

AD-A227 398



NOAA Technical Memorandum NESDIS 30



INSTABILITY BURSTS ASSOCIATED WITH
EXTRATROPICAL CYCLONE SYSTEMS (ECSs)
AND A FORECAST INDEX OF 3-12 HOUR
HEAVY PRECIPITATION

Roderick A. Scofield
Office of Research and Applications
Physical Science Branch

Washington, D.C.
July 1990

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



UNITED STATES
DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

National Oceanic and
Atmospheric Administration
John A. Knauss
Under Secretary

National Environmental Satellite,
Data, and Information Service
Thomas N. Pyke, Jr.
Assistant Administrator

CONTENTS

	<u>Page</u>
Abstract	1
I. Introduction	2
II. Examples of Instability Bursts and Heavy Precipitation	6
III. Relationship of Instability Bursts to ECS Evolution and Cyclogenesis	24
IV. A Forecast Index of 3-12 Hour Heavy Precipitation for ECSSs	33
V. Applications of the Forecast Index to the Forecast of Heavy Snow	39
VI. Summary	72
VII. Outlook	74
VIII. Acknowledgments	75
IX. References	75

Instability Bursts Associated with Extratropical Cyclone
Systems (ECSs) and a Forecast Index of
3-12 Hour Heavy Precipitation

by

Roderick A. Scofield
NOAA/NESDIS/Satellite Applications Laboratory
Washington, DC 20233

ABSTRACT. Instability Bursts (IBs) are one of the primary mechanisms for producing heavy precipitation from Extratropical Cyclone Systems (ECSs). ECSs represent the mesoscale features within synoptic scale weather systems that range in size from subsynoptic scale waves and vortices to large synoptic scale baroclinic leafs, "comma heads" and cloud bands. IBs are depicted in satellite imagery as convective subsynoptic or mesoscale cloud patterns that form or develop rapidly and produce localized heavy precipitation (rain or snow) as the air mass quickly destabilizes. IBs are best detected by using a combination of satellite imagery and instability analyses derived from surface and upper air data and numerical model forecasts. In the satellite imagery, IBs are identified as developing subsynoptic scale wave patterns, baroclinic leaf-type patterns or convective cloud areas (or bands) embedded within the ECS cloud pattern. Often these cloud patterns are growing and becoming colder. In the surface and upper air data (including numerical model forecasts), IBs are associated with: (1) the maximum advection of unstable air, or (2) an upper level disturbance (or jet streak) passing over an unstable air mass. Examples of IBs and heavy precipitation are presented in this study.

There is a relationship between IBs, evolution and deepening of ECSs. IBs appear to be present in most cyclogenetic events; however, other favorable middle-level (vorticity centers and positive

vorticity advection) and upper-level atmospheric conditions (a jet streak and diffluent jet stream pattern) must also be present. IBs when described by the patterns of advection of equivalent potential temperature (θ_e) evolve into recurring patterns prior to and during the development of rapidly deepening surface lows.

An IB by itself is not sufficient to produce heavy precipitation. For heavy precipitation to occur, there must be present (or forecast): a slow moving or regenerative or rapid deepening ECS and moisture. Collectively these characteristics form the basis of a Forecast Index of 3-12 Hour Heavy Precipitation. Applications of this index are presented.

I. INTRODUCTION

One of the greatest challenges for an operational meteorologist is understanding the evolution and characteristics of precipitation within the Extratropical Cyclone System (ECS). ECSs are the mesoscale features within synoptic scale weather systems that range in size from subsynoptic scale waves and vortices to large synoptic scale baroclinic leafs, "comma heads" and cloud bands. Convective bands or areas are a dominant feature of the ECS heavy precipitation areas; as documented by Houze et al. (1981), Herzegh and Hobbs (1980) and Sanders (1984). Heavy precipitation areas associated with ECSs develop and end suddenly, usually over small areas. Instability Bursts (IBs) are one of the primary mechanisms for producing heavy precipitation associated with ECSs. IBs are defined as convective, subsynoptic or mesoscale, cloud patterns that form or develop rapidly and produce localized heavy precipitation (rain or snow) as the air mass quickly destabilizes. Lightning and thunder will sometimes accompany an IB. IBs are best detected by using a combination of satellite imagery and instability analyses derived from surface and upper air data and numerical forecast data. Figure 1 illustrates a Mesoscale Convective System (MCS) over Kansas; Figures 2a, b, c show three examples of ECSs from which 1-2 feet of snow fell over the Washington, DC metropolitan area (Figures 2a,b) and Missouri (Figure 2c). These ECSs (that are actually baroclinic leafs) in Figure 2 look like the summertime MCS in Figure 1; are these ECSs really MCSs?

In satellite imagery, IBs appear as developing subsynoptic scale wave patterns, baroclinic leaf-type patterns, or convective cloud areas (or bands) embedded within the ECS cloud pattern. Often these convective features grow rapidly and the cloud top temperatures become progressively colder in the infrared (IR) imagery. These features appear to form suddenly or "burst" their way into existence like MCSs. IBs are associated with: (1) maximum warm advection of unstable air or (2) an upper level disturbance or jet streak passing over an unstable air mass. IBs

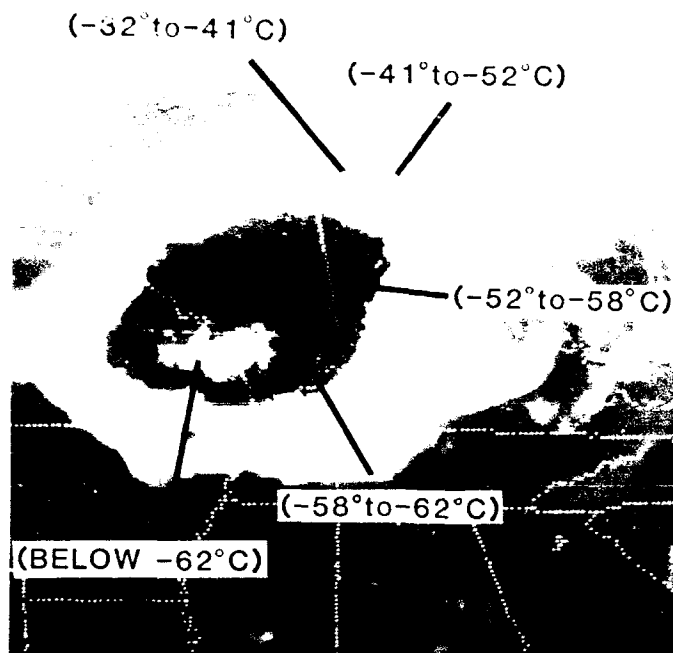


Figure 1. A Mesoscale Convective System (MCS) in the enhanced IR imagery (MB Curve), September 11, 1984, 0800 GMT.

and heavy precipitation can be expected in areas: (1) of positive advection of equivalent potential temperature (θ -e), especially at 850 mb (700 mb in the Western Region) - see Figures 3a, b (θ -e advection is discussed in more detail in the next paragraph); (2) of maximum 850 mb flow from higher to lower K index* values ($K=10-20$ for heavy snow; $K=20-30$ for heavy rain and $K > 30$ for deep convection (see Figure 4) and (3) where significant vertical motion occurs over a moist and rather unstable air mass ($K > 0$, 850 mb θ -e advection can vary from slightly < 0 to slightly > 0 and/or Conditional Symmetric Instability (CSI)) is present (see Figure 4). CSI, which is sometimes called Slantwise Convection, is another cause of the convective bands or areas associated with heavy precipitation in ECSs (Sanders, 1984). As described by Bennetts and Hoskins (1979) and others, CSI is a result of: inertial instability (a horizontal instability; restoring forces are centrifugal), convective instability (a vertical instability; restoring forces are gravitational) and an atmosphere at or near saturation. Approximate criteria for CSI are an atmosphere that is near saturation and possesses a large horizontal temperature gradient and a small Richardson Number (in the lower to middle troposphere).

* K Index takes into account the temperature difference between 850 and 500 mb, the 850 mb dewpoint and the 700 mb depression; experience has shown that these K Index values are most applicable to winter (cold) season precipitation.

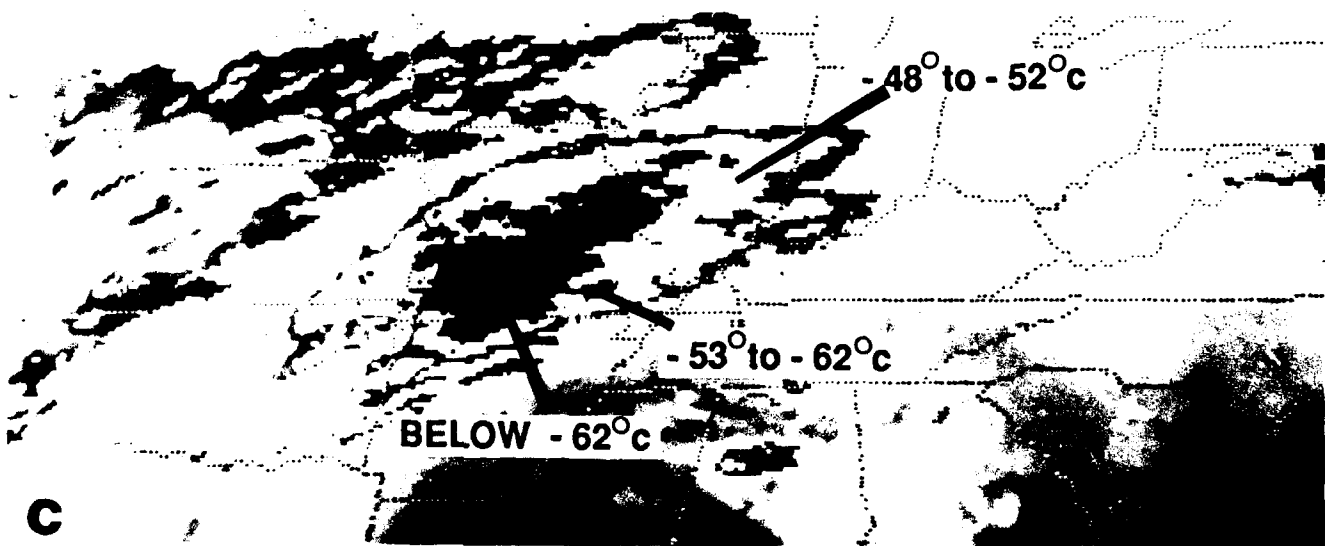


Figure 2. Extratropical Cyclone Systems (ECSs) in the enhanced IR imagery (CC Curve); IR temperature values of the grey shades are shown in "C".

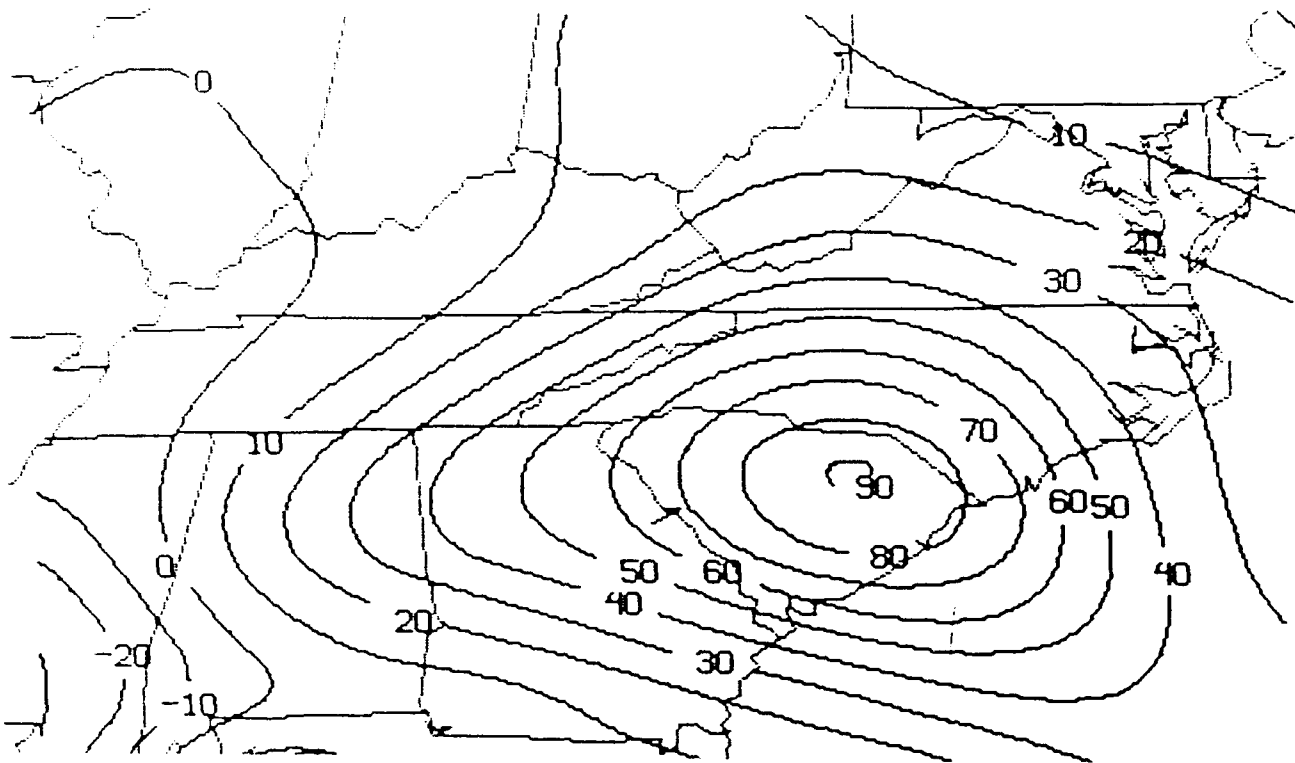


Figure 3a. 850 mb theta-e advection (degrees/day),
January 8, 1988, 0000 GMT.

This paper emphasizes the use of theta-e advection (HERE-AFTER, WRITTEN AS "TEA") and satellite imagery to analyze heavy snow or rain events. TEA is often a conservative/trackable "analysis tool" for locating areas where destabilization (e.g., IBs) of the atmosphere is occurring. Pattern recognition techniques are used on the above (imagery and TEA fields) for analyzing the heavy snow or rain areas. Theta-e ridge axes, maxima and gradients are important for locating where MCSs will develop and propagate (Jiang Shi and Scofield, 1987, Xie Juying and Scofield, 1989 and Scofield and Robinson, 1990). However, TEA patterns appear to be important for locating heavy precipitation within ECSs (Scofield, 1989a,b).

Heavy precipitation (especially, heavy snow, if cold thicknesses and boundary layer temperatures are present) is associated with the following positive 850 and 700 mb TEA patterns:

- o theta-e ridge axes;
- o near areas of theta-e maxima;
- o within areas of theta-e gradients north of the ridge axis (often located 1-3 degrees latitude north of the axis);
- o occasionally, north of ridge axis BUT within areas of weaker theta-e gradients (near the "0" degree advection isopleth) when an upper level system is passing over the area.

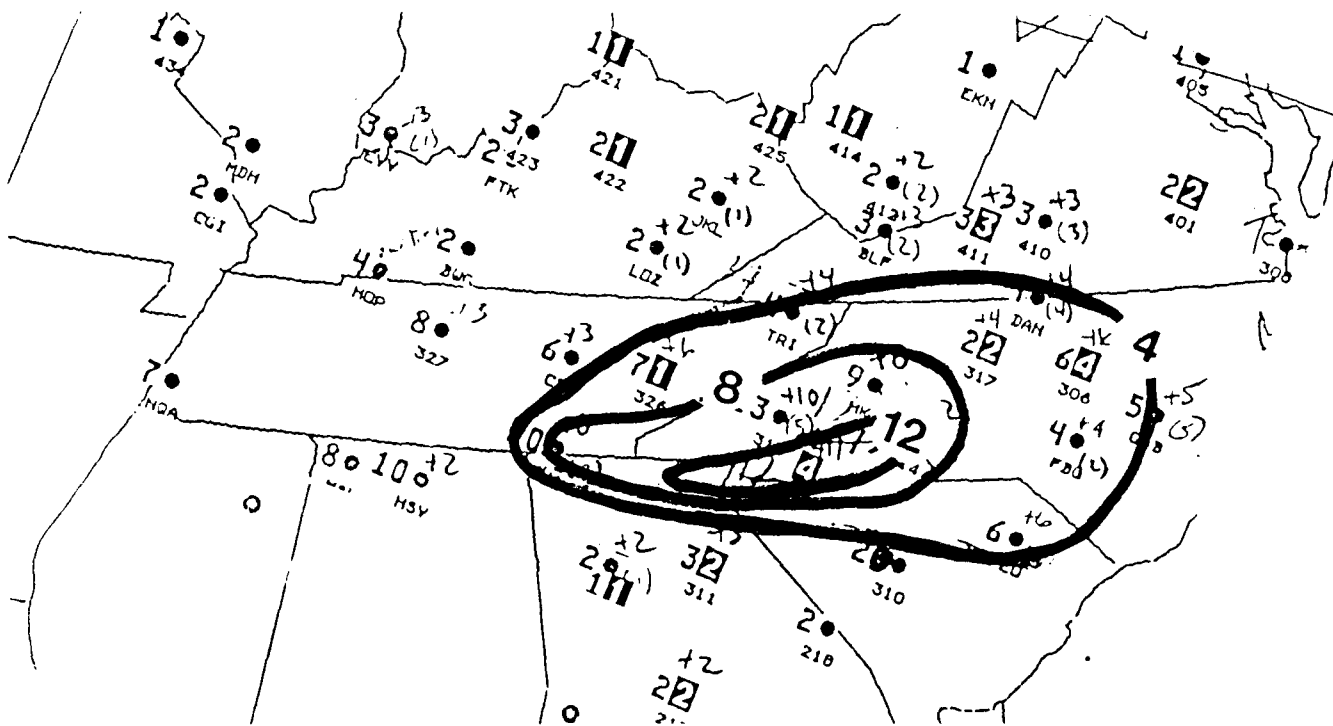


Figure 3b. Twelve hour heavy snowfall (inches) ending at January 8, 1988, 0000 GMT.

However, heavy precipitation areas must be adjusted using the locations of heavy precipitation signatures in the satellite imagery and lifting mechanisms (see Section IV - A Forecast Index Of 3-12 Hour Heavy Precipitation For ECSs). Heavy precipitation (especially thunderstorms/heavy rain) can occur south of the theta-e ridge axis (but still in the positive TEA area) if there are lifting mechanisms and moisture present.

It must be emphasized that TEA (in addition to the other instability analyses like K Index fields and theta-e cross sections) is primarily an analysis tool and can be used for short range prediction as long as the patterns remain conservative and "trackable". TEA is primarily controlled by synoptic scale features. Therefore, there is a relationship to the "conservativeness" and "trackability" of features in the synoptic scale to the predictability of TEA patterns.

An IB by itself is not sufficient to produce heavy precipitation. For heavy precipitation to occur, there must be present (or forecast): a slow moving or regenerative ECS (except in rapidly deepening systems) and moisture. Collectively these items form the basis for a Forecast Index of 3-12 Hour Heavy Precipitation discussed in Section IV.

II. EXAMPLES OF IBs AND HEAVY PRECIPITATION

In this section, IBs are described through the use of satellite imagery and instability analyses derived from conventional data. Instability analyses are presented in one of three forms: K Index fields, TEA fields, and theta-e cross section analyses.

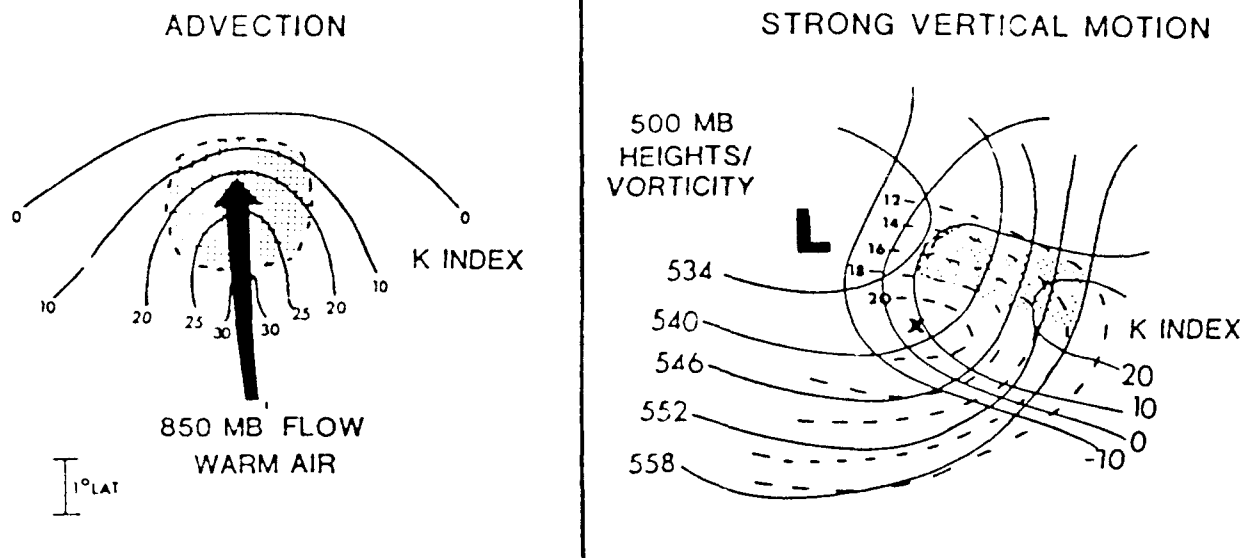


Figure 4. Stability patterns that initiate heavy precipitation in extratropical cyclone systems; stippling represent areas of convective precipitation.

Mid-Atlantic East Coast ECSs (Cloud Bands)
on December 24, 1986 and January 1, 1987

Mid-Atlantic East Coast ECSs occurred on December 24, 1986 and eight days later on January 1, 1987. Both systems had similar: (1) surface and upper air patterns, (2) available moisture and (3) satellite cloud patterns (a wide, elongated cloud band). However, cyclogenesis was stronger with the January system. Nevertheless, the cyclone on December 24th produced very heavy rainfall (2-4 inches) over a large area that resulted in floods in the mid-Atlantic region. The rainfall on January 1st was significant (0.5-1 inch) but substantially less; extreme southeast Virginia and parts of eastern North Carolina did receive 2-3 inches. As shown in Figure 6c, southeast Virginia and eastern North Carolina are close to the IB and maximum destabilization of the atmosphere. Satellite imagery (VISIBLE (VIS) and IR), K Index analyses with the maximum 850 mb winds superimposed and observed rainfall analyses are shown in Figures 5a, b, c, d, respectively, for the December 24 and Figures 6a, b, c, d, respectively, for the January 1 cyclone events. Comparison of these two figures shows a large difference in the stability analyses. Advection of very unstable air (a strong IB) into the mid-Atlantic region occurred on the 24th; the air was more stable (a weak IB) on the 1st. This allowed the precipitation to be more convective ($K > 30$) and less stratiform on the 24th; the precipitation was more stratiform ($K = 20$) on the 1st. The VIS imagery on the 24th shows the clouds associated with the cloud band over Virginia and Maryland to be much more convective (bright and textured) than the ones on the 1st (darker and smoother).

