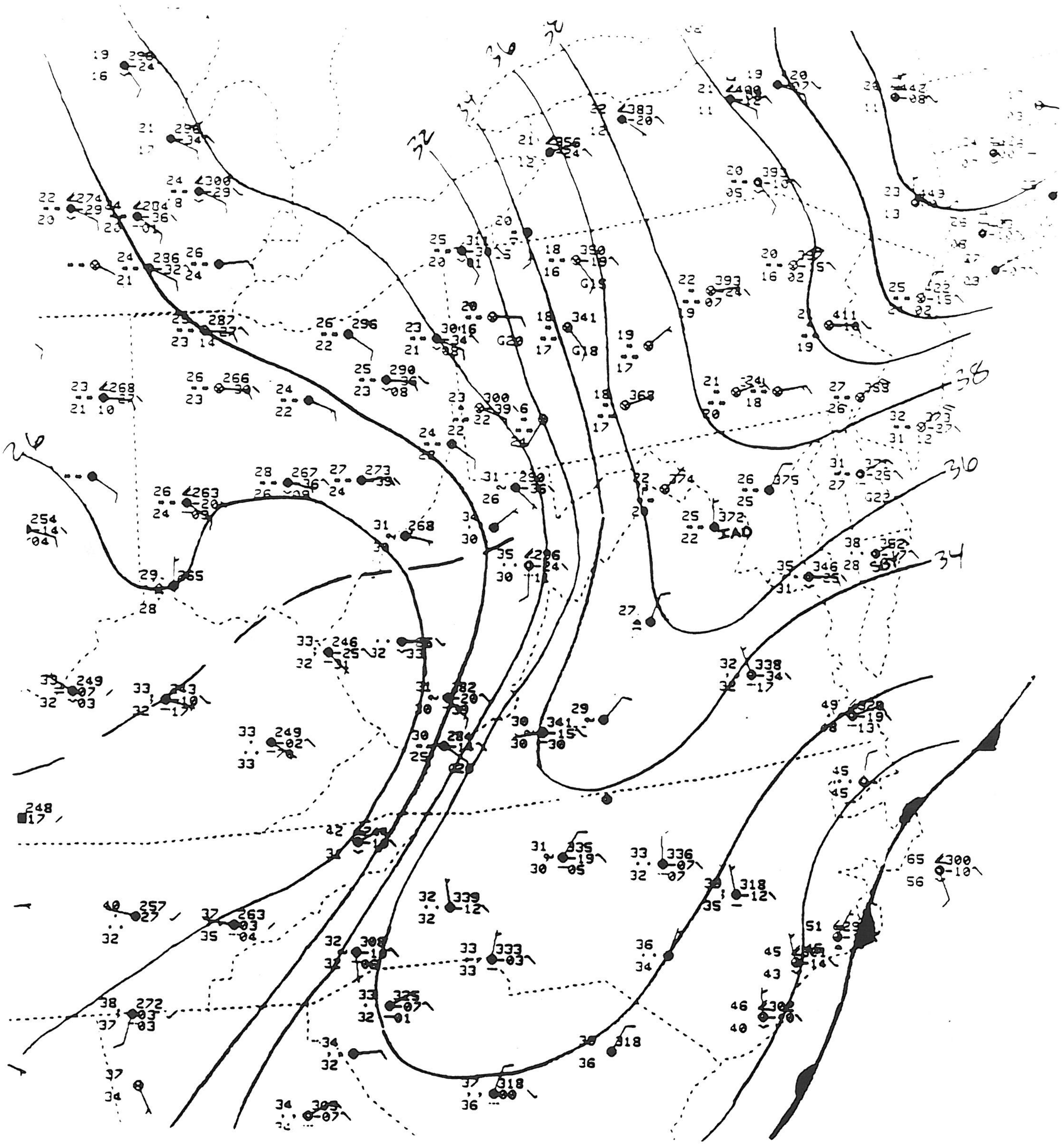

Figure 2. Sea level pressure analysis for 0300 UTC, 28 December 1990.