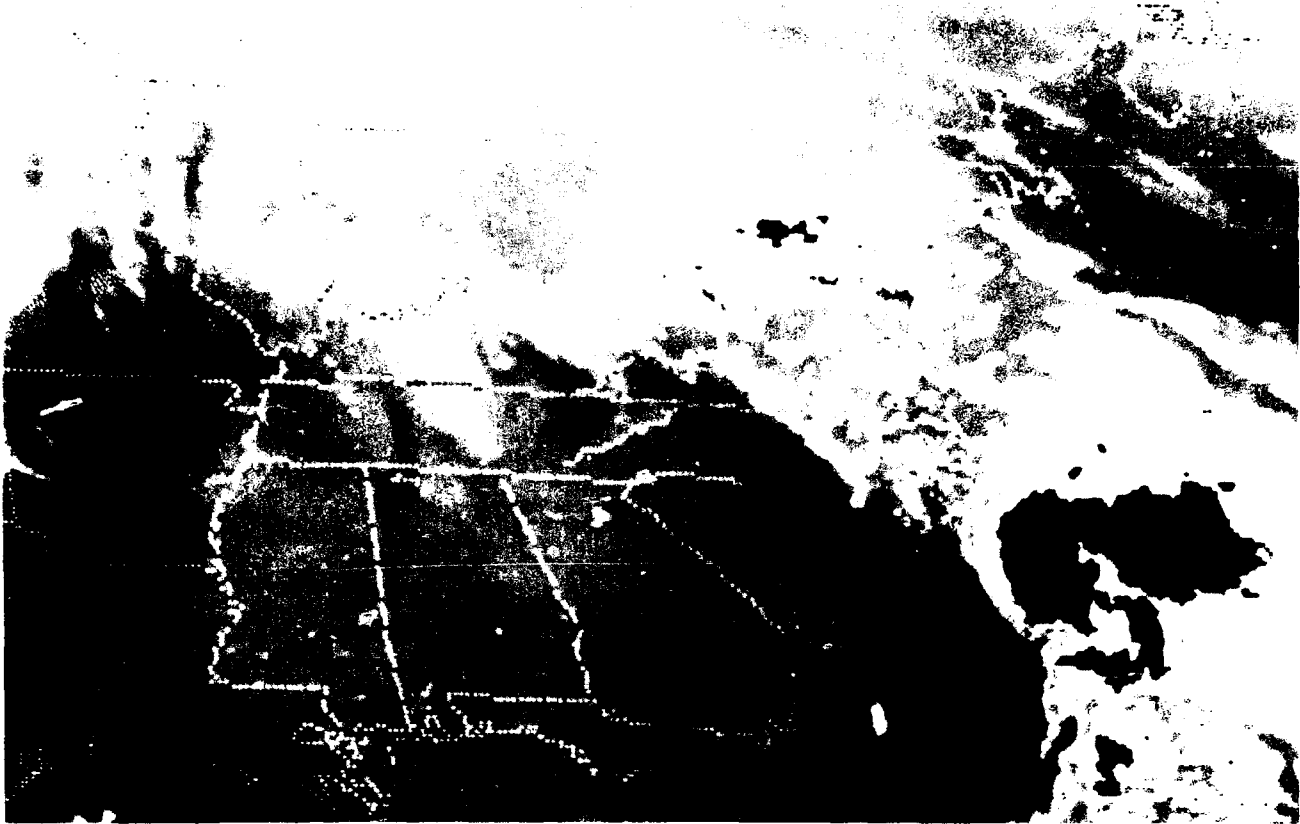


Figure 5a. An Extratropical Cyclone System (ECS) in the enhanced IR imagery (MB Curve), December 24, 1986, 1900 GMT.

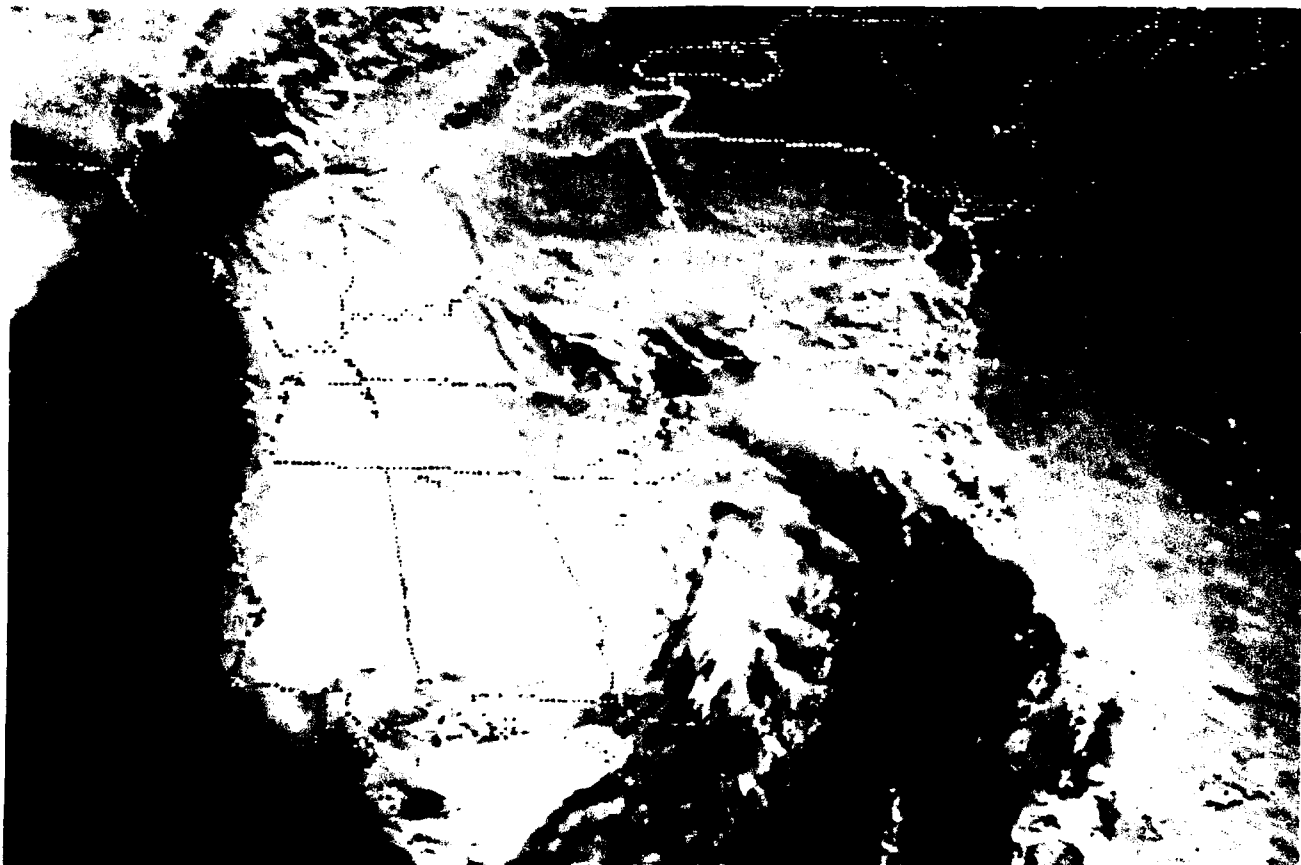


Figure 5b. An Extratropical Cyclone System (ECS) in the VIS imagery, December 24, 1986, 1930 GMT.

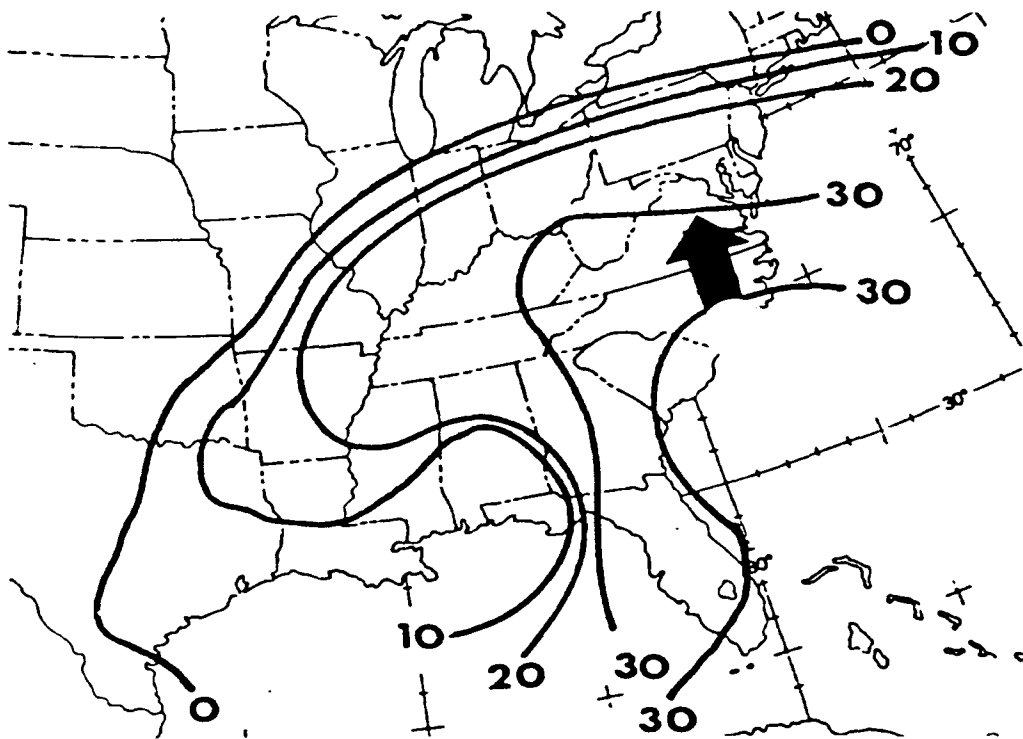


Figure 5c. K Index analyses with 850 mb maximum winds indicated by an arrow.



Figure 5d. Twenty-four hour observed precipitation ending at December 25, 1986, 1200 GMT.

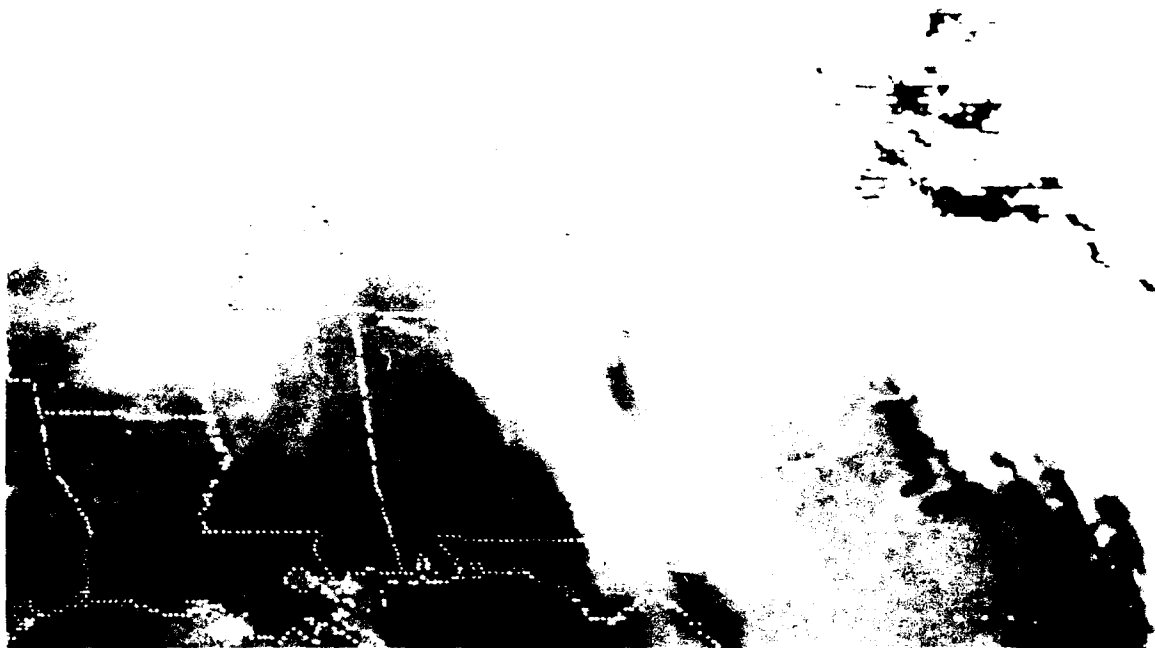


Figure 6a. An Extratropical Cyclone System (ECS) in the enhanced IR imagery (MB Curve), January 1, 1987, 1900 GMT.

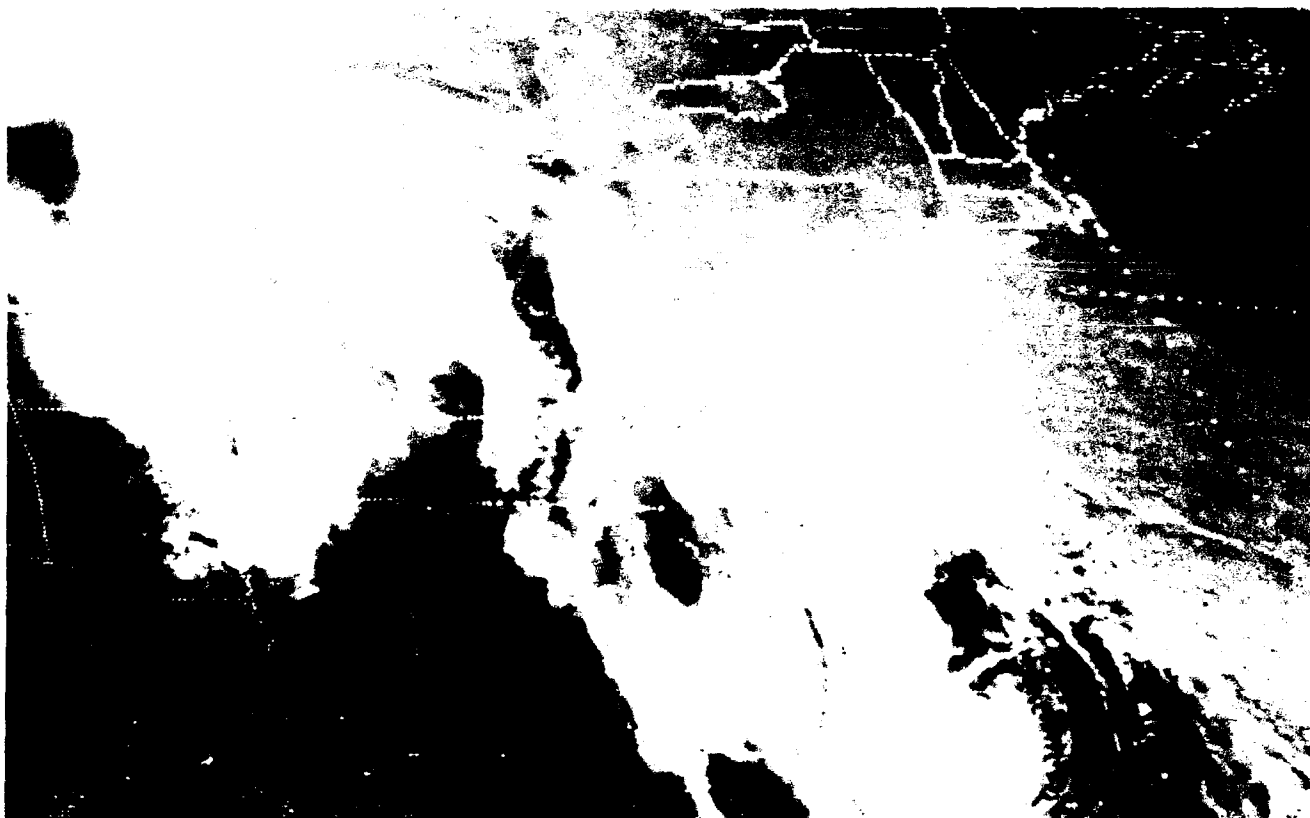


Figure 6b. An Extratropical Cyclone System (ECS) in the VIS imagery, January 1, 1987, 1930 GMT.

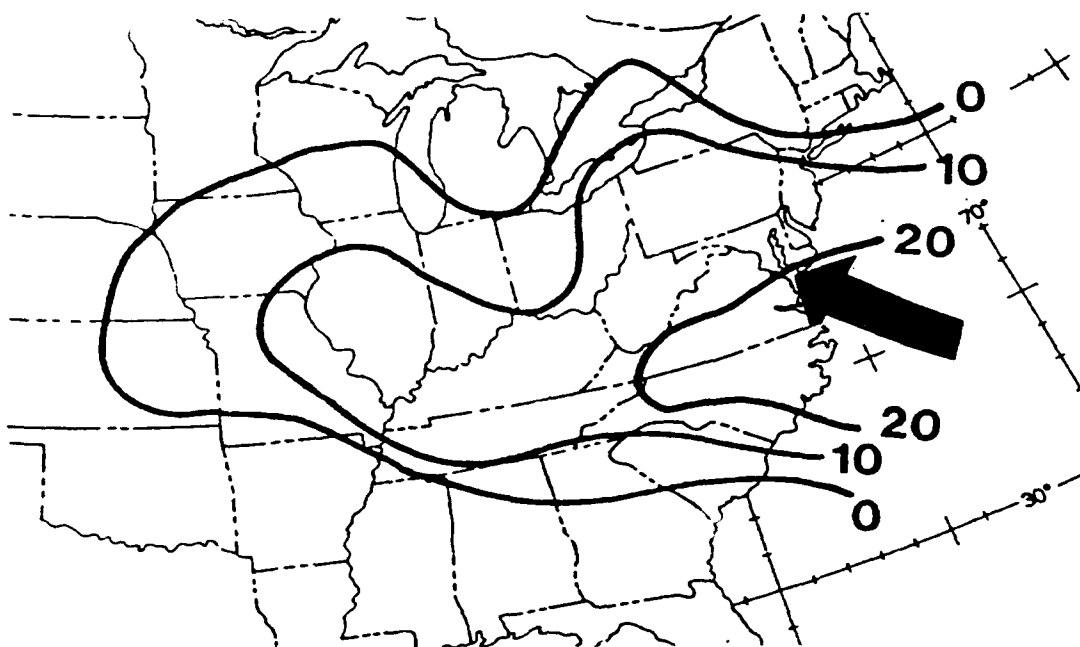


Figure 6c. K Index analyses with 850 mb maximum winds indicated by an arrow.

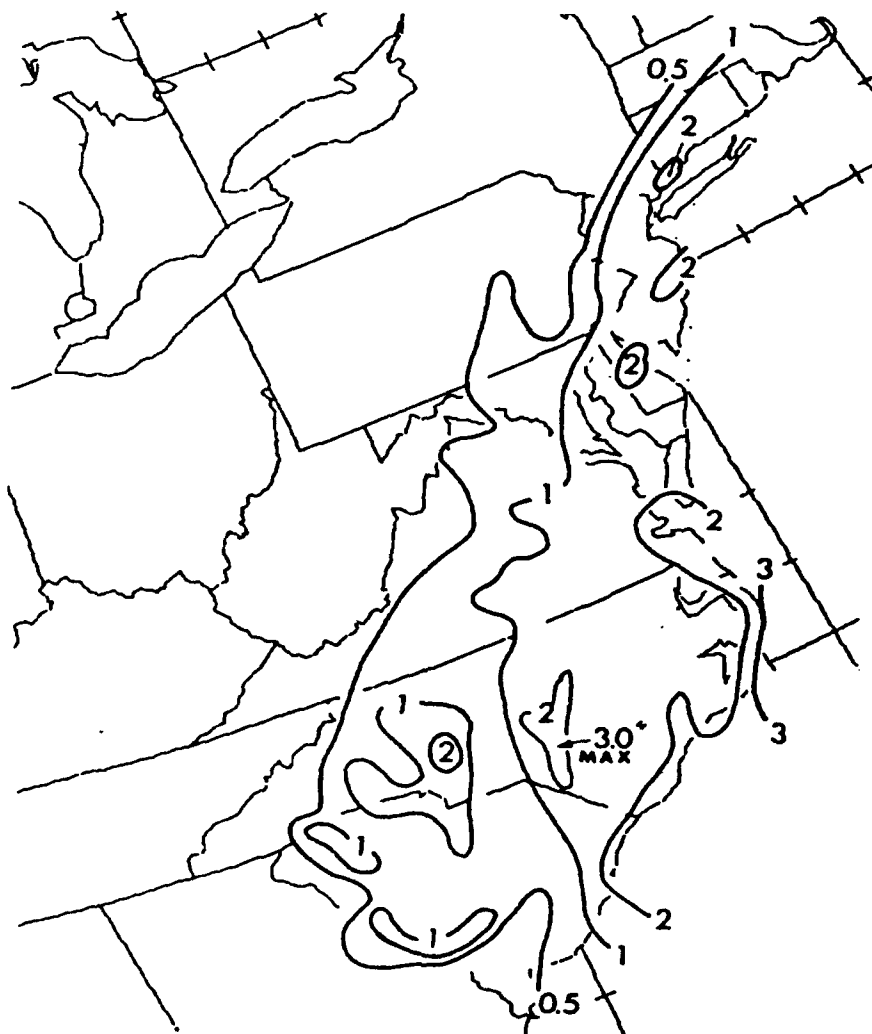


Figure 6d. Twenty-four hour observed precipitation ending at January 2, 1987, 1200 GMT.

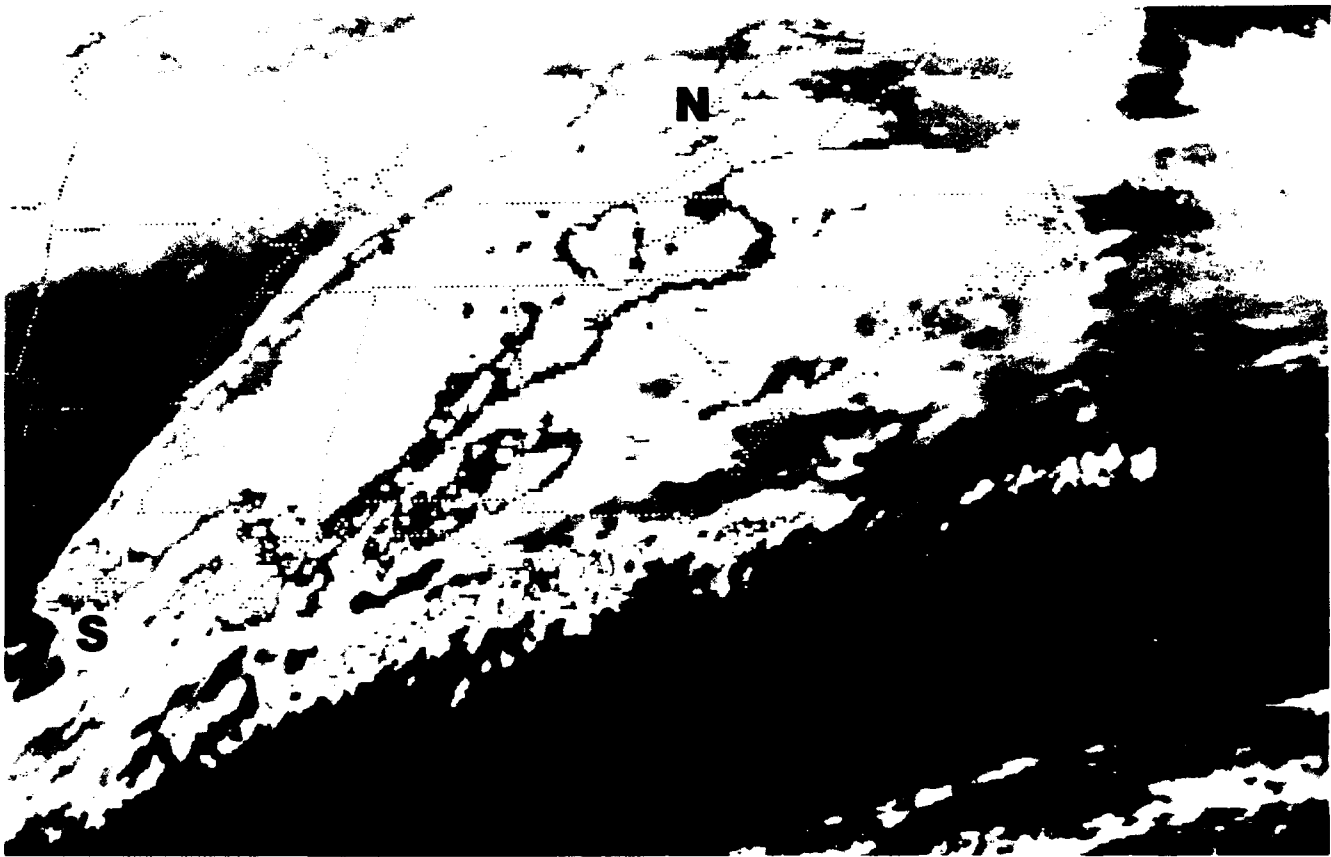


Figure 7a. An Extratropical Cyclone System (ECS) over the southern region and east coast; enhanced IR imagery (CC Curve), January 7, 1988, 1201 GMT.

Southern Region/East Coast Snow Storm (Cloud Bands) on
January 7, 8, 9, 1988

Between January 7-9, 1988, a snowstorm moved from northern Alabama and Georgia to the mid-Atlantic states and New England. Snowfall accumulations ranged from 8-12 inches along the path of the storm. IBs were quite useful in locating the heavy snow areas and in forecasting their movement over 3-12 hours. Satellite imagery, 850 mb TEA analyses and 12 hour heavy snowfall accumulations are shown in Figures 7, 8, and 9, respectively. The 850 mb positive TEA area is quite conservative and trackable as it moved from east-central Mississippi on January 7 at 1200 GMT to the Delaware-New Jersey coast 24 hours later. The advection fields at 1800 GMT and 0600 GMT were interpolated between the two standard upper air sounding periods of 0000 and 1200 GMT. As discussed in Section I, the heaviest snow usually occurs along and north of the axis of maximum TEA and especially in the tightest theta-e gradients. In the satellite imagery a cloud band is observed (at N-S) with embedded convective areas. A cloud band oriented northeast-southwest from Kentucky to Louisiana on January 7, 1200 GMT became more north-south from Virginia to northern Florida, 12 hours later. By January 8, 1200 GMT, the cloud band was located off the east coast; a weak surface low of 1012 mb was located near Cape Hatteras.

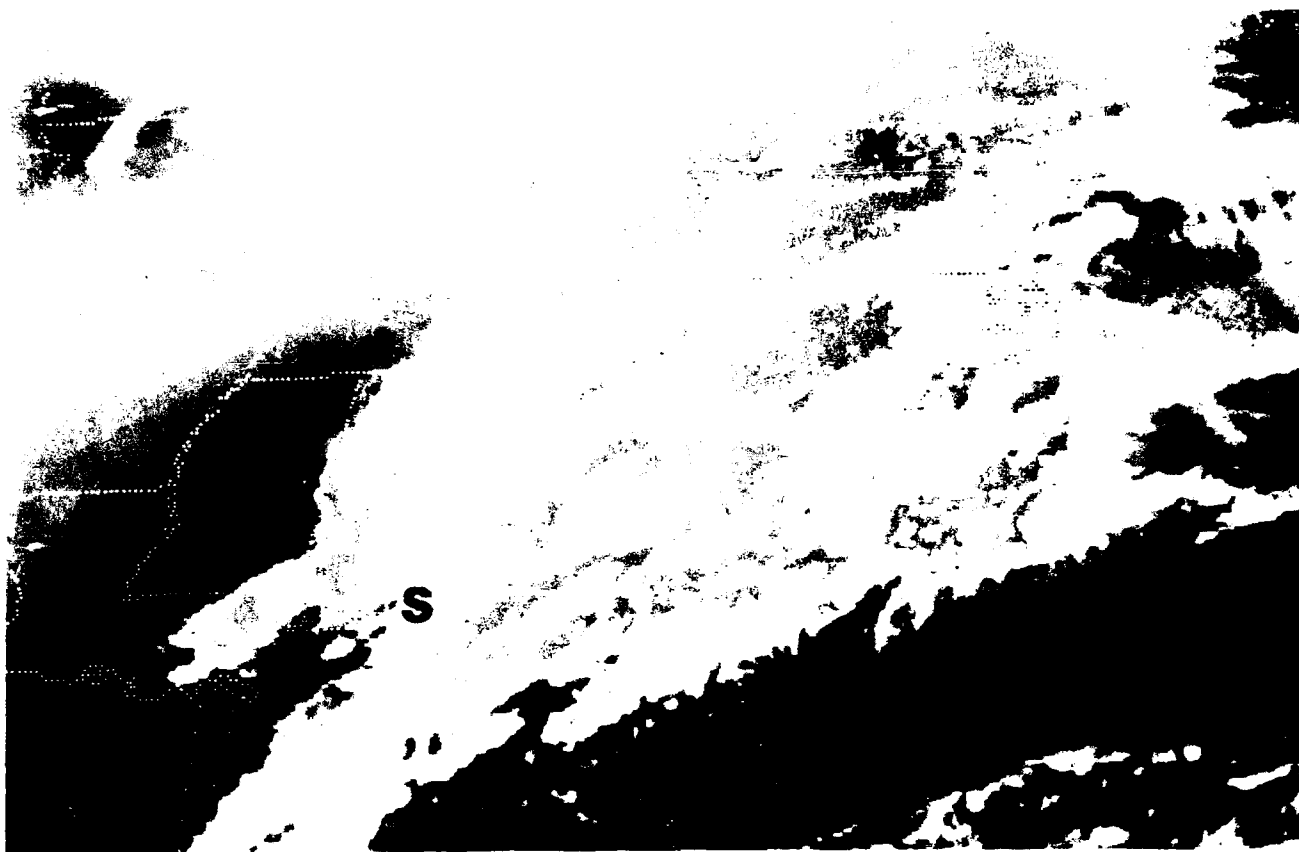


Figure 7b. An Extratropical Cyclone System (ECS) over the southern region and east coast; enhanced IR imagery (CC Curve), January 7, 1988, 1801 GMT.

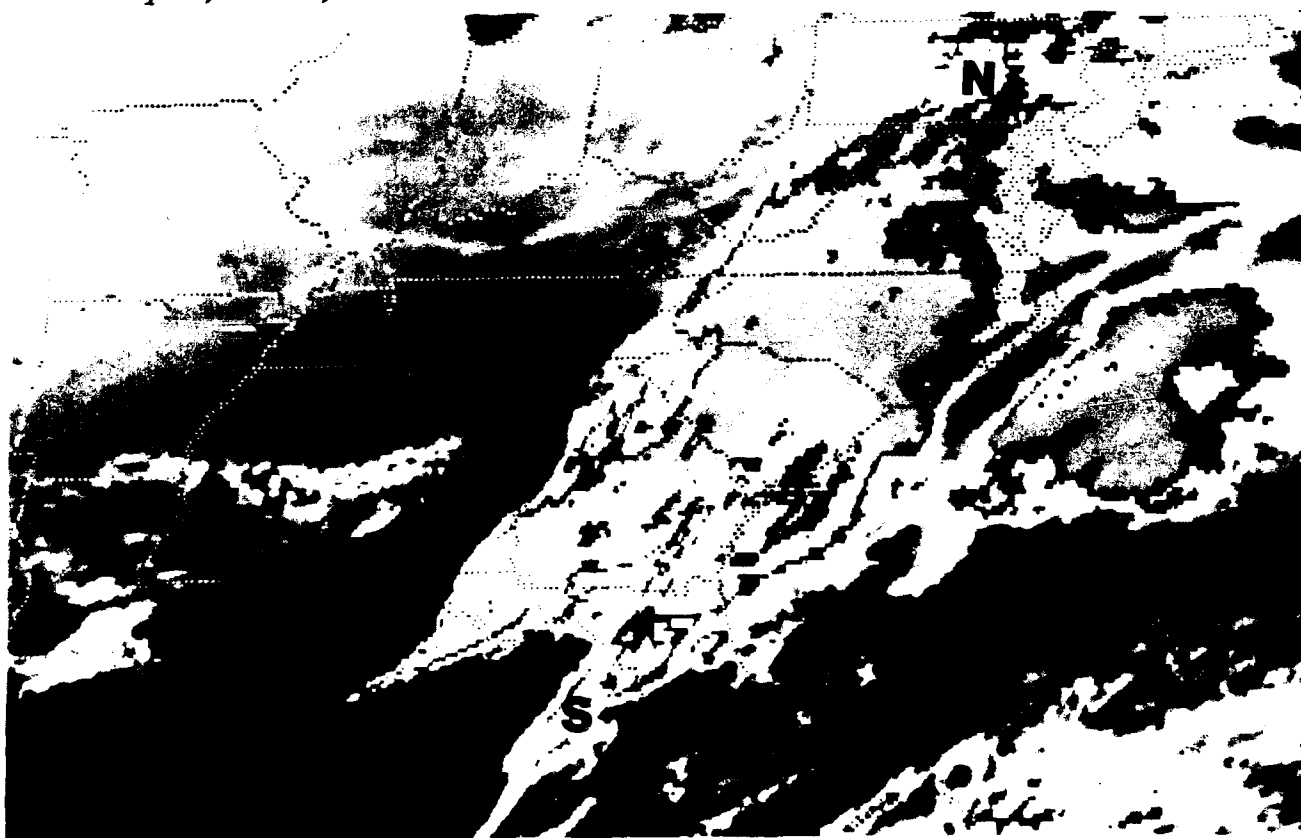


Figure 7c. An Extratropical Cyclone System (ECS) over the southern region and east coast; enhanced IR imagery (CC Curve), January 8, 1988, 0001 GMT.

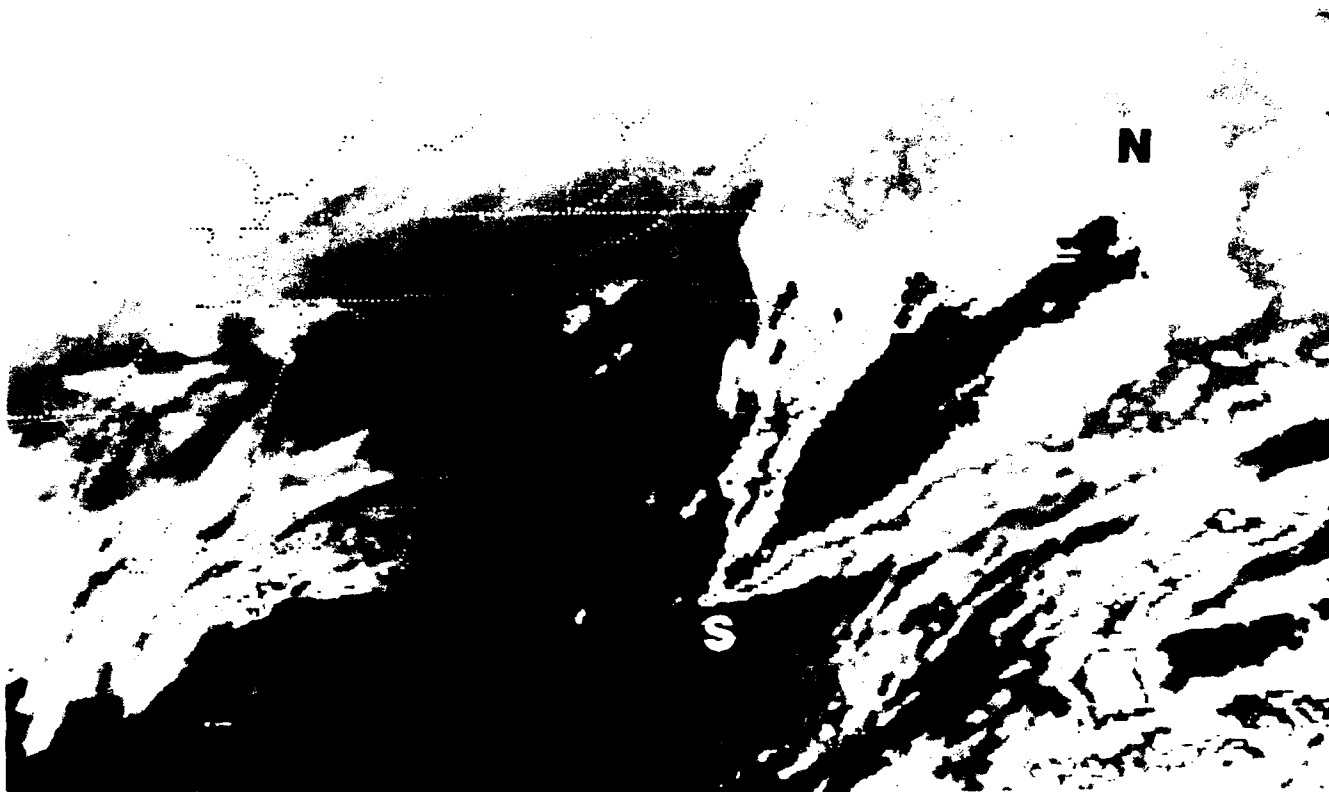


Figure 7d. An Extratropical Cyclone System (ECS) over the southern region and east coast; enhanced IR imagery (CC Curve), January 8, 1988, 0601 GMT.

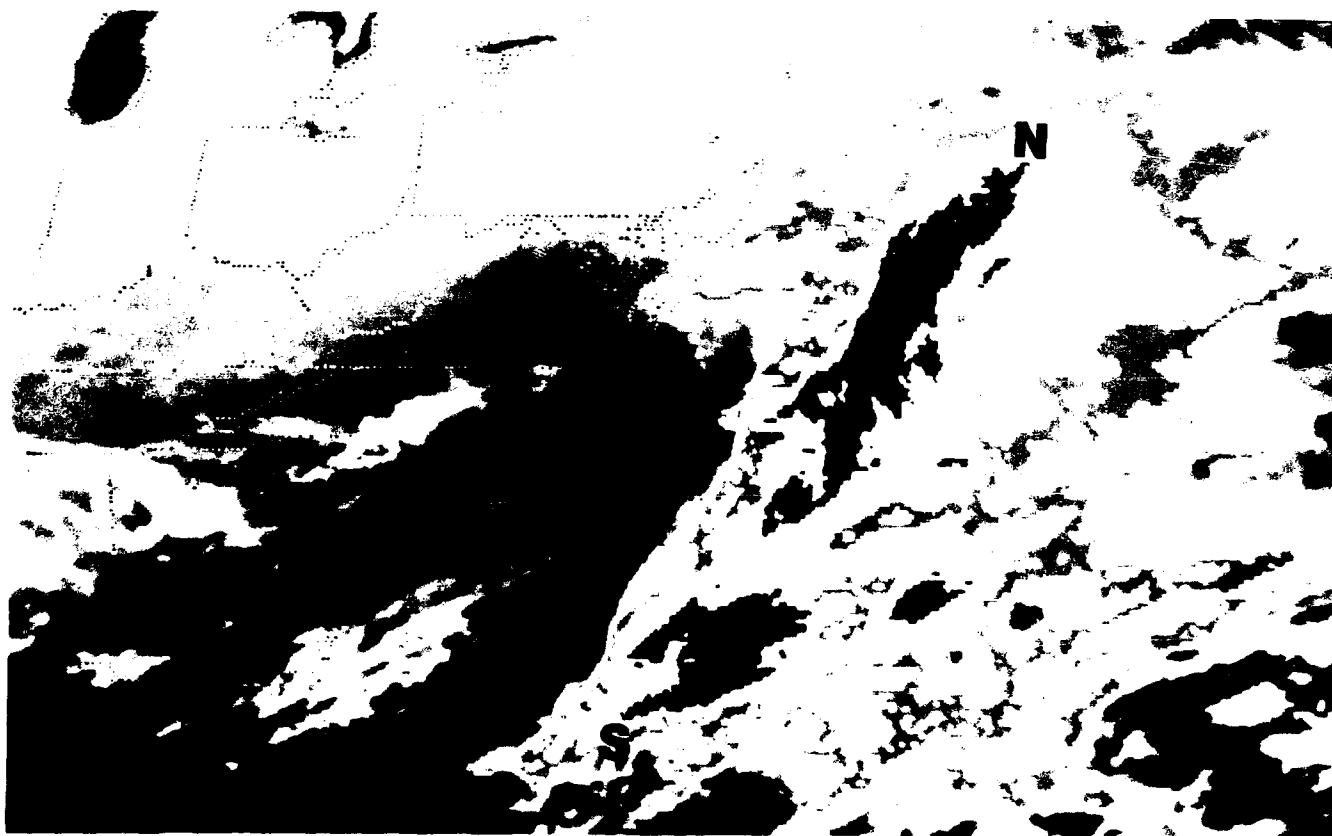


Figure 7e. An Extratropical Cyclone System (ECS) over the southern region and east coast; enhanced IR imagery (CC Curve), January 8, 1988, 1201 GMT.

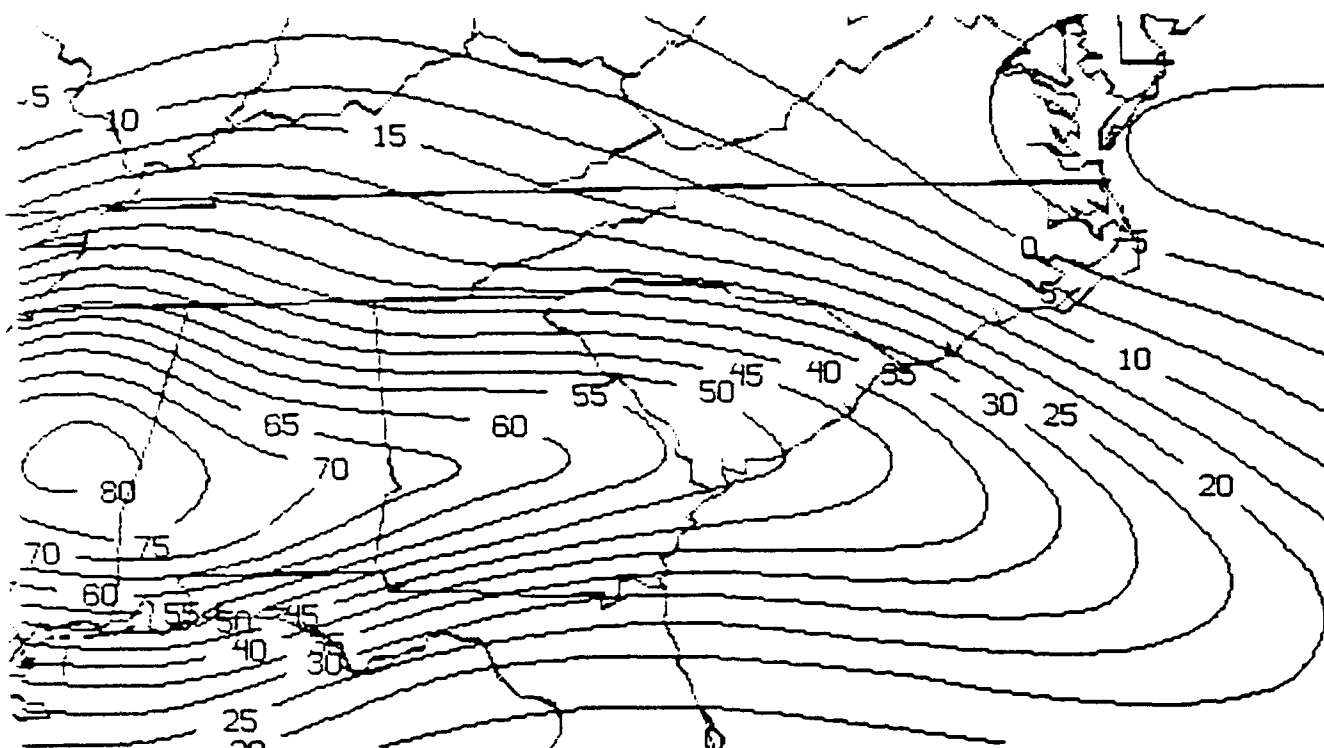


Figure 8a. 850 mb theta-e advection (degrees/day), January 7, 1988, 1200 GMT.

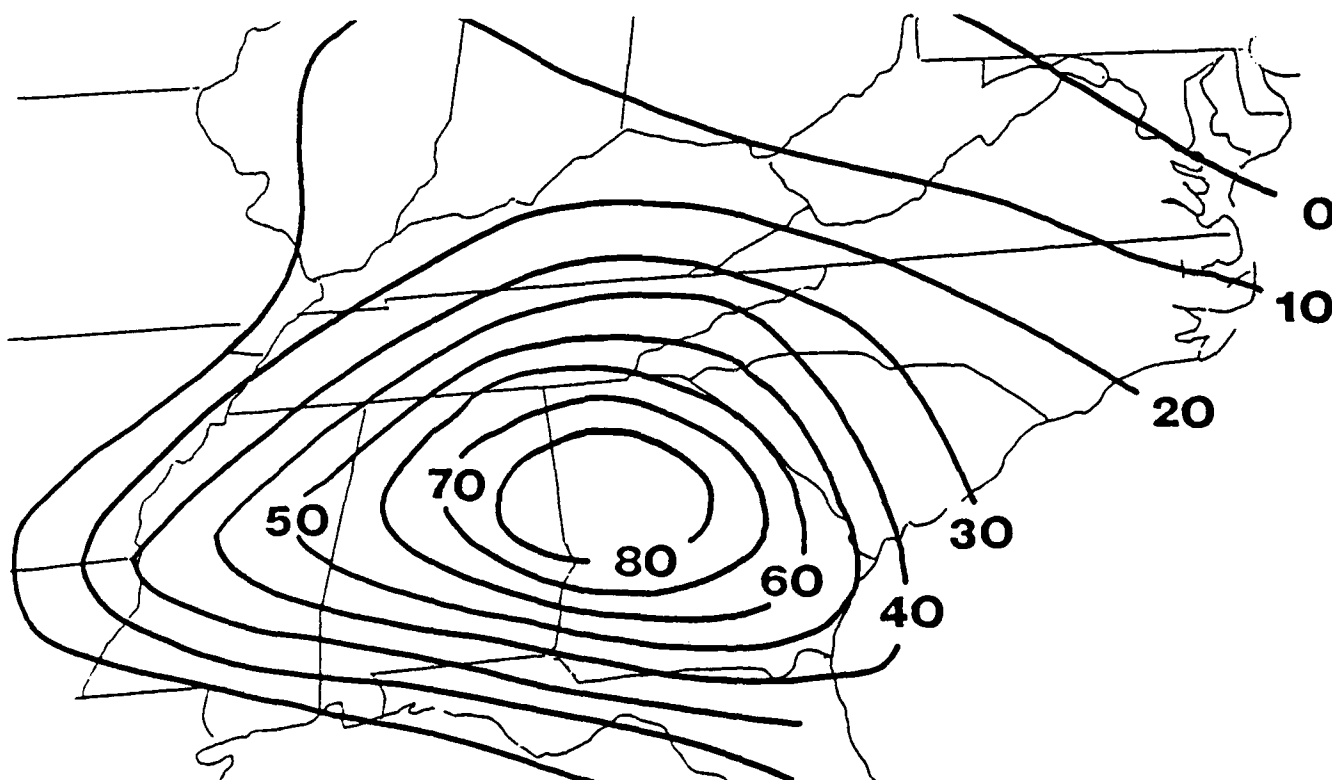


Figure 8b. Interpolated 850 mb theta-e advection (degrees/day) January 7, 1988, 1800 GMT.