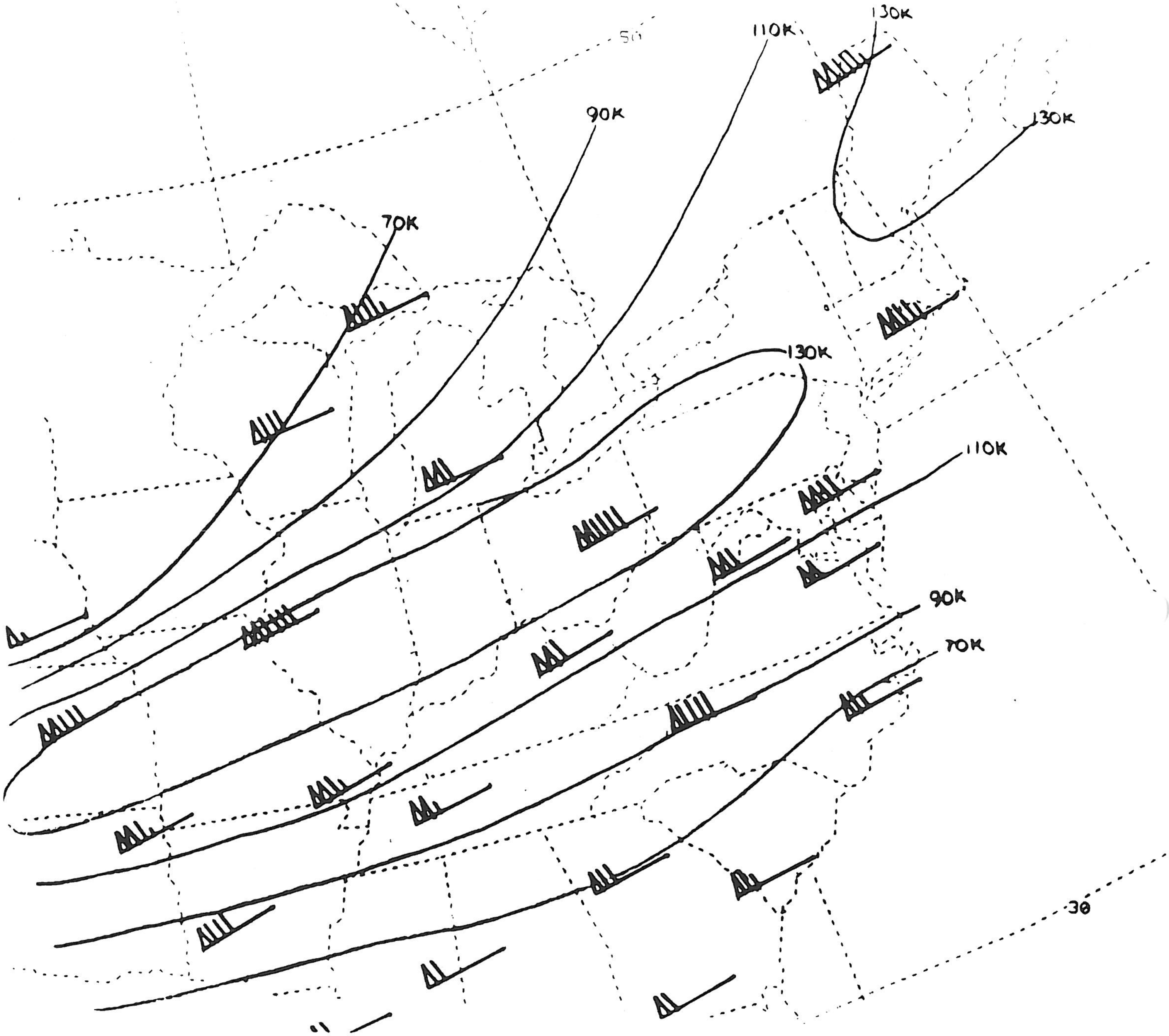

Figure 3a. 300 mb analysis for 1200 UTC, Decmber 27 1990.

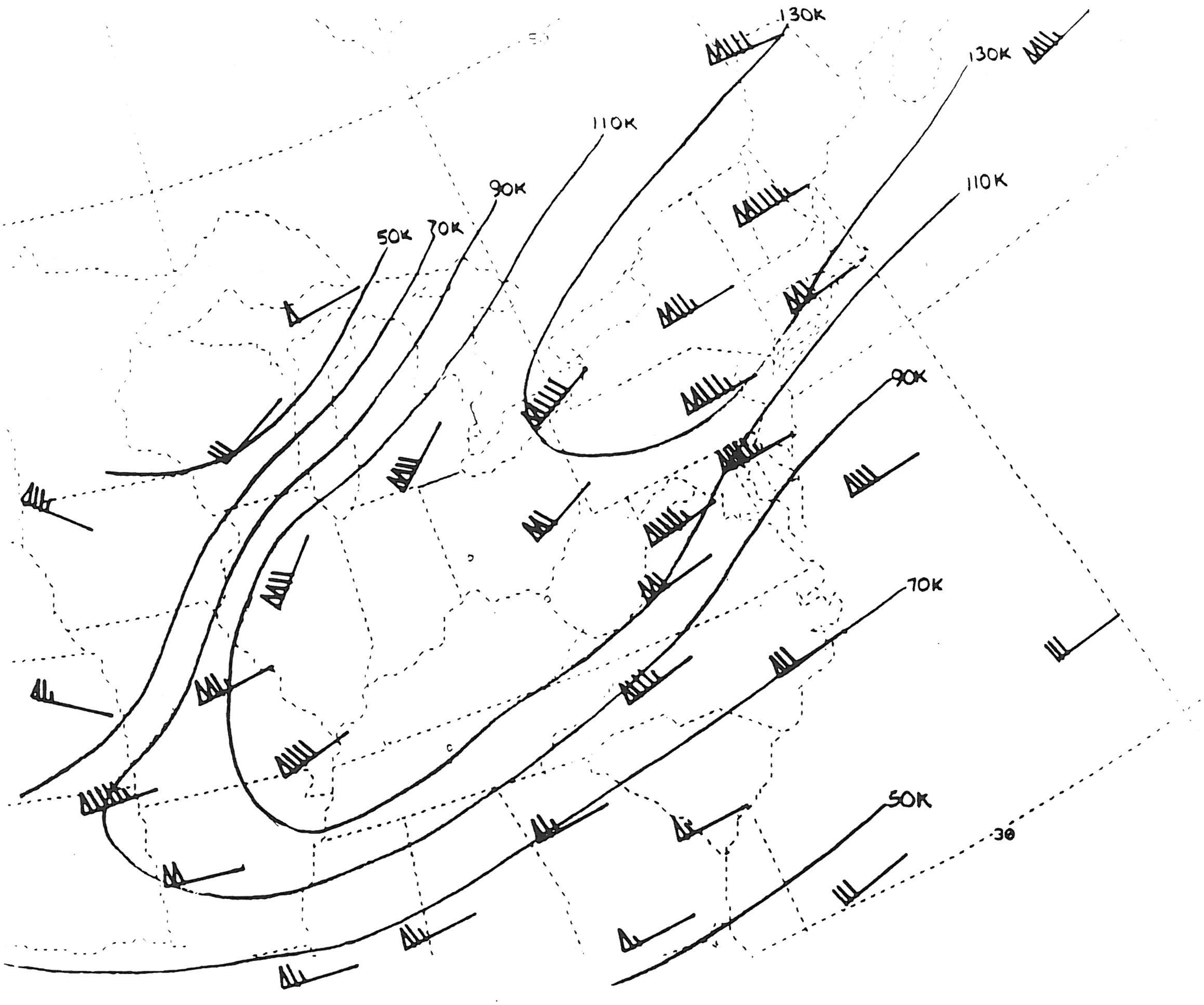

Figure 3b. 300 mb analysis for 0000 UTC, Decmber 28 1990.