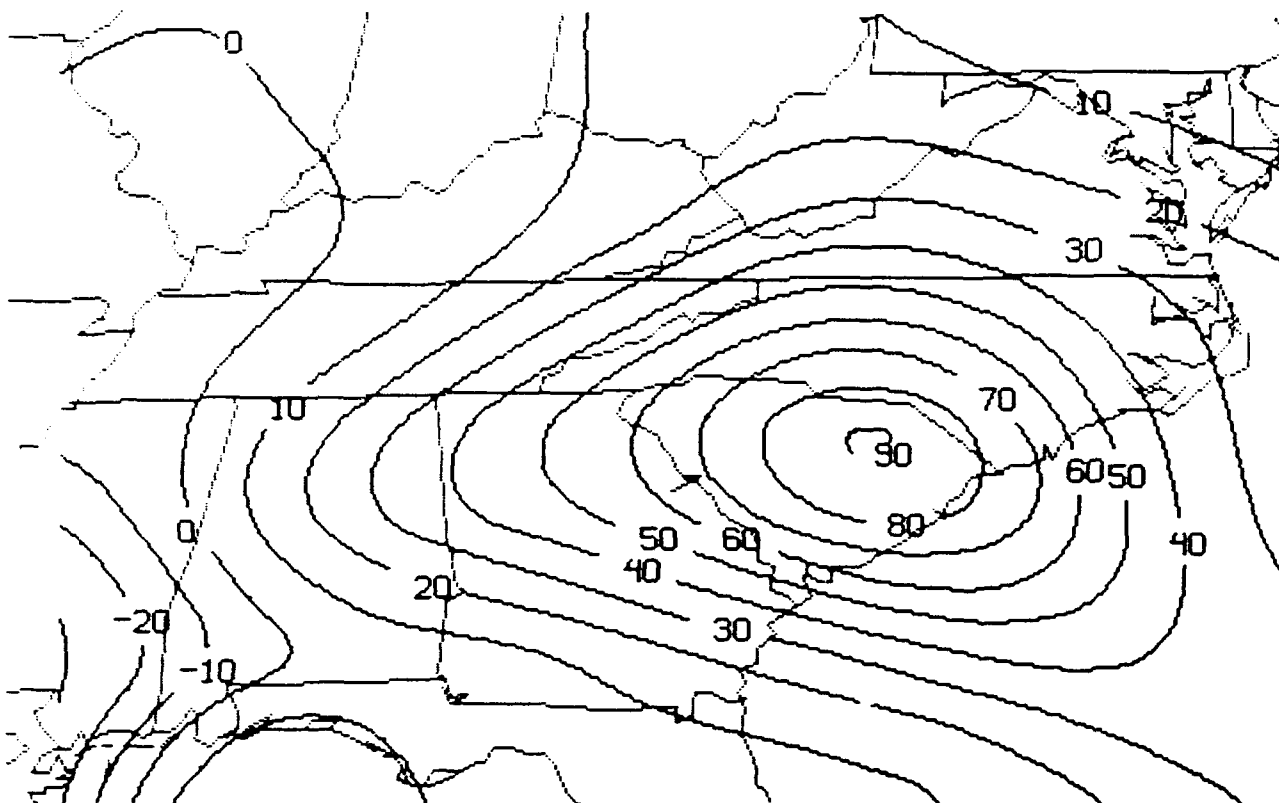


Figure 8c. 850 mb theta-e advection (degrees/day), January 8, 1988, 0000 GMT.

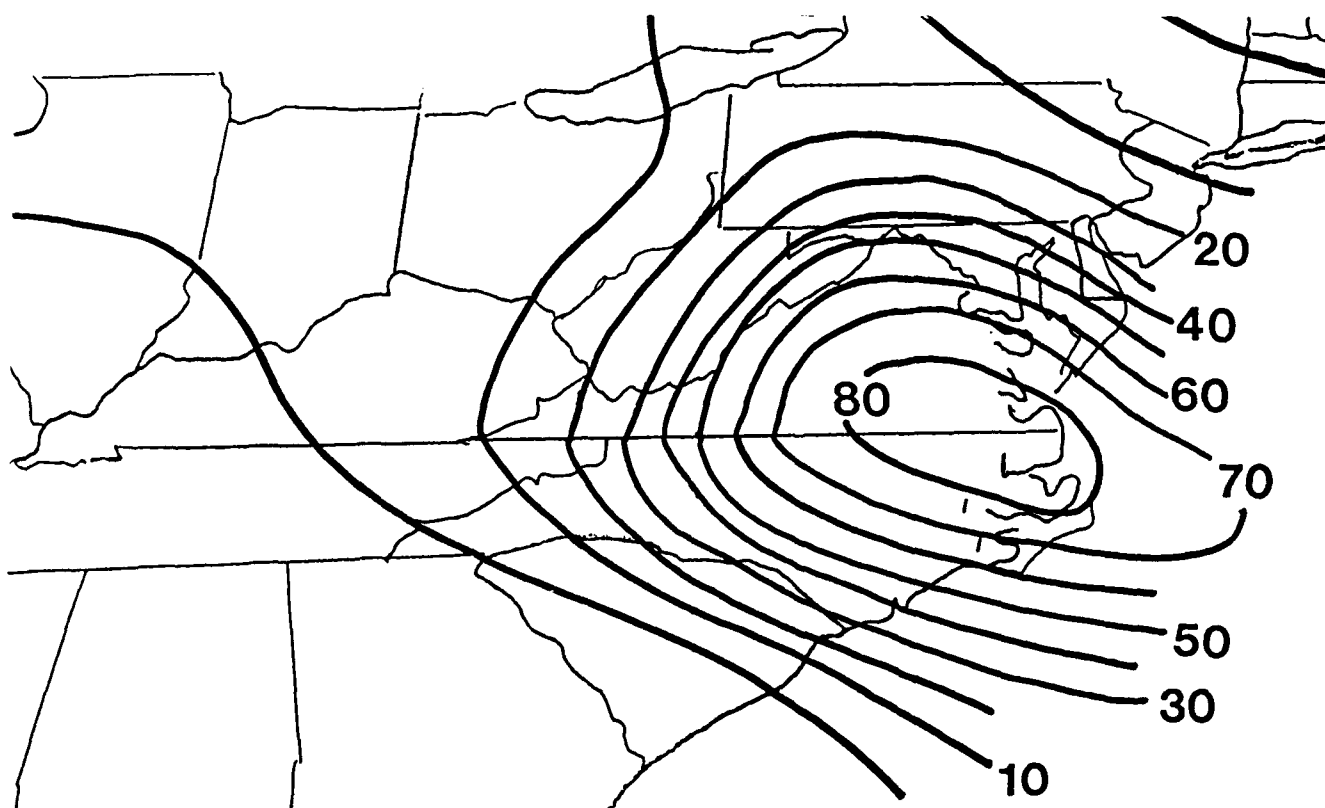


Figure 8d. Interpolated 850 mb theta-e advection (degrees/ day) January 8, 1988, 0600 GMT.

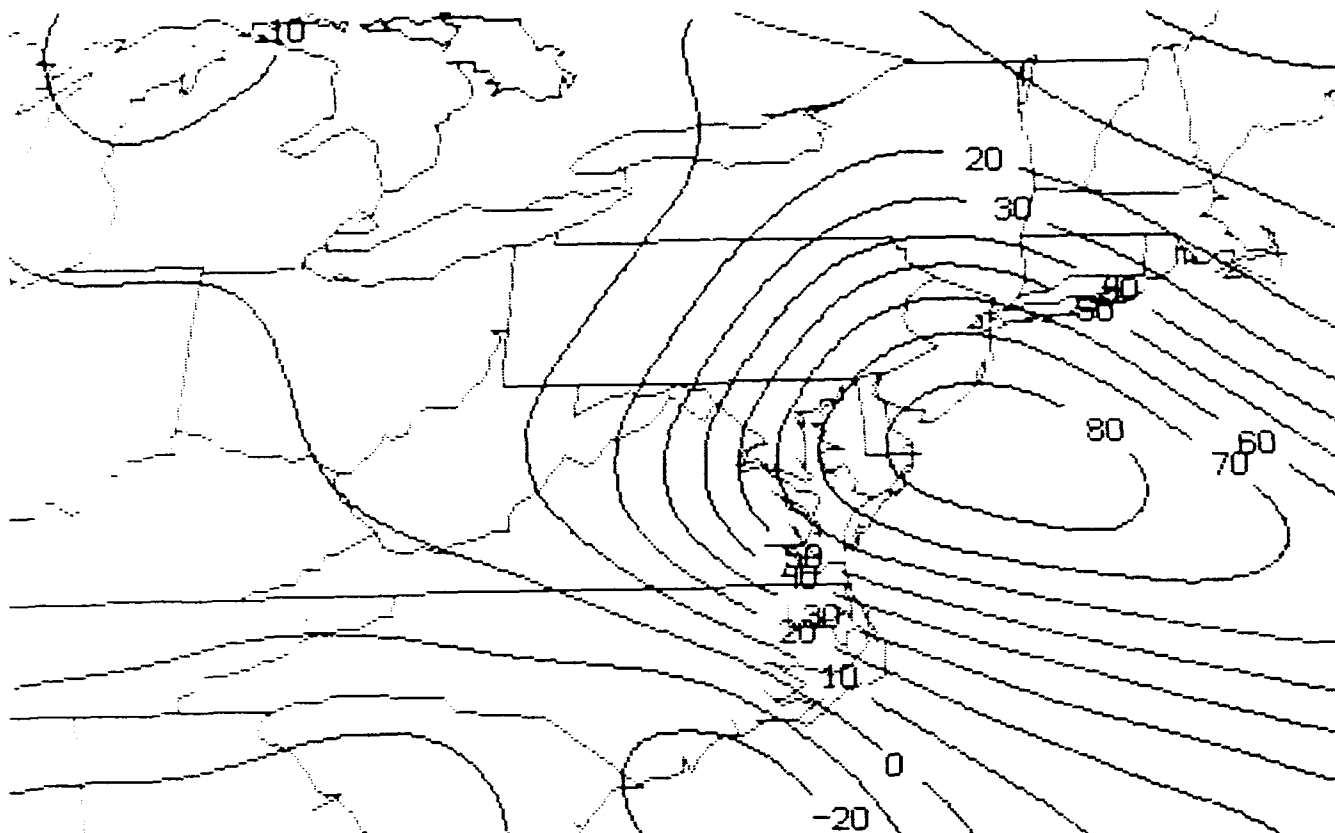


Figure 8e. 850 mb theta-e advection (degrees/day), January 8, 1988, 1200 GMT.

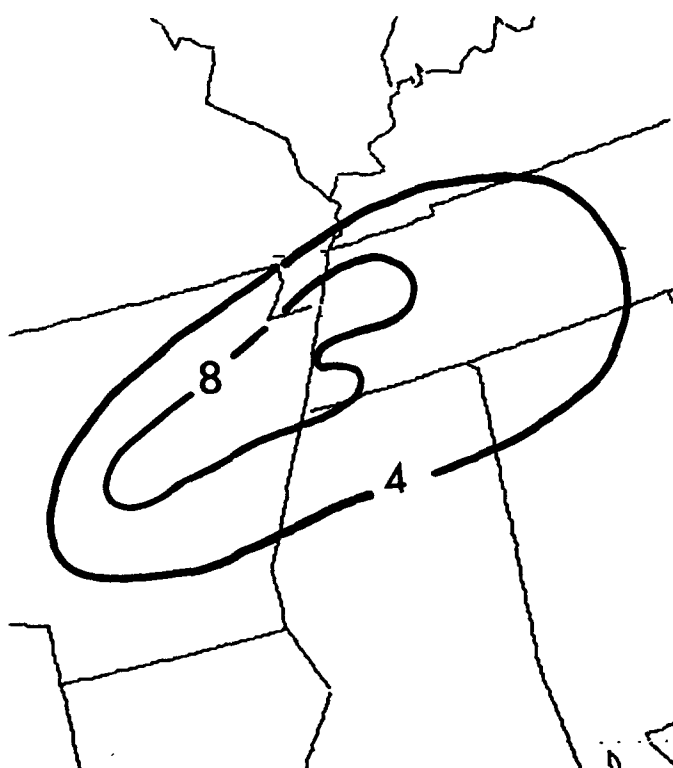


Figure 9a. Twelve hour heavy snowfall (inches) ending at January 7, 1988, 1200 GMT.

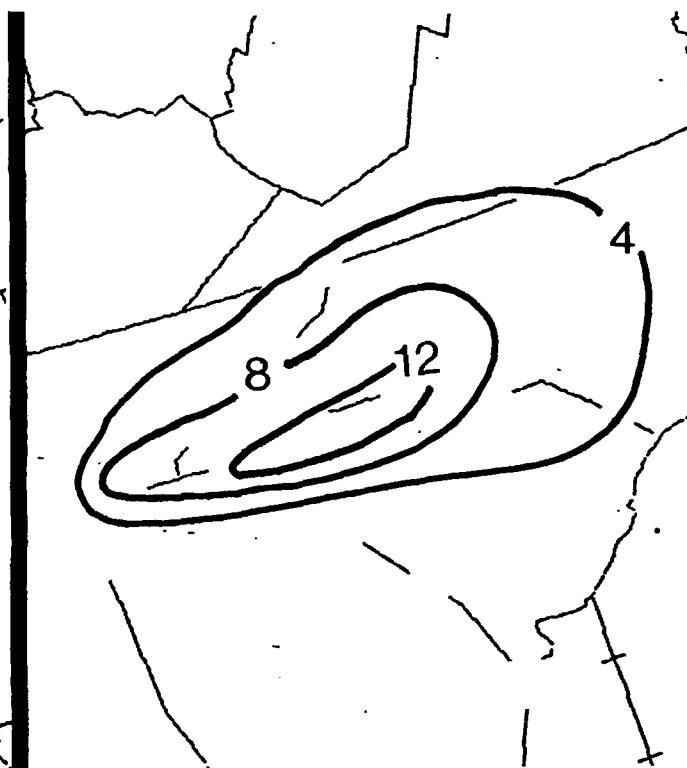


Figure 9b. Twelve hour heavy snowfall (inches) ending at January 8, 1988, 0000 GMT.



Figure 9c. Twelve hour heavy snowfall (inches) ending at January 8, 1988, 1200 GMT.



Figure 9d. Twelve hour heavy snowfall (inches) ending at January 9, 1988, 0000 GMT.

West Coast Heavy Precipitation Events: Comma
Head/Cloud Bands on January 17, 1988 and
Cloud Bands on January 8, 1990

On January 17, 1988, a rapidly intensifying surface cyclone occurred off the west coast of California. Heavy precipitation was associated with the cyclone. IBs and satellite imagery were used to locate the axis of heavy precipitation. Satellite imagery, 850 mb TEA analyses and 24 hour rainfall accumulations are shown in Figures 10a, 11a, and 12a, respectively. Heavy rain occurred along the axis of maximum positive TEA at 850 mb. The area of positive TEA was associated with the large main comma head/cloud band and several smaller embedded convective bands in the satellite imagery. Recent analyses revealed that significant positive TEA patterns (Figures 10b, 11b, and 12b) were associated with a series of subsynoptic-scale waves and cloud bands that produced devastating flash floods over Oregon and Washington, January 8-10, 1990. Experience has shown that the 700 mb TEA analyses is better for analyzing west coast precipitation than 850 mb. This is probably due to the effects of terrain and the strong middle to upper level dynamics (the presence of intense vorticity centers and jet streaks) of the weather systems. Satellite characteristics of heavy precipitation events associated with ECSs in the Western Region is published in a Tech Memo by Fleming and Spayd, 1986.

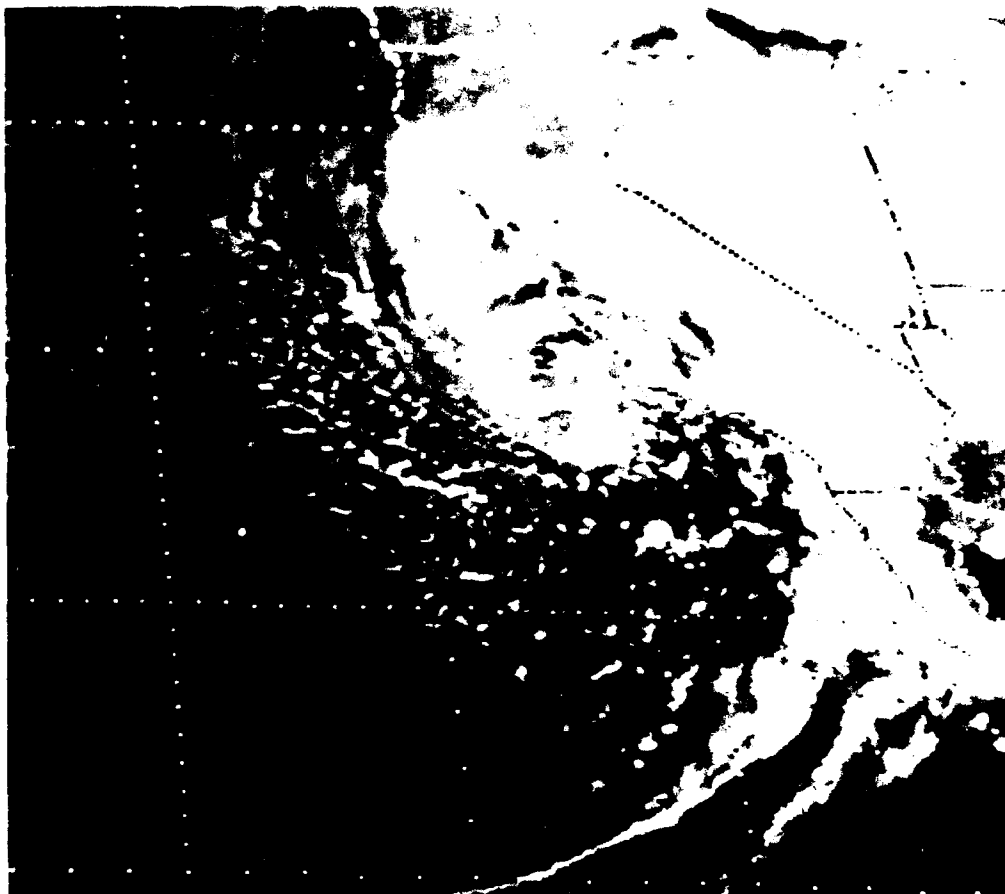


Figure 10a. An Extratropical Cyclone System (ECS) over the west coast of California, VIS imagery, January 17, 1988.

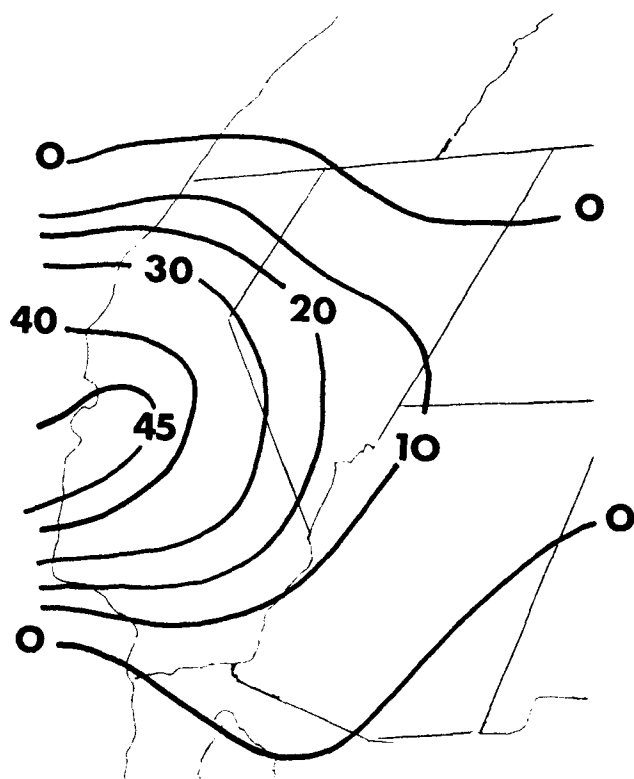


Figure 11a. 850 mb theta-e advection (degrees/day), January 17, 1988, 1200 GMT.

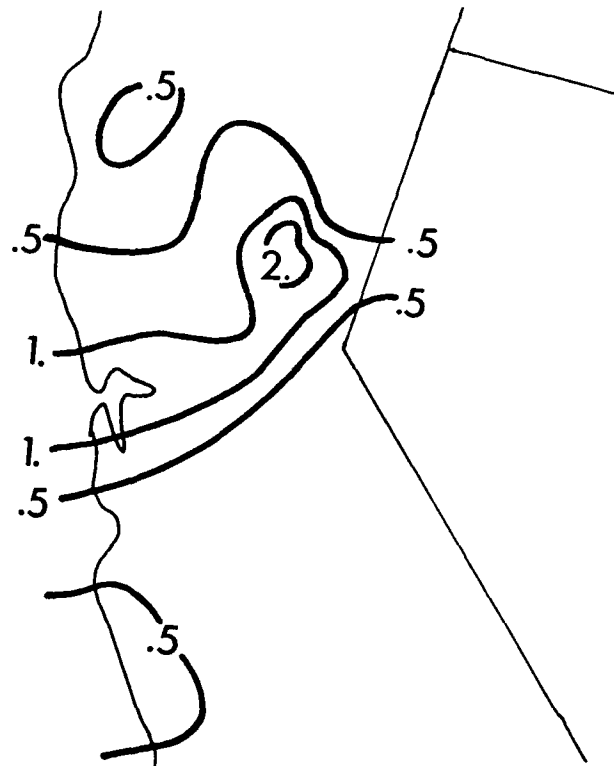


Figure 12a. Twenty-four hour observed rainfall (inches) ending at January 17, 1988, 1200 GMT.

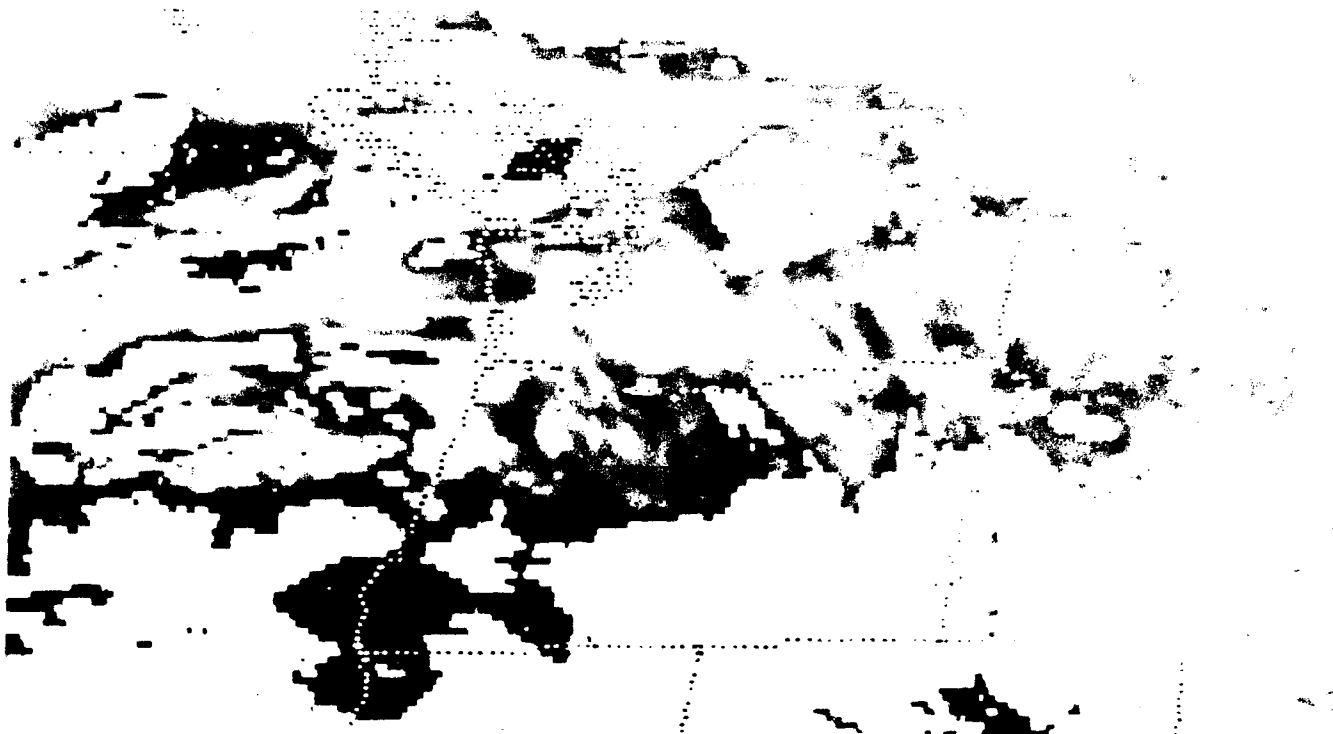


Figure 10b. An Extratropical Cyclone System (ECS) over the west coast of Washington and Oregon in the enhanced IR imagery (MB Curve), January 8, 1990, 2301 GMT.