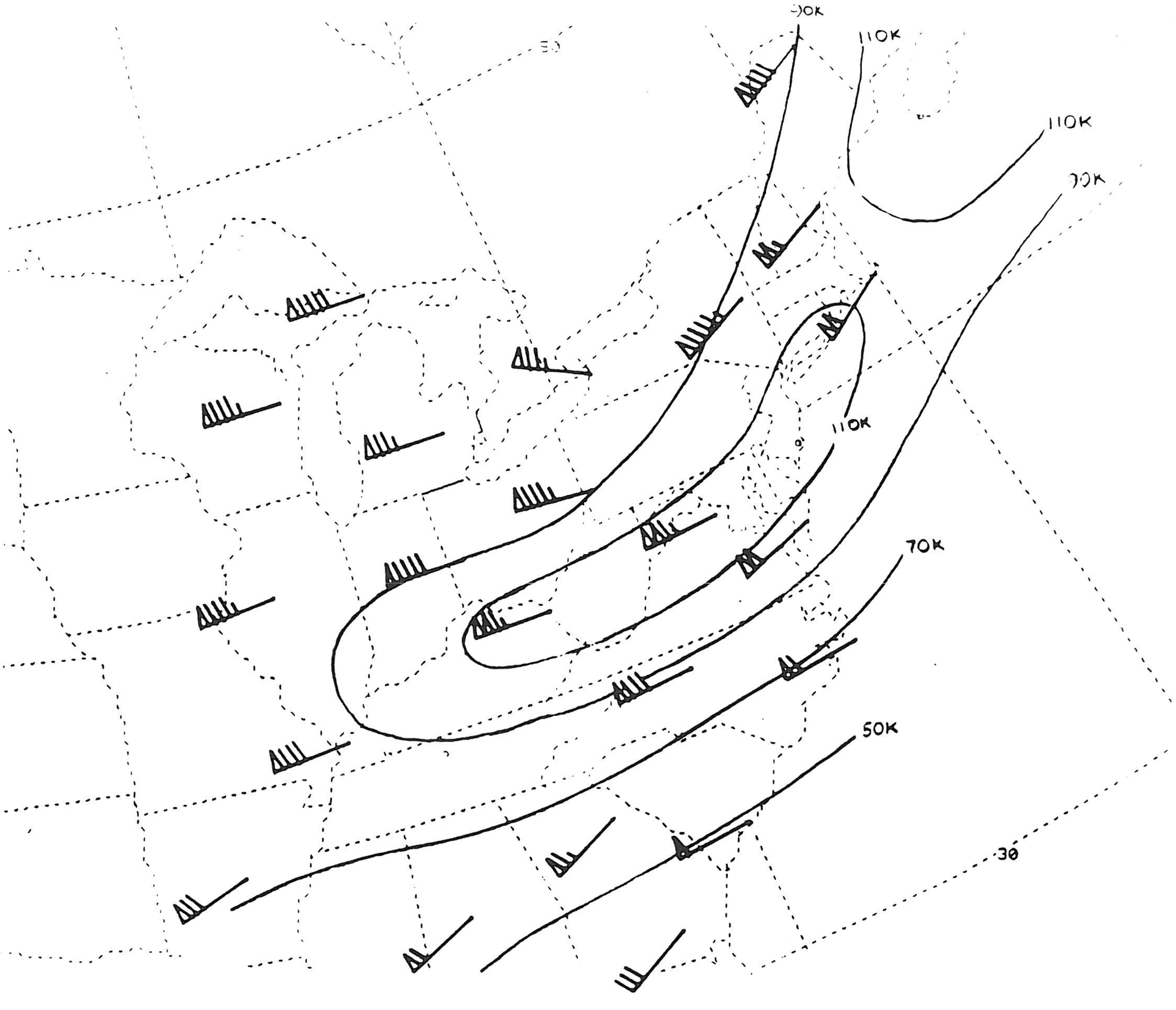

Figure 3c. 300 mb analysis for 1200 UTC, Decmber 28 1990.

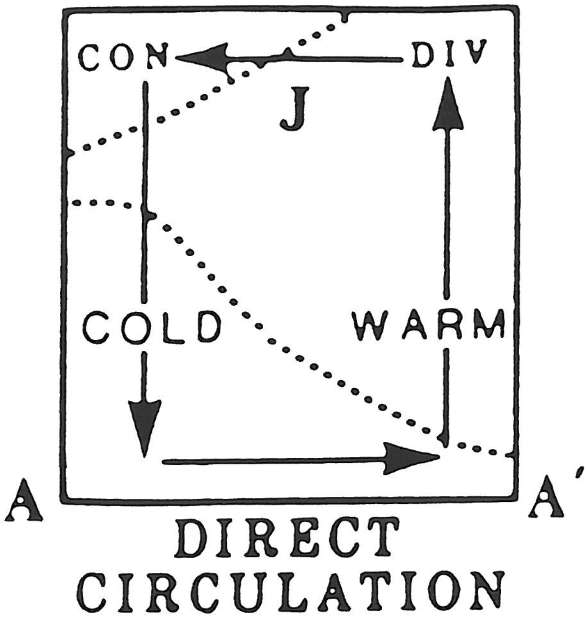

Figure 4. Vertical cross section illustrating direct circulation associated with the right entrance region of a jet streak. The illustration includes isentropes (dotted lines), position of the upper jet (J), relative positions of warm and cold air, upper divergence, ageostrophic components, and vertical motions (from Uccellini and Kocin 1987).

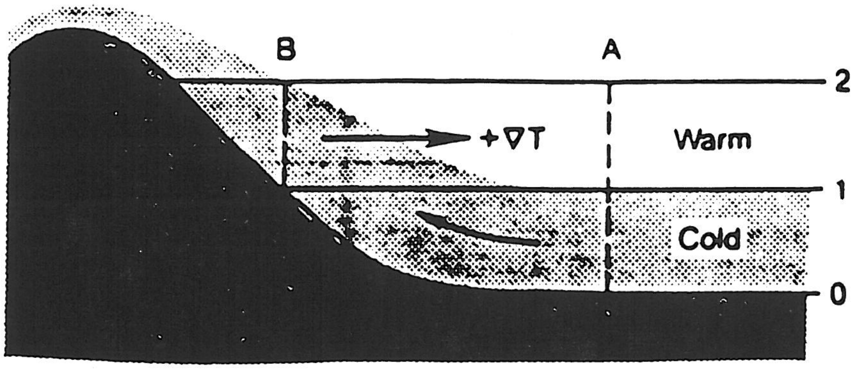

Figure 5. Schematic representing cold air damming in which a stable air mass is blocked by a mountain range (from Schwerdtfeger 1975).