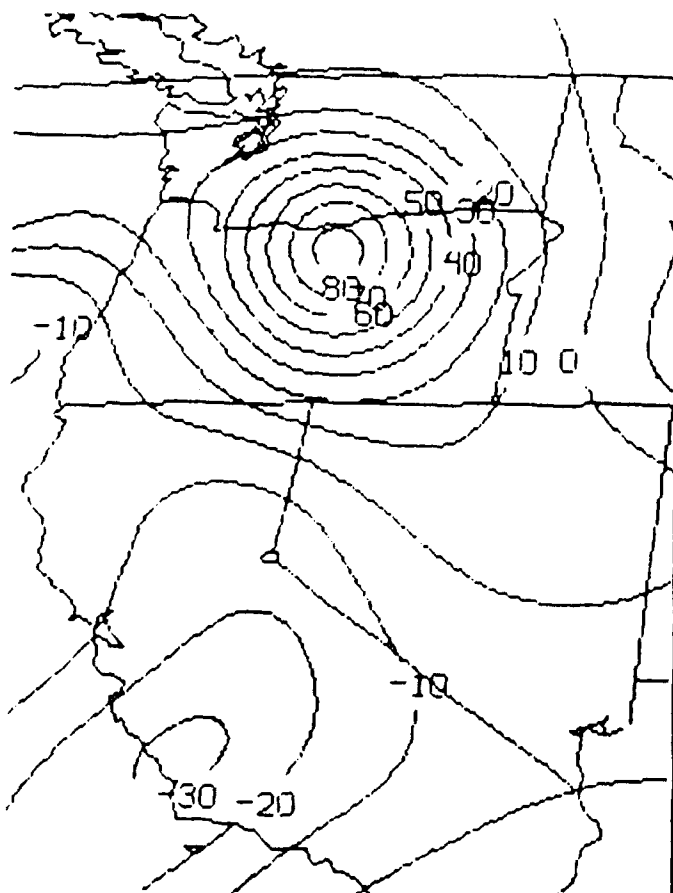


Figure 11b. 700 mb theta-e advection (degrees/day), January 9, 1990, 0000 GMT.

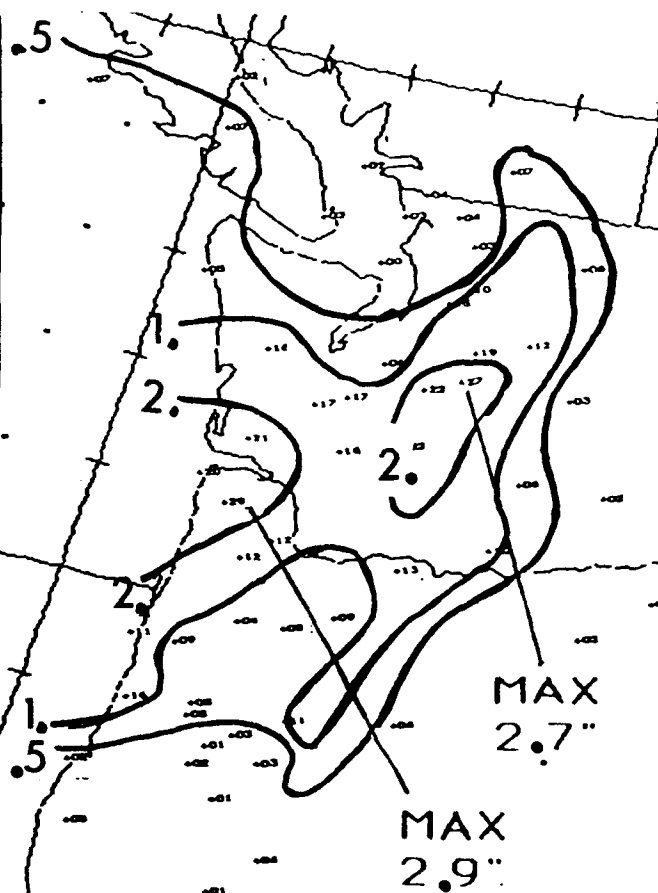


Figure 12b. Twenty-four hour observed rainfall (inches) ending at January 9, 1990, 1200 GMT.

Missouri, Illinois, and Indiana Snowstorm (Comma
Head/Cloud Band) of January 31, 1982

A major snowstorm blanketed Missouri, Illinois, and Indiana with 15-25 inches of snow on January 31, 1982. Thunder and cloud to ground lightning were observed at many locations. Cross sectional analyses of theta-e and momentum surfaces were quite useful in locating the IB associated with the heavy snow band. The cross sections were obtained from publications by Moore, 1986 and Moore and Blakley, 1988. The cross sections were derived from upper air stations along a line from Centerville, Alabama to Green Bay, Wisconsin (Figure 13). Satellite imagery, cross sectional analyses and total snowfall accumulations for the storm are displayed in Figures 14, 15, and 16, respectively. The theta-e cross section in Figure 15a shows the strongest low level positive TEA occurring between Nashville (BNA), Tennessee and Salem (SLO), Illinois (just south of the observed heaviest snow area). Satellite imagery shows a developing comma with an increasingly anticyclonic "head" and cloud band passing over the area. Convective instability areas (theta-e decreasing with height) is indicated by the stippled region above SLO in Figure 15a and CSI (theta-e decreasing with height along a constant momentum surface) is indicated by the dotted lines above SLO in Figure 15b. In this case, both the convective instability area and CSI are collocated. However, there are instances in heavy ECS precipitation events where convective instability is not present BUT CSI is present. Cross sectional analyses routines for determining the presence of convective instability and CSI are available on the National Weather Service Automation of Field Operations and Services (AFOS) System (Barker, 1987).

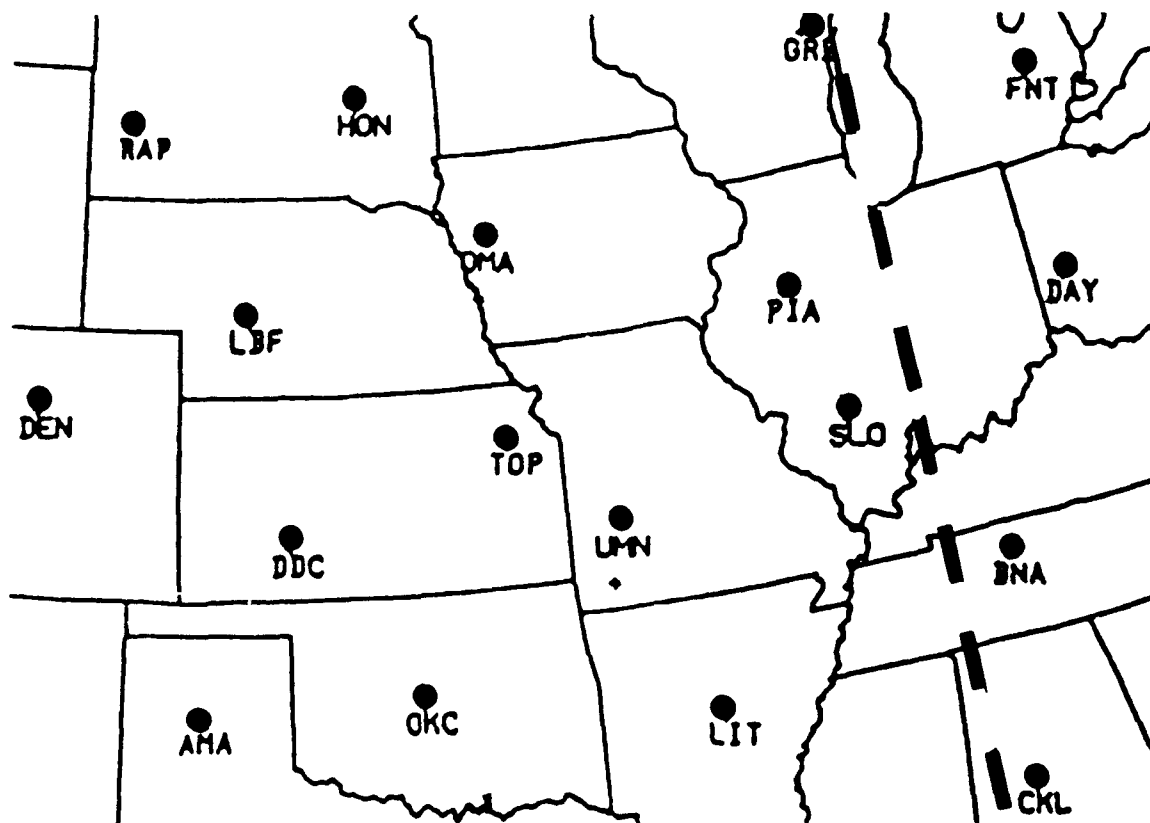


Figure 13. Location of upper air stations used in cross section analysis.

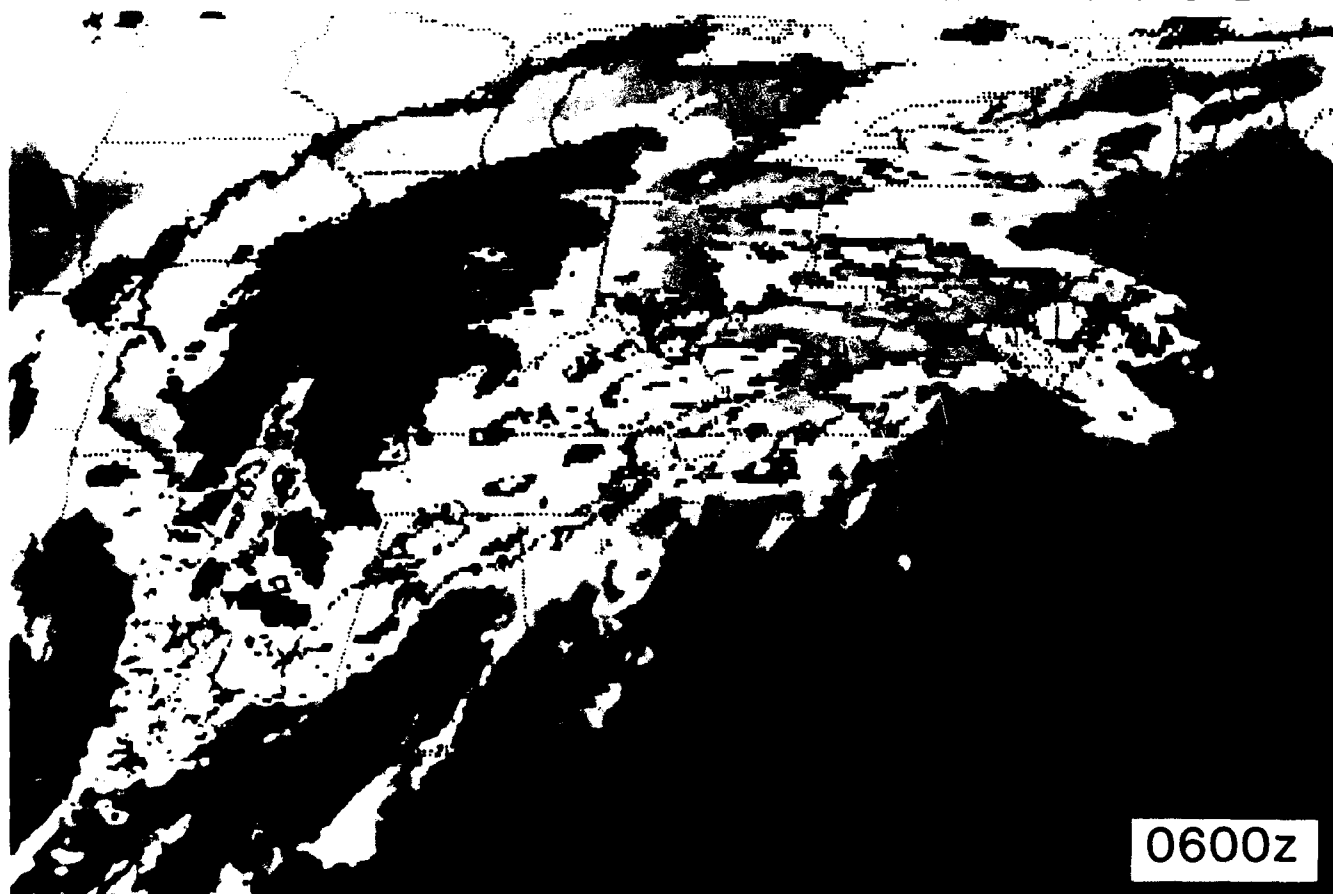
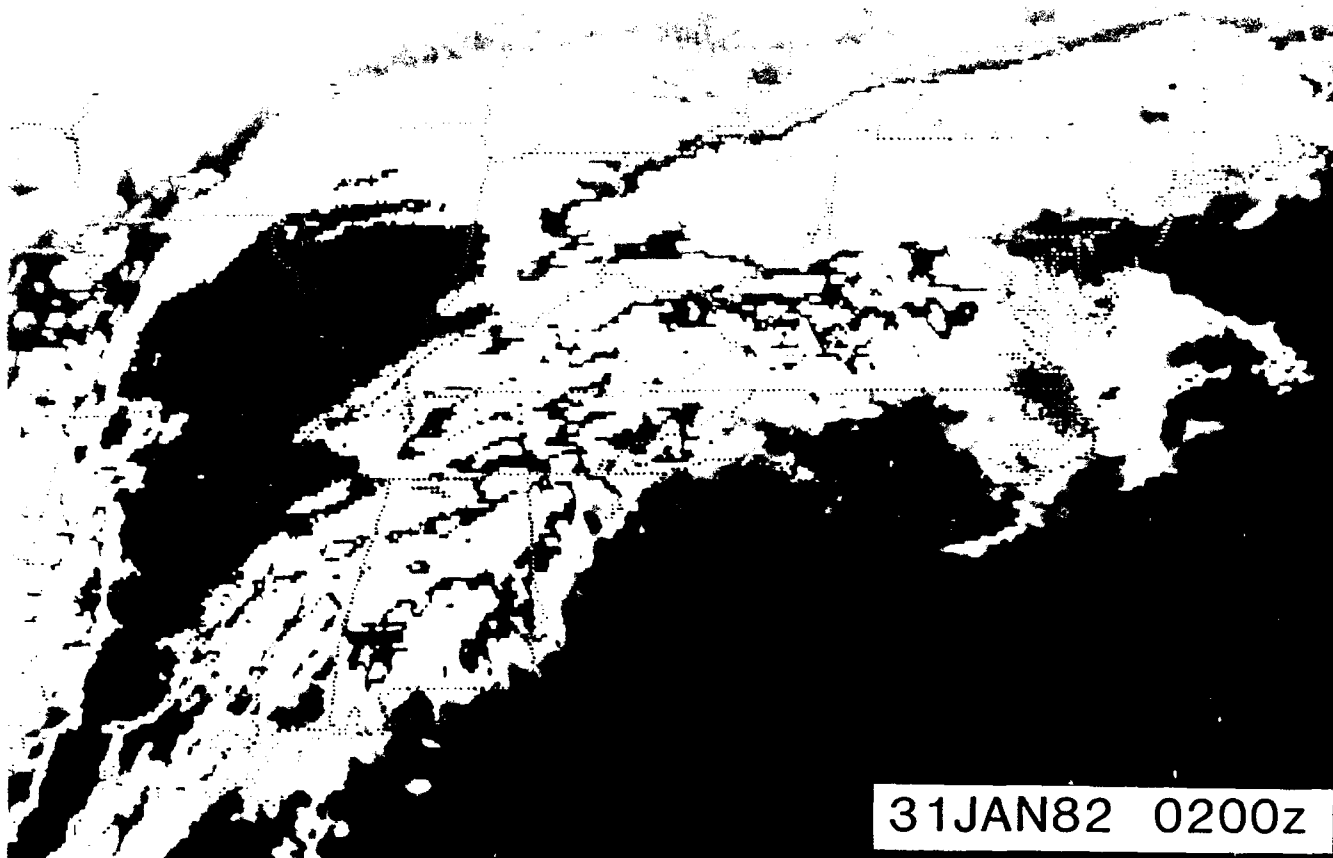


Figure 14. An Extratropical Cyclone System (ECS) in the enhanced IR imagery (CC Curve), January 31, 1982.

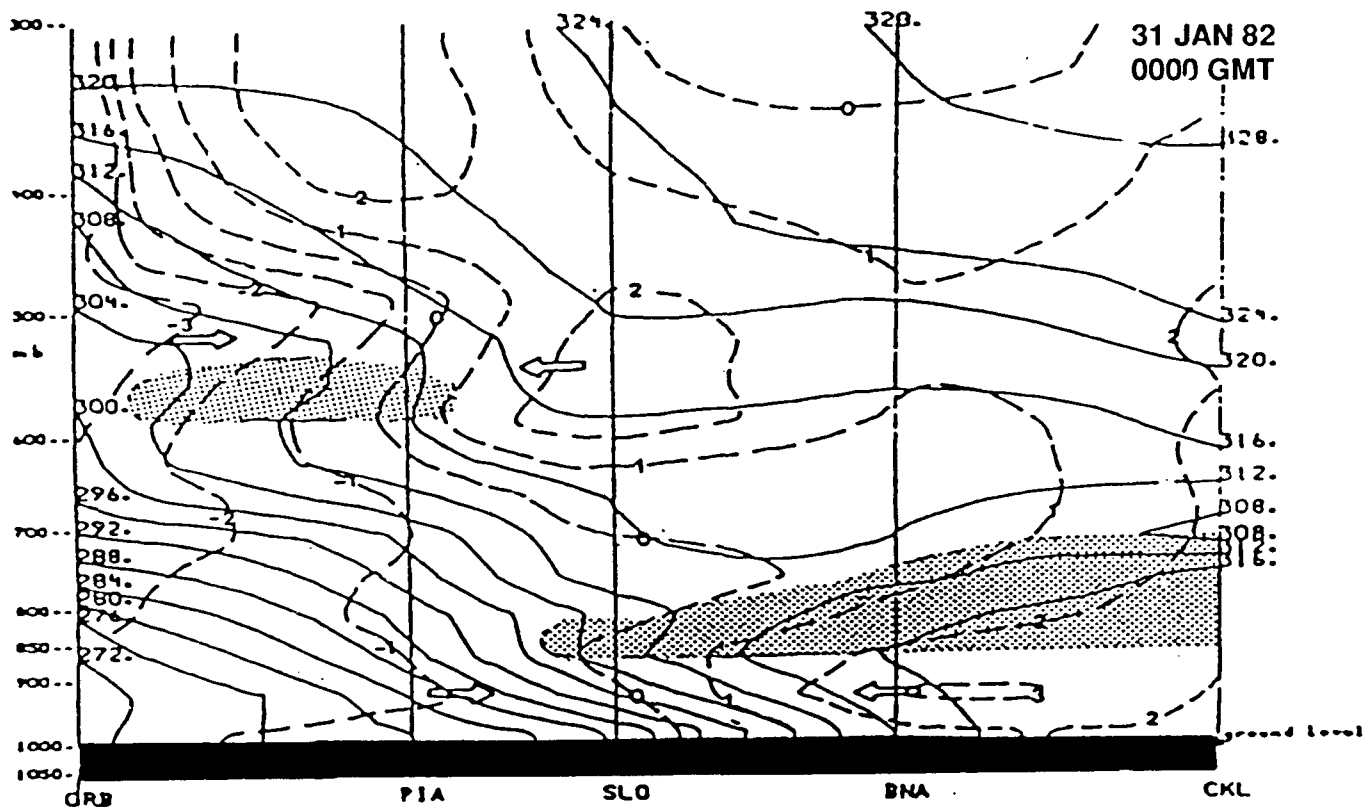


Figure 15a. Cross sectional analysis of theta-e (solid lines, $^{\circ}\text{K}$) and the wind component parallel to the plane of the cross section (dashed lines, m/s). Maximum low level winds indicated by arrow; convective instability areas are stippled.

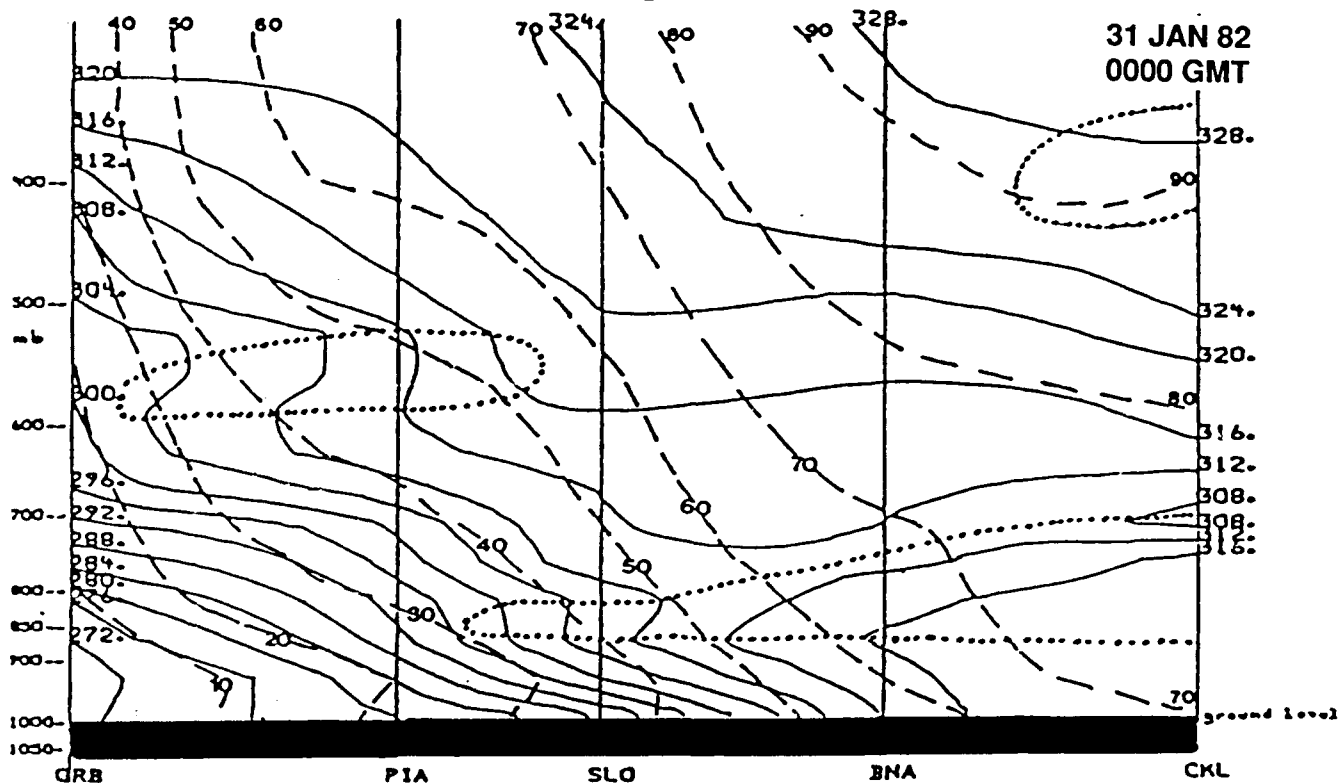


Figure 15b. Cross sectional analysis of theta-e (solid lines, $^{\circ}\text{K}$) and momentum (dashed lines, m/s). Conditional symmetric instability areas are indicated by dotted lines.

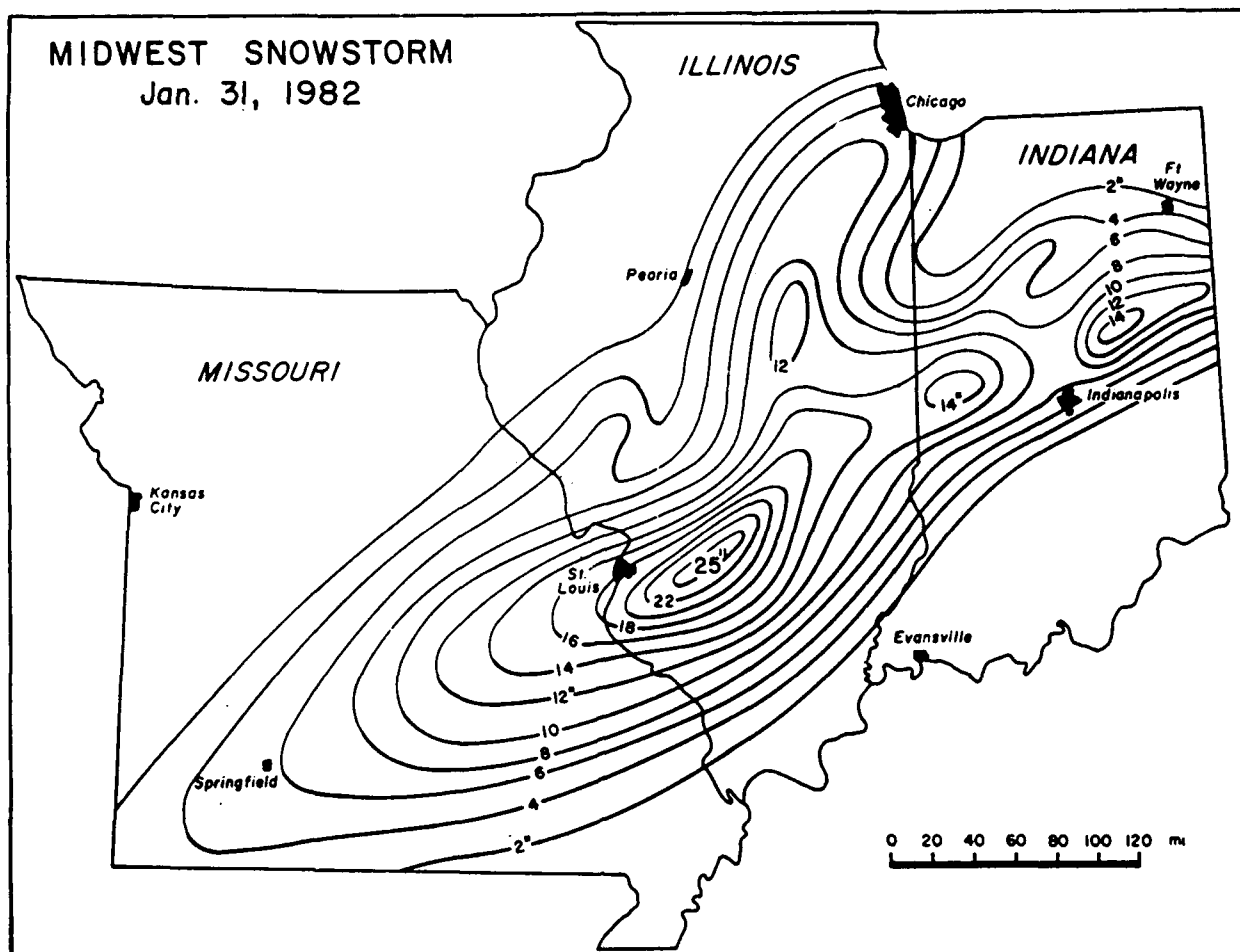
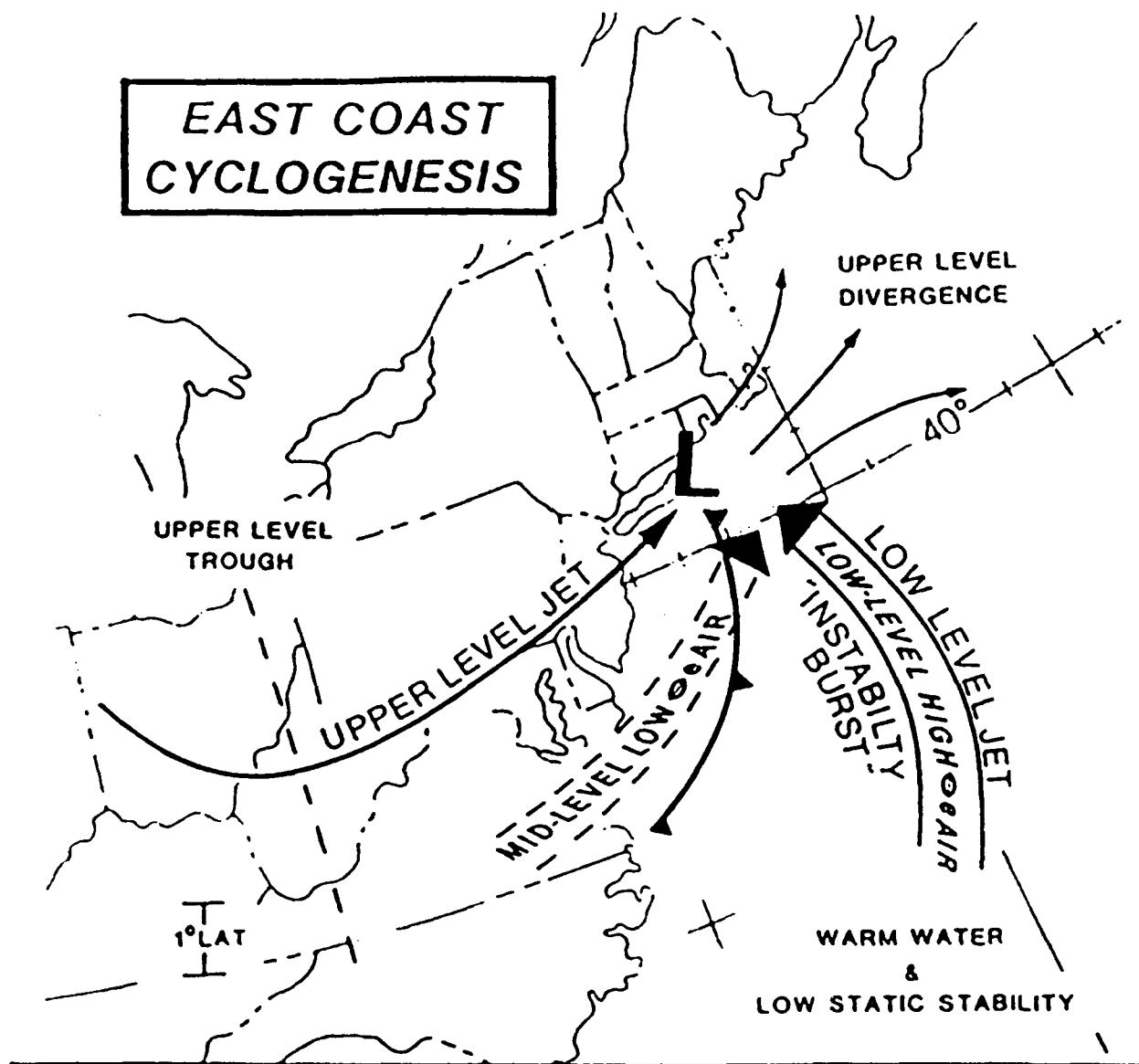


Figure 16. Total snowfall accumulations (in inches) for the ECS.

III. RELATIONSHIP OF IBs TO ECS EVOLUTION AND CYCLOGENESIS

There is a relationship between IBs, evolution (Scofield and Spayd, 1984) and deepening of ECSs. IBs appear to be present in most cyclogenetic events but other favorable atmospheric conditions must also be present. Other favorable atmospheric conditions are summarized in a check list developed by Auciello (1988) for predicting meteorological "bombs" in the western North Atlantic Ocean. In this check list, the intensity, speed, and coastal crossing of the 500 mb vorticity maxima and the existence of a jet streak of 120 knots or greater at 250 or 300 mb just south of the 500 mb vorticity maximum are of primary importance.

A conceptual model of East Coast cyclogenesis is shown in Figure 17. Rapid deepening occurs where "everything comes together" and the satellite imagery shows an evolution from the formation of a dry slot on the rear edge of a cloud band to the development of a distinct hooked shaped cloud pattern.



SATELLITE SIGNATURES OF CYCLOGENESIS

- A COMMA HEAD PATTERN UNDERGOING EVOLUTION
(POSSIBLY FROM A LEAF OR SUB-SYNOPTIC SCALE SYSTEM)
- RAPID CLOUD TOP COOLING
- RAPID INCREASE IN CONVECTION
(SOMETIMES JUST A PERSISTENCE IN CONVECTION)
- LOW LEVEL POSITIVE VORTICITY, CONVERGENCE AND
STABILITY DECREASE FROM SATELLITE WINDS AND SOUNDINGS

Figure 17. A conceptual model of east coast cyclogenesis.

IBs and the Cyclogenesis of November 20-21, 1988

The IBs in this event are represented by the 850 mb TEA. It is interesting that the TEA patterns exhibit significant "pattern changes" prior to and during the rapid deepening of surface lows. In fact, the "pattern changes" take on an evolutionary characteristic that is common to most cyclogenetic events. The evolution involves the development of a pronounced couplet of positive and especially negative TEA areas which becomes larger (in magnitude and size) with time and better organized. Often the orientation of the advection couplet evolves from a west to east orientation (negative advection to the west and positive advection to the east) in the very early stages of cyclogenesis to a north-south orientation (negative to south and positive to north) during the period of rapid development. Of course it is necessary at the same time to analyze the satellite imagery for ECS evolution.

The 850 mb TEA analyses (with the location and intensity of the surface low superimposed), enhanced IR imagery and 24 hour precipitation analyses are illustrated in Figures 18, 19, 20, respectively. The TEA pattern begins as an ill-defined couplet on November 19, 0000 GMT and evolves into a pronounced northeast-southwest advection couplet by November 21, 0000 GMT. A weak, disorganized, surface low pressure area in Texas on November 19 at 0000 GMT underwent rapid deepening (26 mbs) during the next 60 hours ending November 21, 1200 GMT. Most of this deepening took place between November 20, 1200 GMT and November 21, 1200 GMT; by November 21, 1200 GMT, the surface low had deepened to 978 mb and was located off the coast of Maine. A pronounced convective cloud band from (C-B) is seen in the satellite imagery at November 19, 0000 GMT. This cloud band (Figure 19a) gradually evolved into a comma head/comma tail (Figure 19b) and then to a distinct hooked shaped cloud pattern (Figure 19c). The precipitation analyses in Figure 20, showed significant rainfall occurring from November 19, 1200 GMT to November 21, 1200 GMT. Comparing Figures 18, 19, and 20, shows that the occurrence of heavy precipitation is related to the occurrence of positive 850 mb TEA and satellite precipitation signatures (e.g., convective cloud bands) and less on the formation of the advection couplet. In other words, heavy precipitation can occur with or without the couplet. However, rapidly deepening surface cyclones are normally associated with the evolution of a pronounced north-south advection couplet.

There are two additional comments before going to the next section:

(1) Figure 18e is a typical north-south advection couplet (negative to the south and positive to the north) associated with rapidly deepening surface low pressure systems. This pattern is not surprising since most surface cyclogenetic, "occluded" events are associated with warm air advection to the

north of the surface low and cold air advection to the south of the low. However, surface low pressure systems in their formative stages (Figures 18b,c) are often associated with west-east oriented advection couplets (negative to the west and positive to the east);

(2) The TEA pattern on November 19, 0000 GMT (Figure 18a) is a good example of WHY TEA analyses must be used with satellite imagery to analyze heavy precipitation. Comparing the TEA in Figure 18a with the satellite imagery in Figures 19a,b shows the following:

- (a) despite the presence of positive TEA, no precipitation occurs over Iowa---only cirrus clouds;
- (b) However, the positive TEA area over southwest Tennessee (Figure 18a) goes from cirrus clouds (Figure 19a) to an area of thunderstorms 24 hours later (Figure 19b).

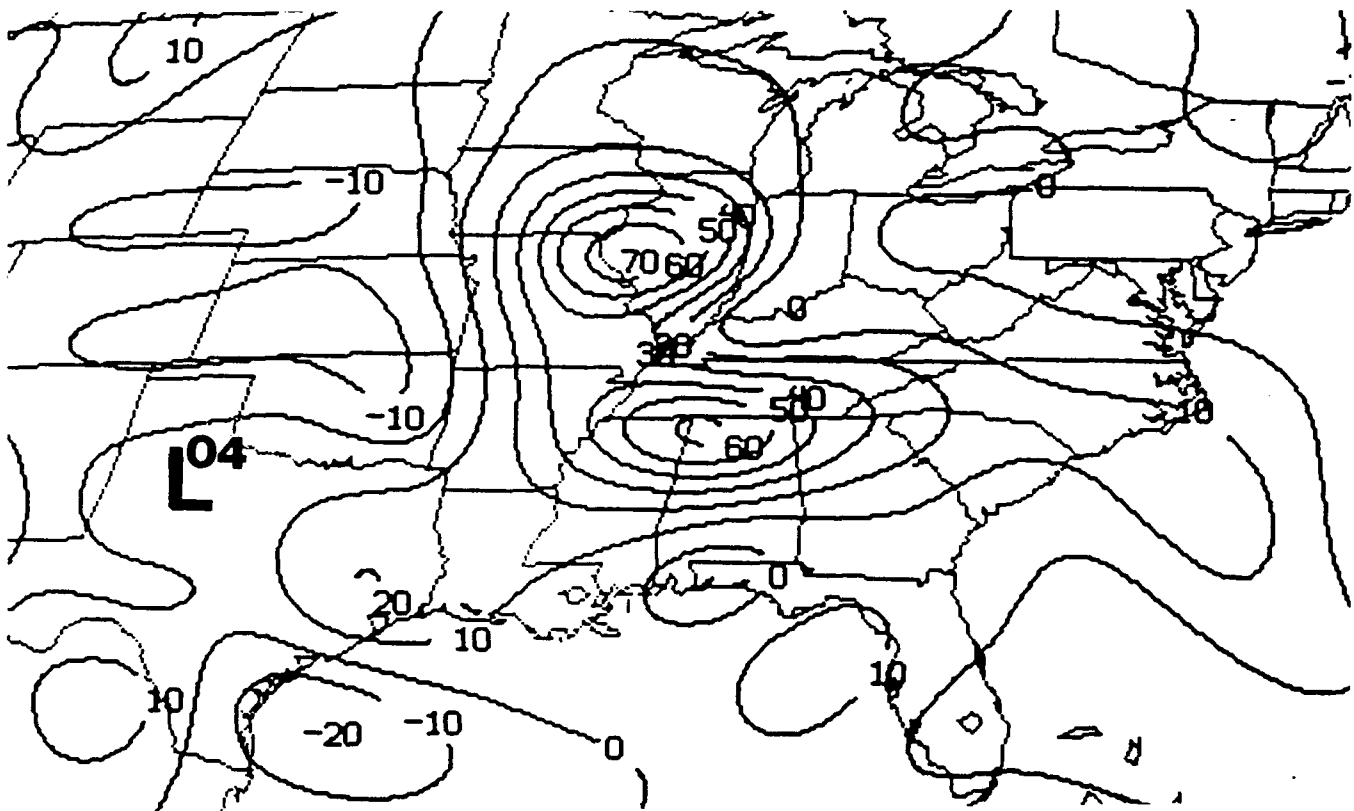


Figure 18a. 850 mb theta-e advection (degrees/day), November 19, 1988, 0000 GMT.

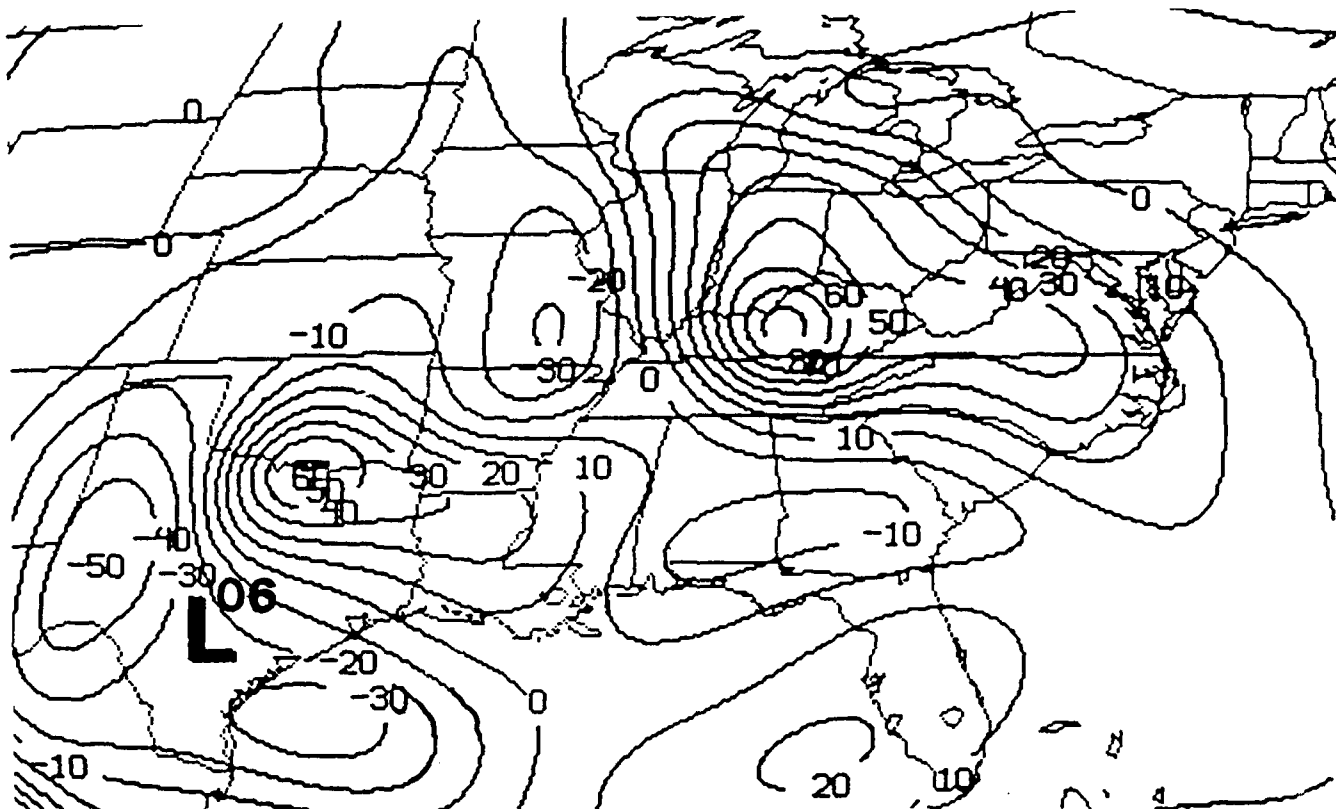


Figure 18b. 850 mb theta-e advection (degrees/day), November 19, 1988, 1200 GMT.

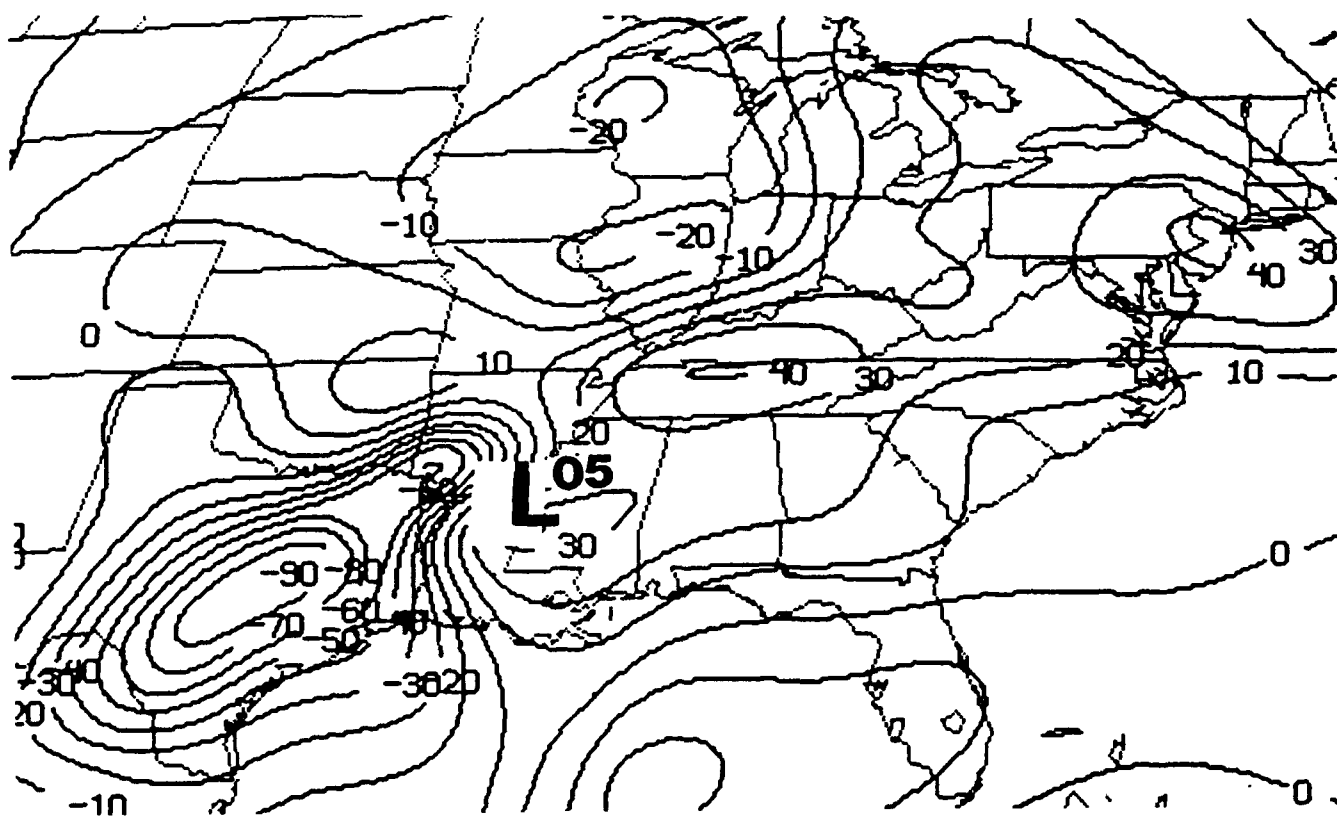


Figure 18c. 850 mb theta-e advection (degrees/day), November 20, 1988, 0000 GMT.