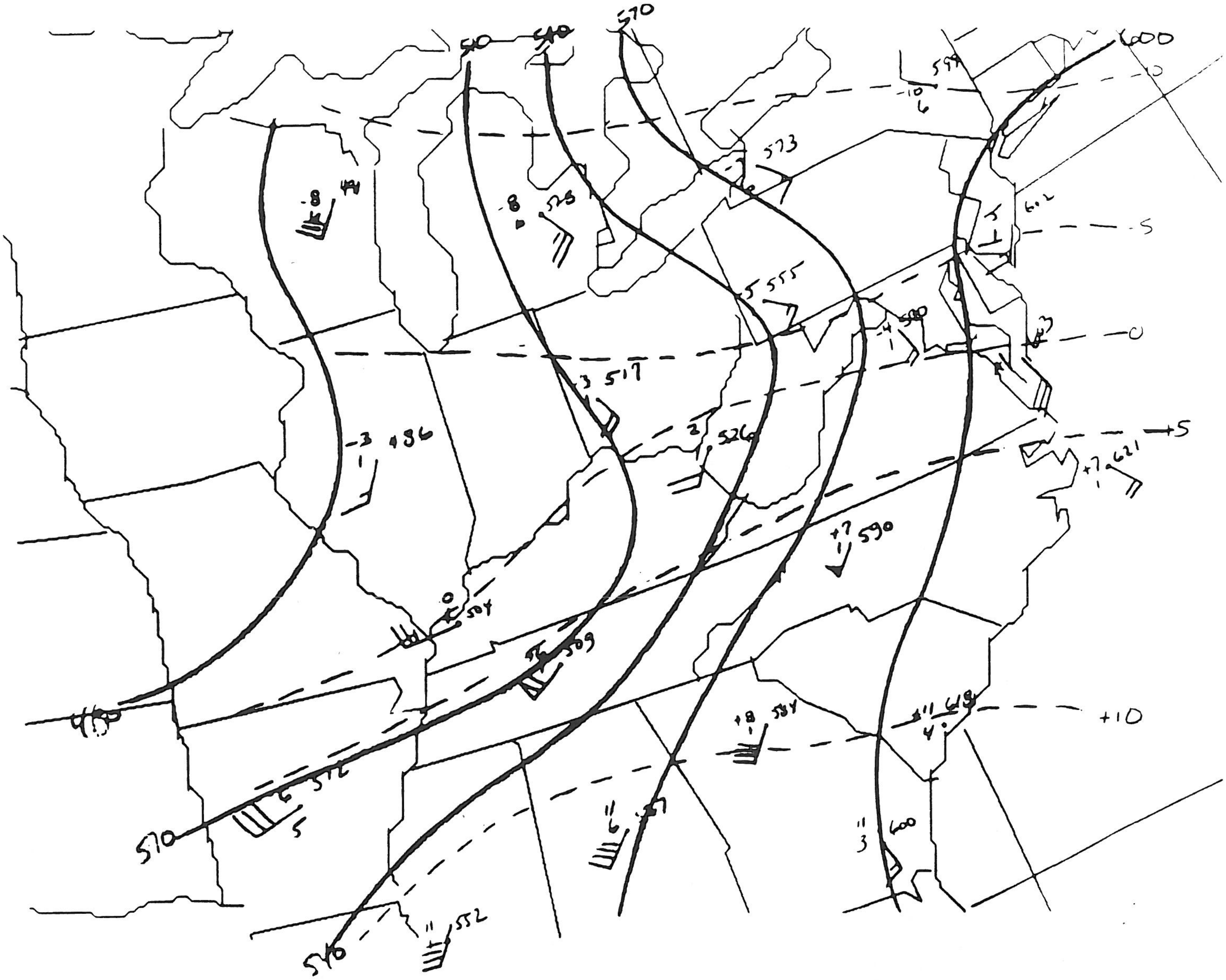

Figure 6. 850 mb analysis for 0000 UTC, 28 December 1990.