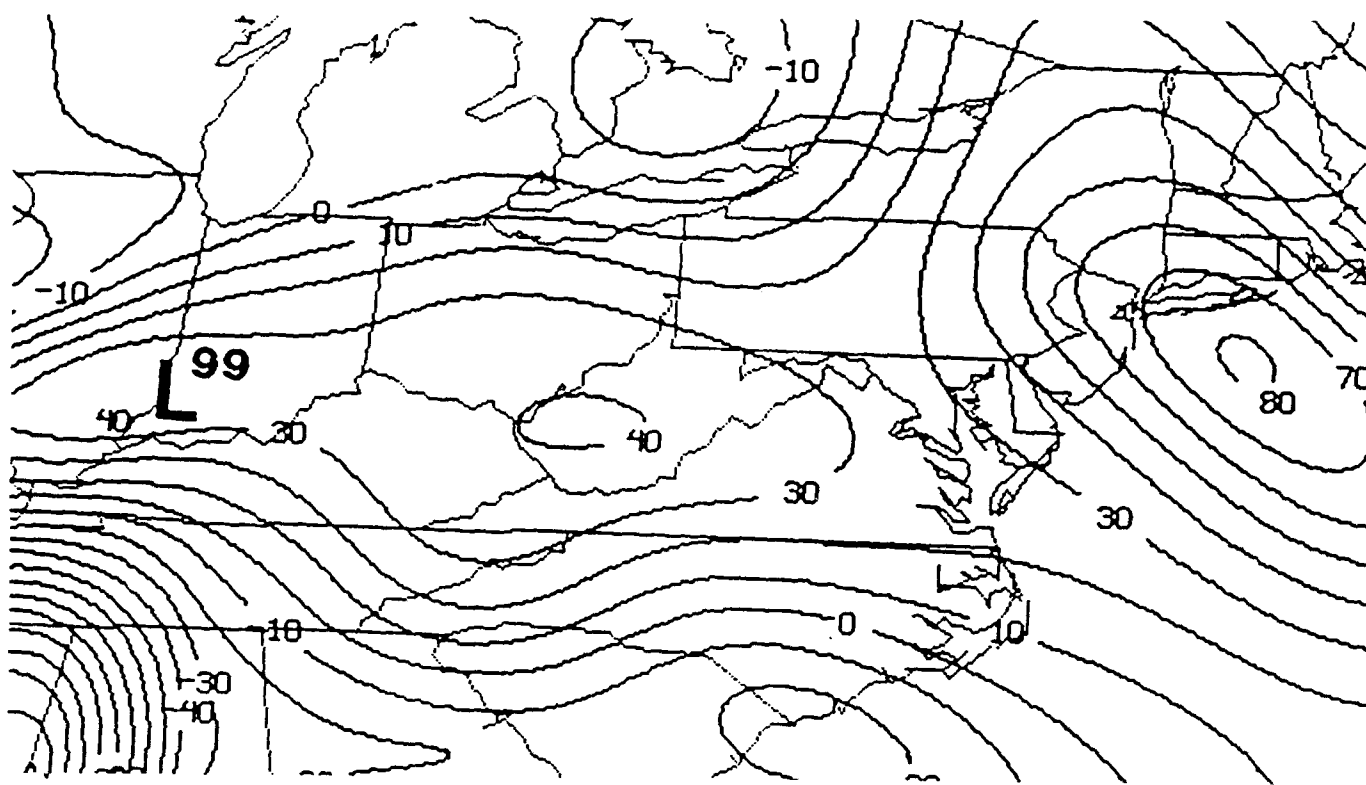


Figure 18d. 850 mb theta-e advection (degrees/day), November 20, 1988, 1200 GMT.

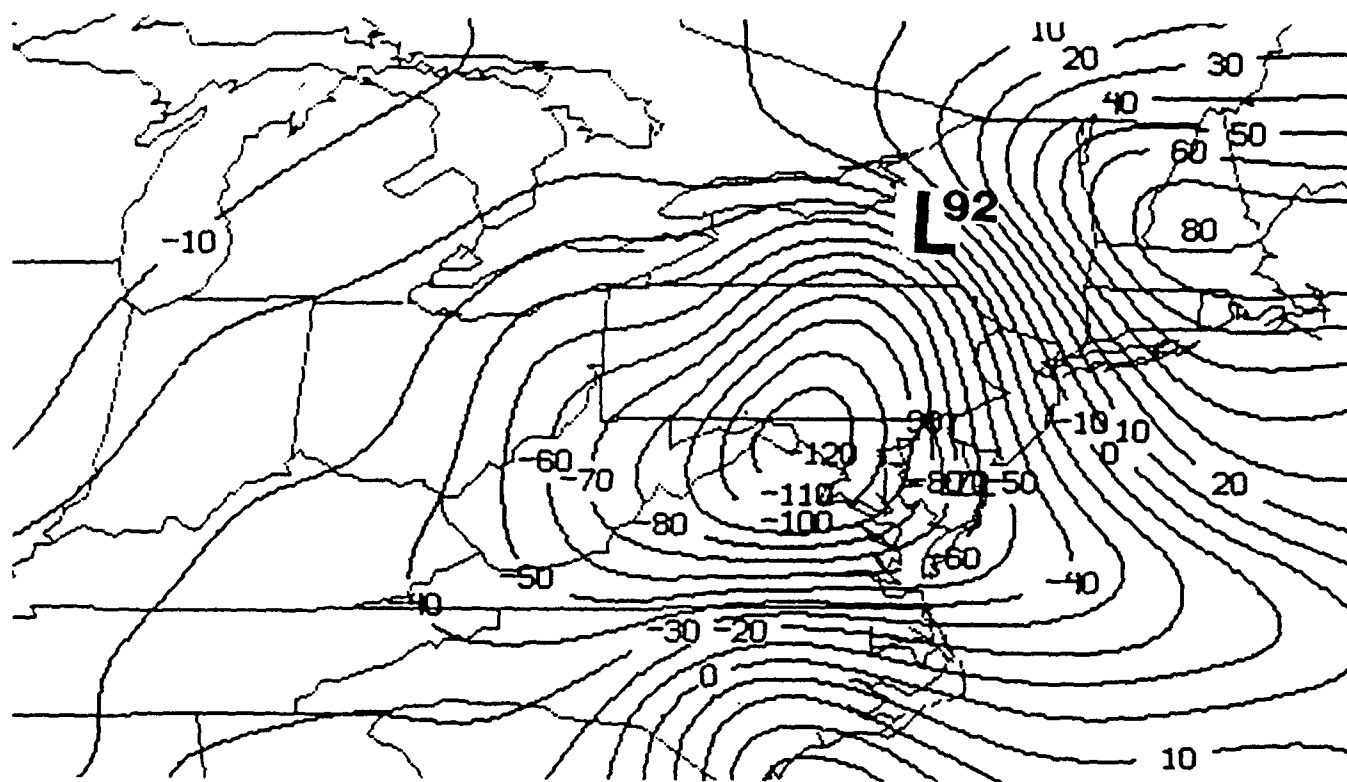


Figure 18e. 850 mb theta-e advection (degrees/day), November 21, 1988, 0000 GMT.

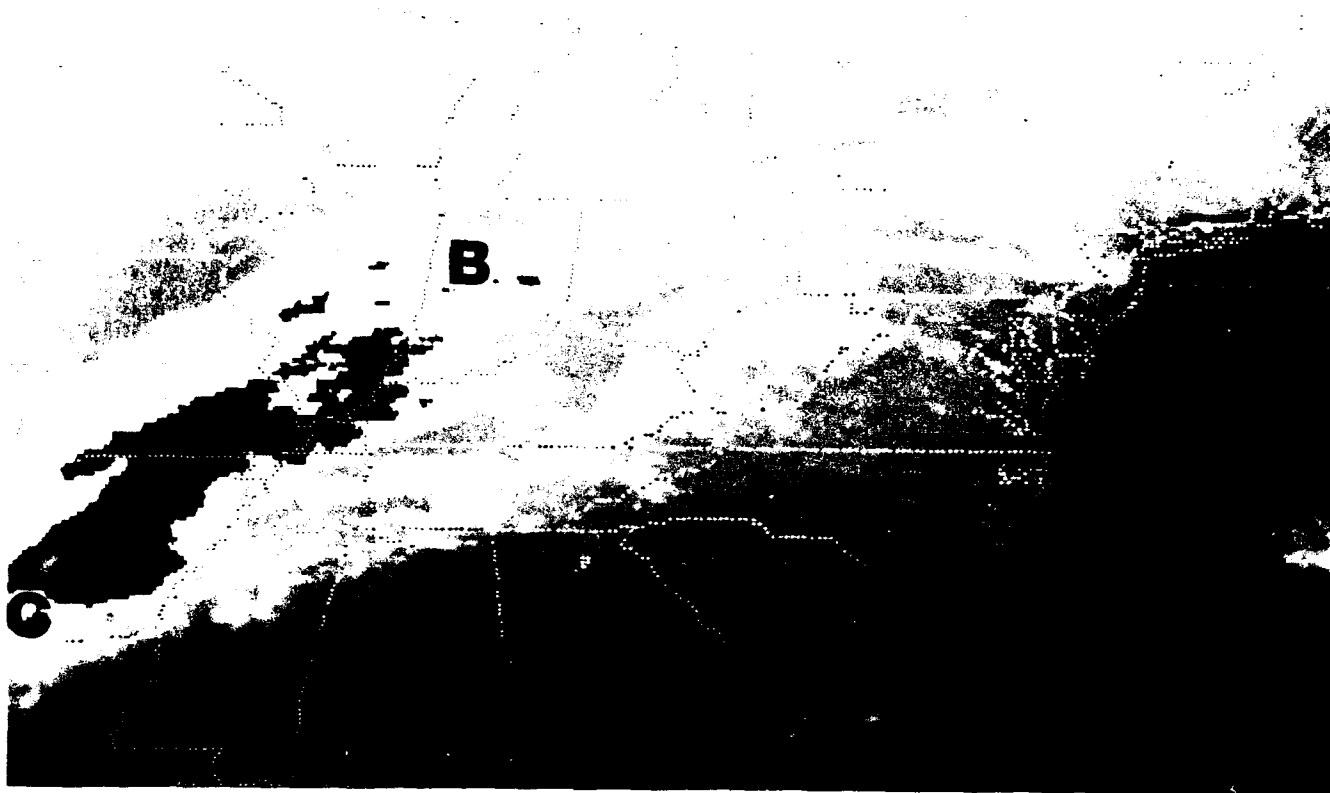


Figure 19a. Convective cloud band; enhanced IR imagery (MB Curve); November 19, 1988, 0000 GMT.



Figure 19b. Comma head/comma tail; enhanced IR imagery (MB Curve); November 20, 1988, 0000 GMT.

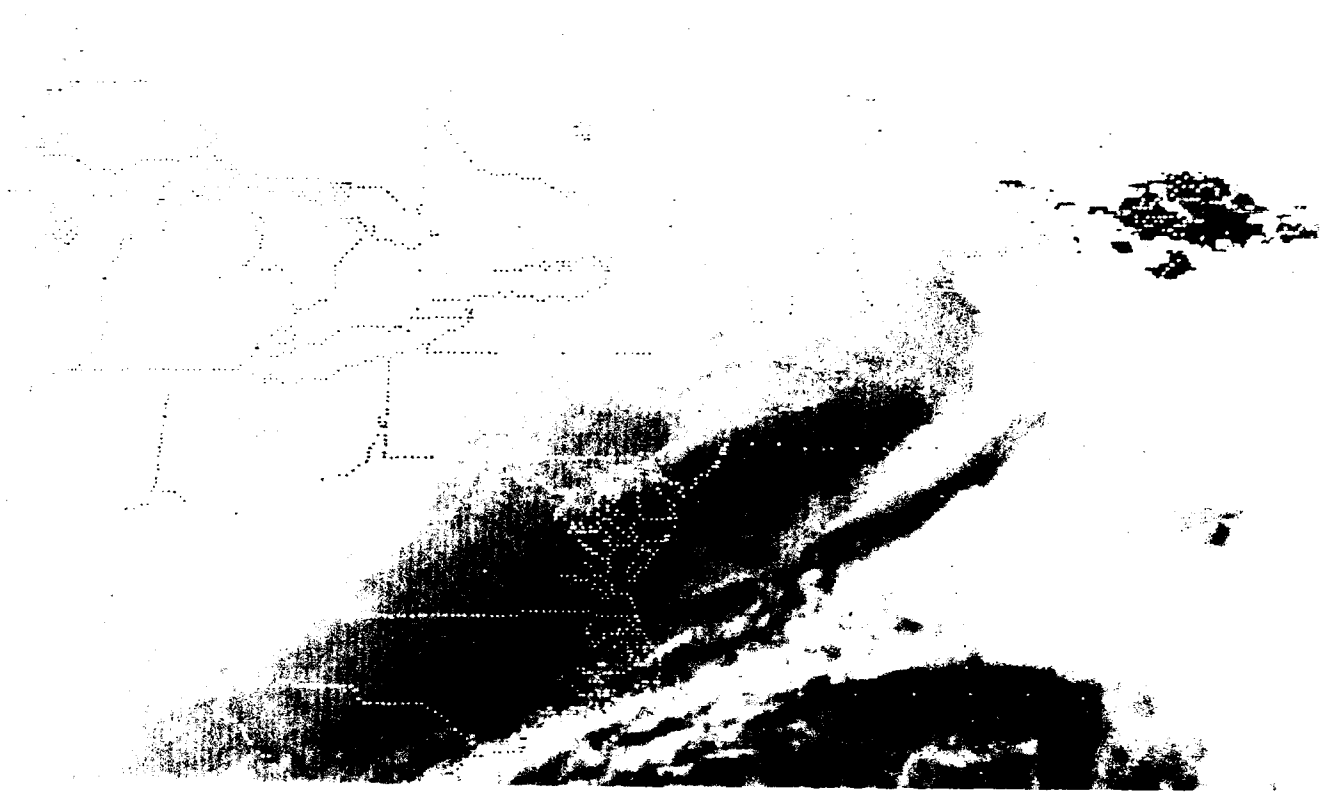


Figure 19c. Hook-shaped cloud pattern; enhanced IR imagery (MB Curve); November 21, 1988, 0600 GMT.

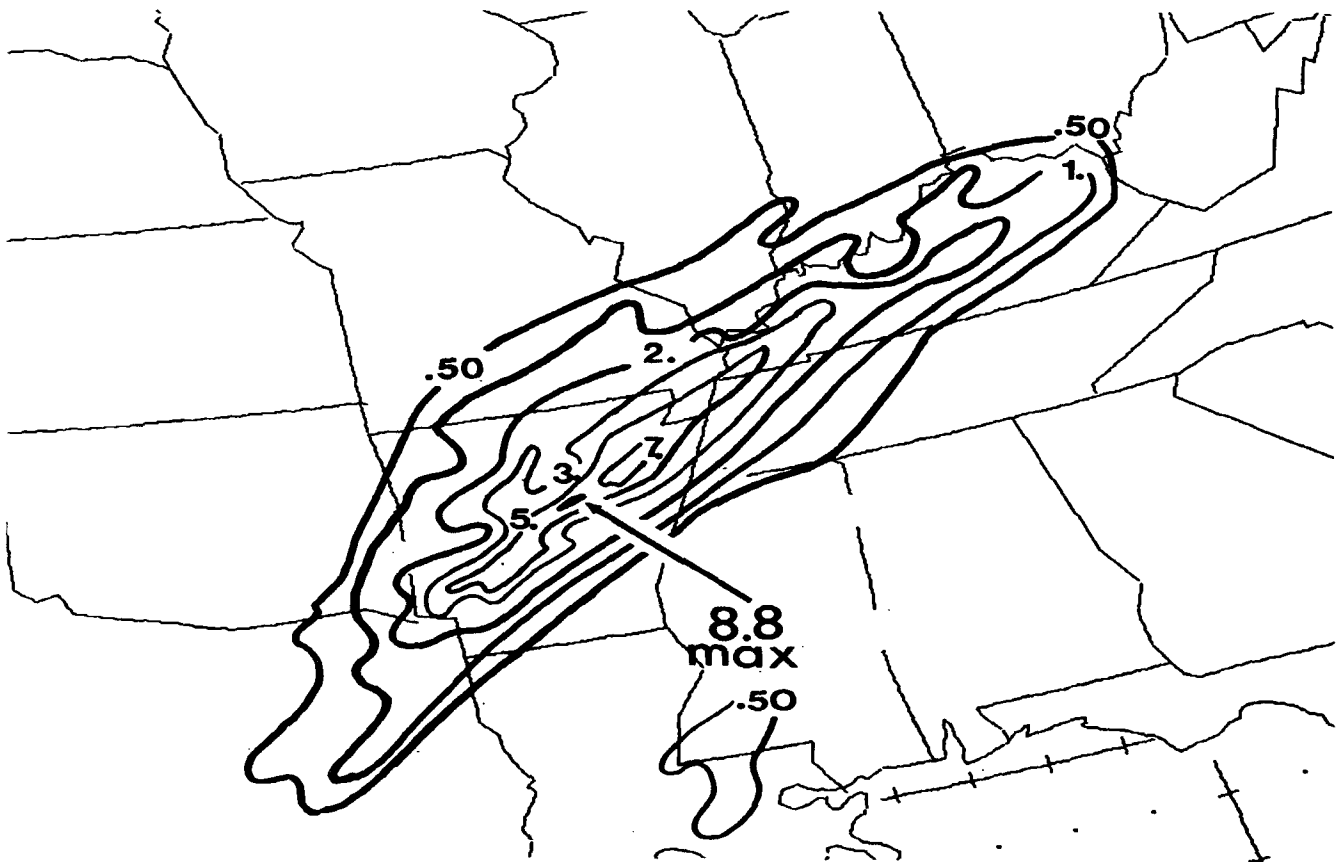


Figure 20a. Twenty-four hour observed precipitation (inches) ending at November 19, 1988, 1200 GMT.

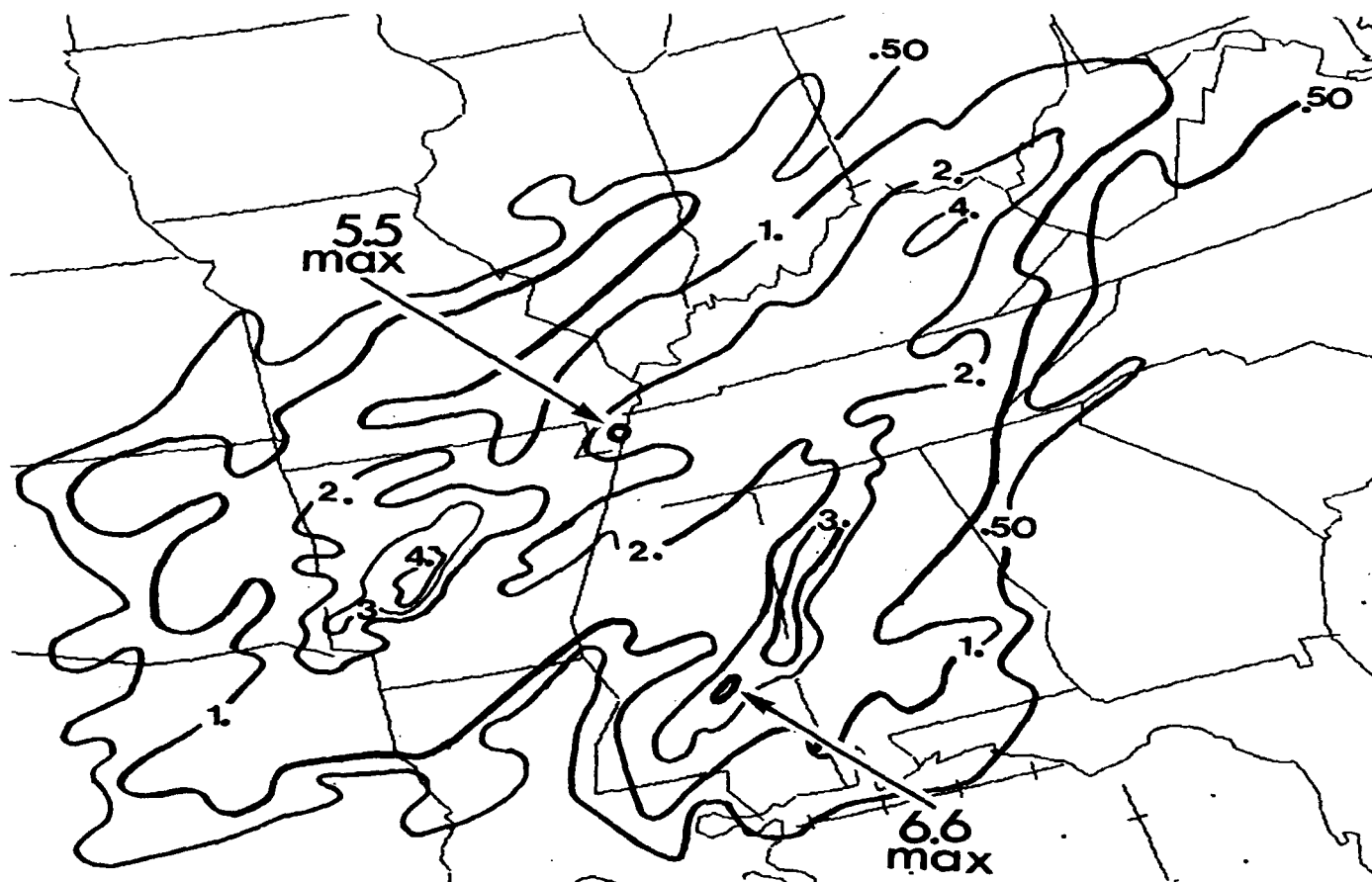


Figure 20b. Twenty-four hour observed precipitation (inches) ending at November 20, 1988, 1200 GMT.

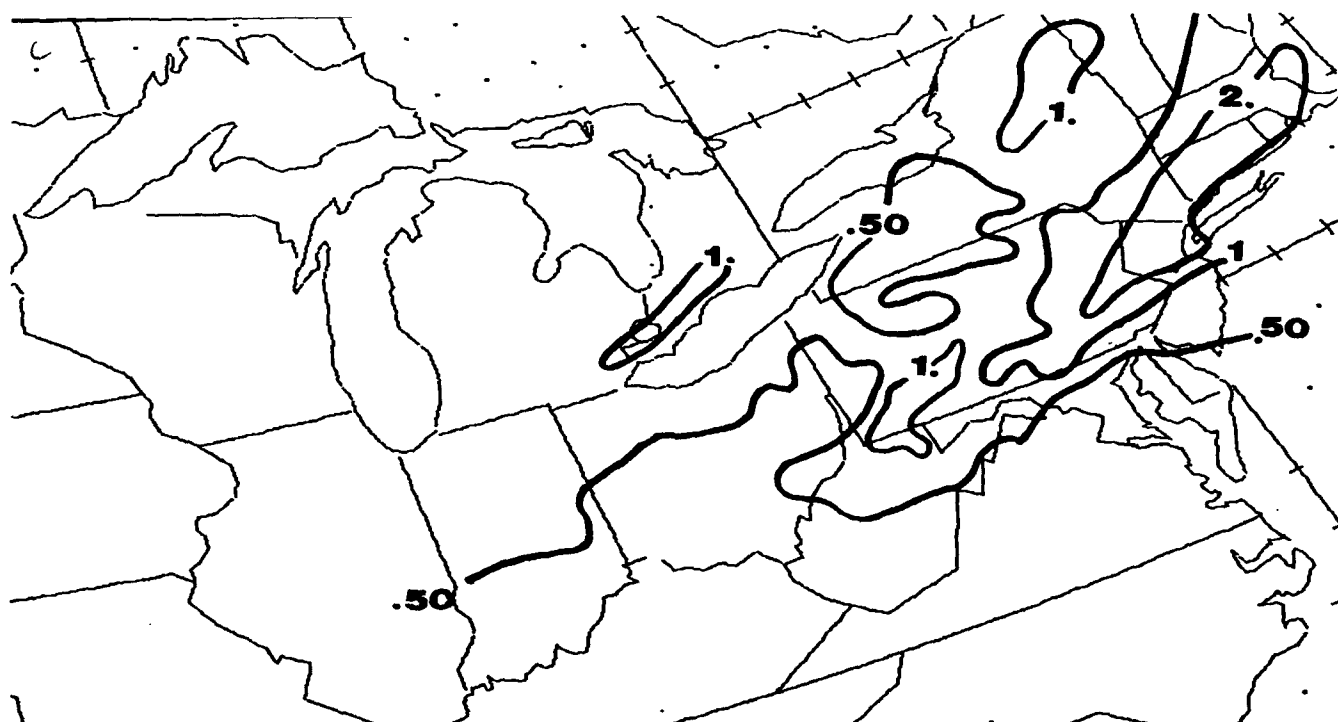


Figure 20c. Twenty-four hour observed precipitation (inches) ending at November 21, 1988, 1200 GMT.

IV. A FORECAST INDEX OF 3-12 HOUR HEAVY PRECIPITATION FOR ECSs

IBs by themselves are not sufficient to produce heavy precipitation. For heavy precipitation to occur, there must be present (or forecast): a slow moving or regenerative ECS (except in rapidly deepening systems) and moisture. Collectively these items form the basis for a Forecast Index of 3-12 Hour Heavy Precipitation. The Index, presented in the form of a Decision Tree (Figure 21), is discussed in the following paragraphs.

The Index is applicable to many types of ECSs. The following are ECS cloud patterns that are readily detectable in the satellite imagery:

- o Comma Head;
- o Baroclinic Leaf;
- o Subsynoptic Scale Waves;
- o Cloud Band;
- o Overrunning;
- o Vortices;
- o Combinations or variations of the above.

Enhanced IR, VIS, and 6.7 μm water vapor imagery are used to analyze these ECSs. Water vapor imagery is particularly useful in analyzing mid to upper level synoptic scale systems such as mid-level vortices and upper level jet streaks (Scofield and Funk, 1986 and Funk, 1986).

Based on the examination of many ECS events in the satellite imagery, schematics of the evolution of cloud patterns associated with moderate to heavy precipitation were developed for many of the above mentioned "types of" ECSs. The schematics are used as an aid in analyzing the location and magnitude of precipitation within ECS cloud patterns. In addition, the schematics may be used to anticipate developments within the evolving ECS cloud pattern for use in the short range prediction of precipitation. Five basic categories of evolution schematics have been developed: the Comma Head, Baroclinic Leaf, Subsynoptic-scale Wave, Cloud Band and Overrunning (Scofield and Spayd (1984) and Scofield and Jiang Shi (1987)). These categories have been refined for the Western Region (Fleming and Spayd, 1986). The following is a brief description of each category:

COMMA HEAD

The Comma Head is a cloud pattern shaped like a "COMMA" and consists of three subcategories: (1) rapidly deepening and occluding surface low development; (2) weak surface low development and (3) no surface low development. Comma heads normally evolve such that new cloud development and sometimes new comma heads occur in the southern portion of the original comma head. In addition, warm top convective cloud bands are often observed merging into the southern portion of the comma head. Heaviest precipitation normally occurs in the southern edge of the comma head in association with the development of warm top convective clouds or new comma heads and cloud band mergers.

BAROCLINIC LEAF

The Baroclinic Leaf is a cloud pattern shaped like a "LEAF". The baroclinic leaf is associated with frontogenesis aloft and is often the early, "pre-comma" stage of the comma head. Baroclinic leafs normally evolve in a similar manner to the Comma Head---"new cloud development and sometimes new leafs occur in the southern portion of the original baroclinic leaf". As a result, the heaviest precipitation normally occurs in the southern edge of the baroclinic leaf.

SUBSYNOPTIC-SCALE WAVE

The Subsynoptic-Scale Wave is a cloud pattern shaped like a "WAVE" and consists of two subcategories: (1) waves along the rear of a baroclinic zone and (2) waves in an overrunning zone. Subsynoptic-scale waves normally evolve from a flat (no pronounced curvature) transient wave to a mature, small scale, comma head/tail and finally to a "sheared-out", dissipating wave. Heaviest precipitation often occurs when the wave is evolving from the transient to the mature stage.

CLOUD BAND

The Cloud Band is a cloud pattern shaped like a "COLD FRONTAL BAND". Cirrus clouds comprise most of the cloud band. However, those bands which possess low-level tails are active (contain precipitation). In addition, when newer active cloud bands develop in the rear (western portions) of the baroclinic zones, the older bands in the front (eastern portions) of the baroclinic zones often dissipate. Convective elements embedded within an active band will often become colder (in the IR imagery) upwind and propagate across the band.

OVERRUNNING

Precipitation elements and bands possess warm tops in the IR imagery and are embedded in a large anticyclonic flow of cirrus. Animation is best for distinguishing convective elements/bands from cirrus. Precipitation elements/bands often appear as textured areas in the VIS imagery. Within the overrunning zone, the boundary layer is cold or cool, winds veer strongly with height and the air is lifted isentropically until it becomes unstable and deep convection is initiated. Convective elements/bands form perpendicular to the 850 mb flow (low-level axis of maximum winds) and nearly parallel to the 500 mb flow. The more unstable and moist the overrunning air is, the heavier the precipitation. Unstable air can be detected by the presence of MCSs in the satellite imagery.

The Forecast Index is a five step Decision Tree (Figure 21). This Decision Tree methodology is similar to the one used for the 3-12 Hour Heavy Precipitation Forecast Index for MCSs (Jiang Shi and Scofield, 1987 and Xie Juying and Scofield, 1989).

3-12 HOUR HEAVY PRECIPITATION FORECAST INDEX FOR EXTRATROPICAL CYCLONE SYSTEMS (ECSSs)

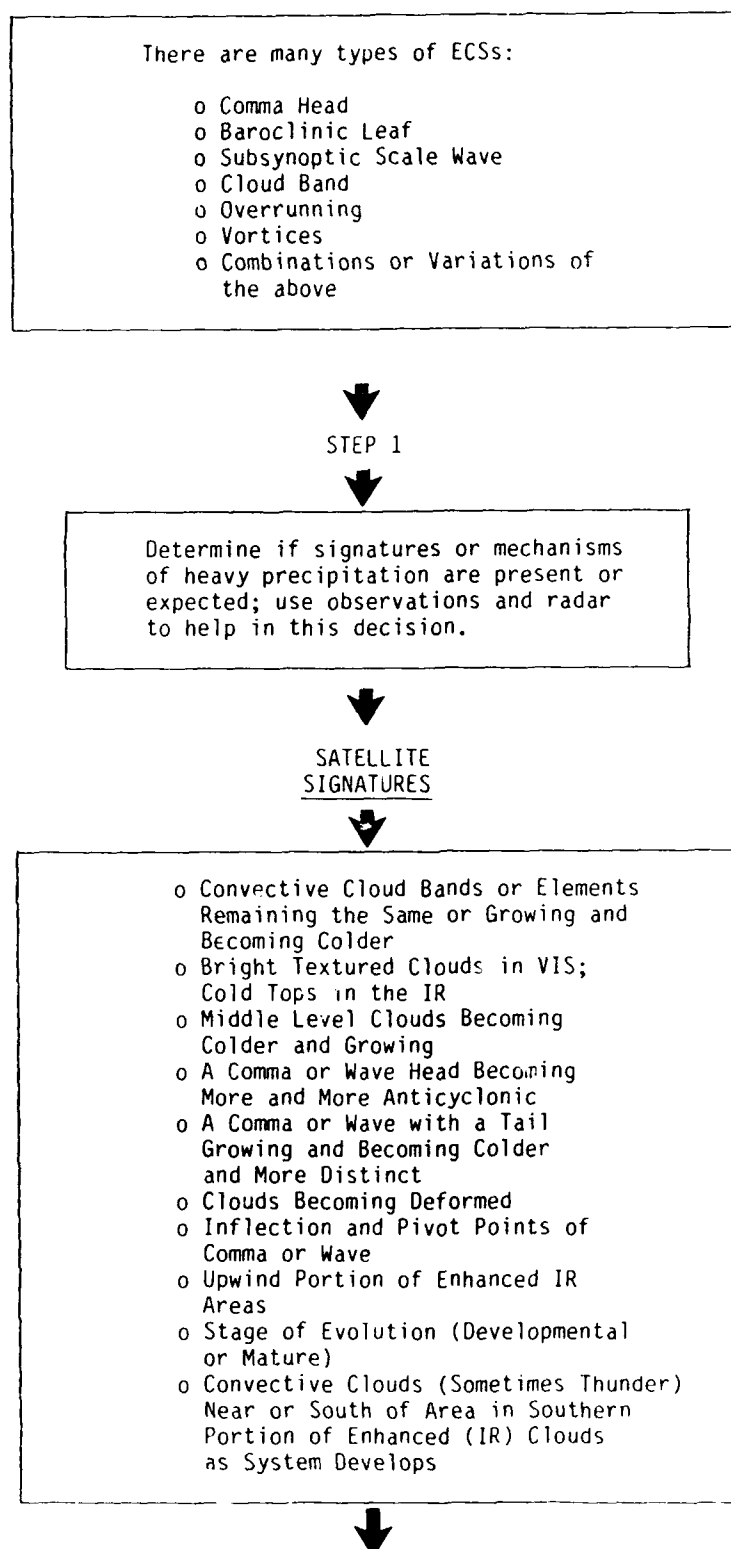


Figure 21a. Forecast Index "Decision Tree" of 3-12 Hour Heavy Precipitation from ECSSs.

MECHANISMS

LOW LEVEL FORCING:
(usually necessary for Heavy Precipitation)

- o Instability Bursts (advection of unstable air ($\nabla \cdot \nabla \theta_e$) 850 or 700mb > 0 or strong lifting of unstable air; unstable air sometimes produced by cold air advection aloft)
- o Warm Air Advection
- o Maximum Inflow
- o Upslope Flow
- o A Boundary

MIDDLE LEVEL FORCING:

- o Maximum Positive Vorticity Advection
- o Deformation Zones

UPPER LEVEL FORCING:

- o A Diffluent Jet Max just southwest or west of heavy precipitation area
- o In a "Split Flow Situation" the southern system comes into phase with the northern one (or vice versa)
- o Deformation Zones

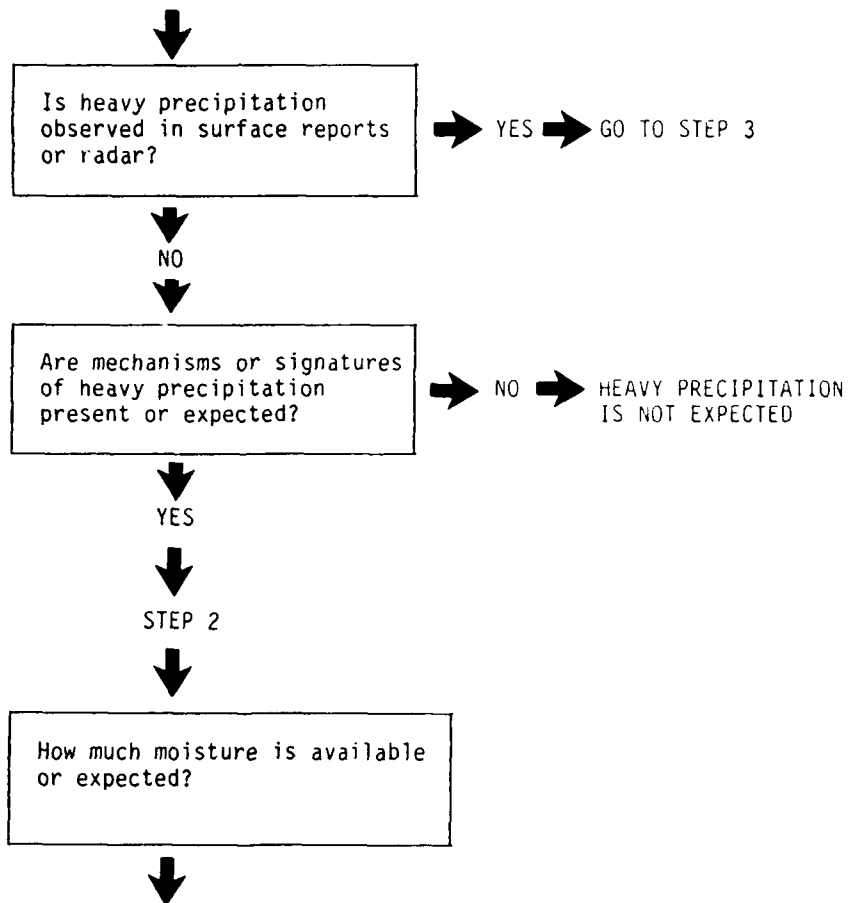


Figure 21b. Forecast Index "Decision Tree" of 3-12 Hour Heavy Precipitation from ECSSs.

CRITERIA FOR ECS TO PRODUCE
HEAVY PRECIPITATION

- o sfc-500 mb Precipitable Water > 0.50 Inches
- o sfc-500 mb Relative Humidity of $\geq 50\%$
- o sfc (or 850 mb) Moisture Convergence
- o Moisture Advection

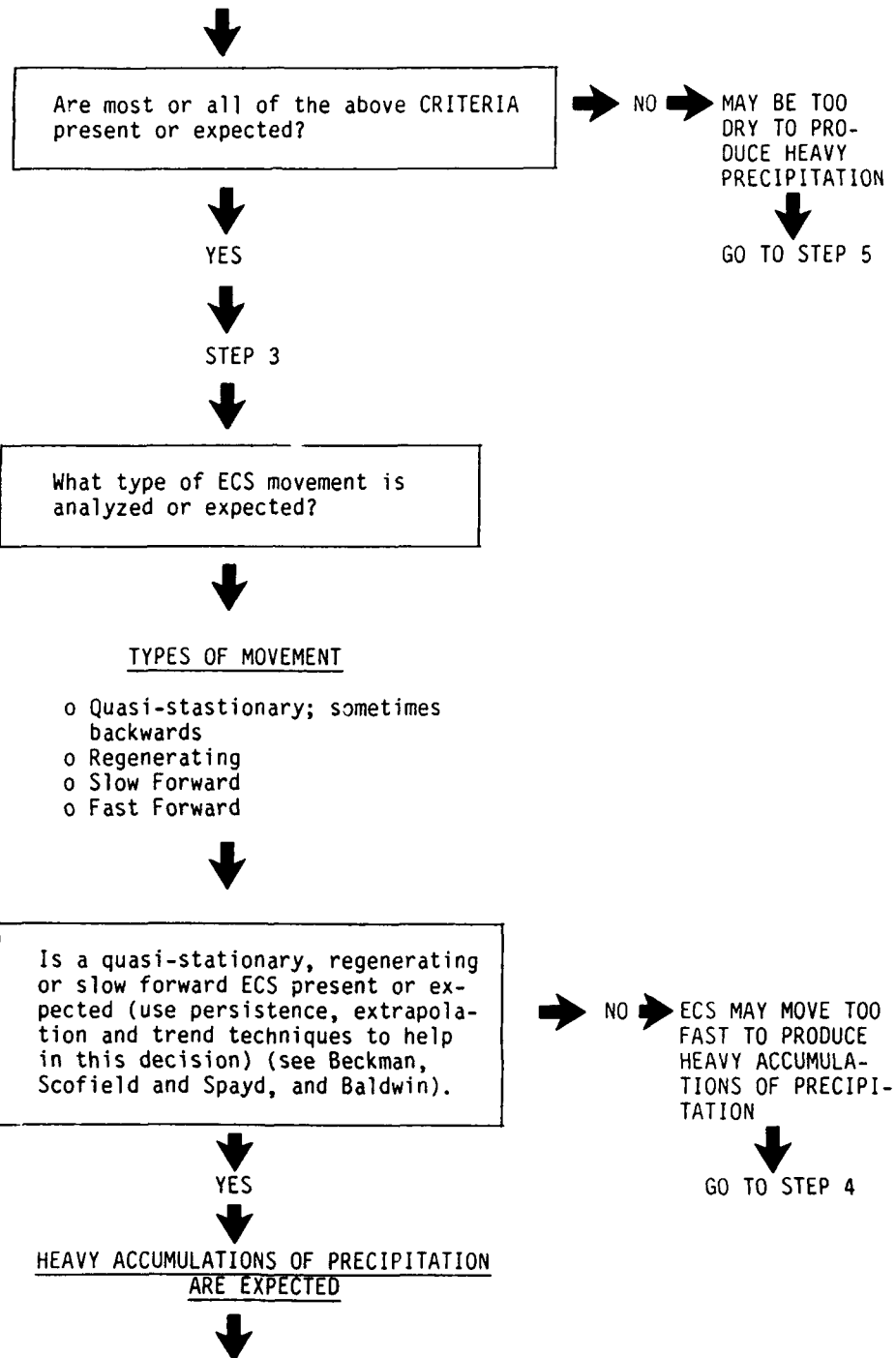


Figure 21c. Forecast Index "Decision Tree" of 3-12 Hour Heavy Precipitation from ECSs.

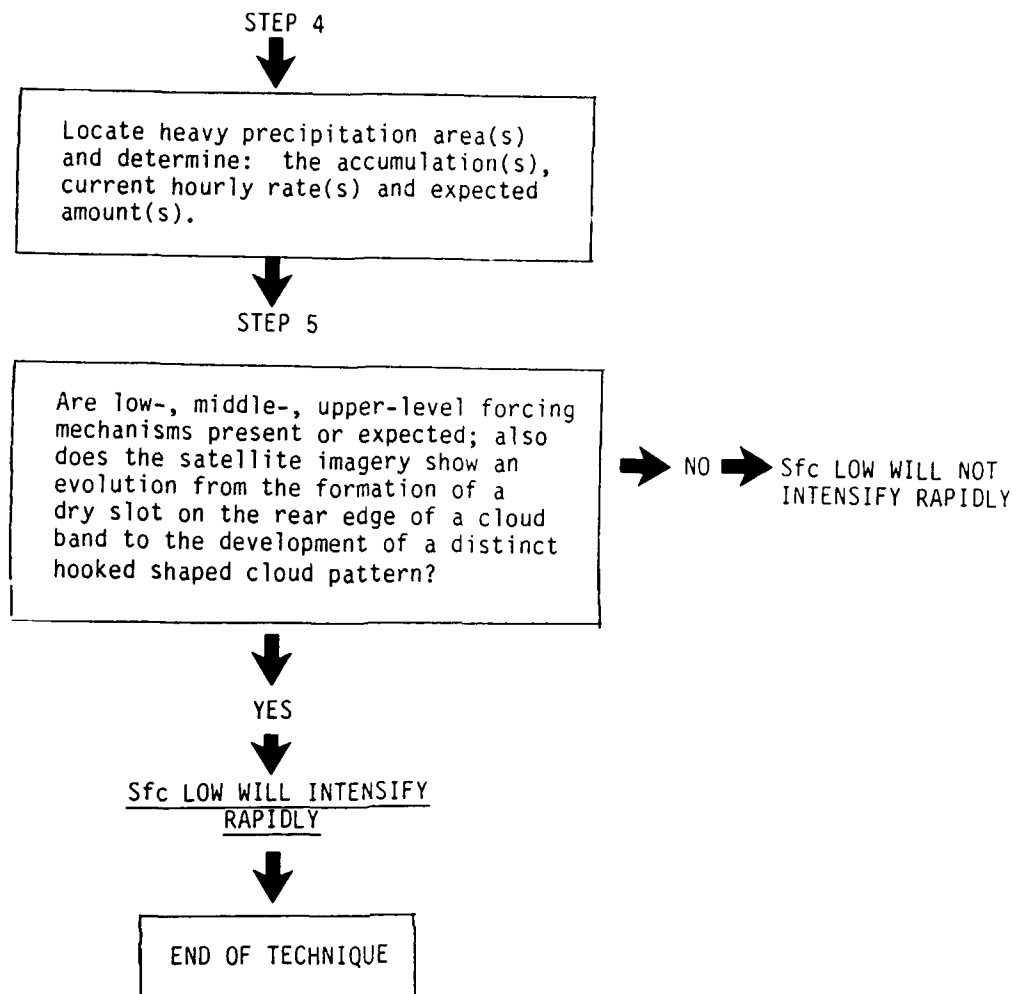


Figure 21d. Forecast Index "Decision Tree" of 3-12 Hour Heavy Precipitation from ECSs.

Step 1 (Figures 21a,b) determines if satellite signatures and mechanisms of heavy precipitation are present or expected over the next 12 hours. Satellite signatures of heavy precipitation and mechanisms of low, middle and upper level forcing are presented. Twelve hour forecasts from the National Meteorological Center's (NMC) Nested Grid Model (NGM) are extremely useful for determining if mechanisms that support heavy precipitation are going to occur. IBs (a low level forcing mechanism) are determined from the 850 mb TEA fields; they are very conservative features that can be "tracked" over 12 hour periods (between 0000 and 1200 GMT and vice versa). As shown in the previous section north to south oriented TEA couplets are often associated with rapidly deepening surface lows.

Step 2 (Figures 21b,c) presents "moisture" criteria to determine if ECSs will produce heavy precipitation. The moisture criteria consider how much moisture is present NOW and how much will

become available over the next 12 hours. Experience has shown that these moisture criteria are most applicable to winter (cold) season precipitation.

Step 3 (Figure 21c) uses the satellite imagery to determine the type of ECS movement that is present or expected. ECSs that are quasi-stationary, regenerating and slowly moving eastward most often produce heavy amounts of precipitation. ECSs that move rapidly eastward normally produce lighter amounts of precipitation with one EXCEPTION - RAPIDLY DEEPENING SURFACE LOWS. Rapidly deepening surface lows usually move rapidly northeastward and deposit an abundance of precipitation.

Step 4 (Figure 21c) locates the heavy precipitation within the ECS. Satellite imagery is used in this heavy precipitation analysis. Accumulations, current hourly rates and outlooks (and location) of heavy precipitation over the next 12 hours are computed. Persistence, extrapolation and trend techniques and precipitation forecasts from the NGM are used in these computations. Beckman (1987), Scofield and Spayd (1984), and Baldwin (Personal Communication) have developed techniques to accomplish Step 4.

Steps 1-4 comprise the Forecast Index of 3-12 Hour Heavy Precipitation for ECSs. Step 5 (Figures 21c,d) is optional and provides a list of mechanisms and satellite signatures associated with rapidly deepening surface lows. The five steps of this technique allow the forecaster in a logical way to use satellite imagery, surface and upper air observations and the NGM to analyze and forecast heavy precipitation from ECSs.

V. APPLICATIONS OF THE FORECAST INDEX TO THE FORECAST OF HEAVY SNOW

The Index can be used for analyzing and forecasting heavy rain or heavy snow from ECSs. However, in this section, the Index is used for analyzing and forecasting heavy snow from ECSs occurring in the central, southern, and eastern regions of the U.S. For each case, the following data are provided:

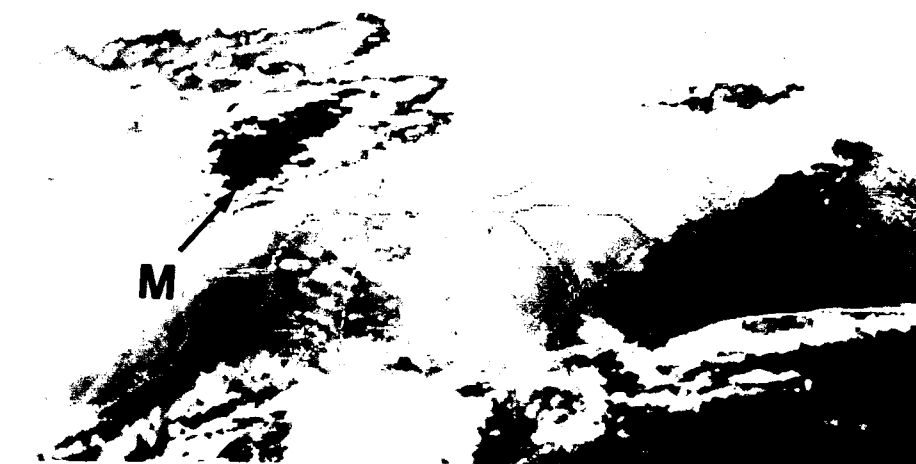
- o Satellite imagery;
- o Low level forcing information (location of surface lows and of IBs);
- o Middle level forcing information (location of 500 mb vorticity centers and Positive Vorticity Advection (PVA));
- o Upper level forcing information (location of jet streaks);
- o 1000-500 mb precipitable water and relative humidity;
- o 12 hour observed snowfall;
- o 24 hour observed precipitation.

Central Region Snowstorm of December 14-16, 1987

On December 14-16, 1987, a snowstorm initiated by IBs occurred from Oklahoma northeastward to Michigan. Thunder was reported at many locations (Heppner, 1988). In fact, the ECS "baroclinic leaf" cloud system (M) that "burst" into existence around December 14, 1301 GMT (see Figure 22) looked like a MCS. A radar depiction (Figure 23) at 1335 GMT shows convective elements (C) embedded within the precipitation area over Missouri. Figure 22 shows the evolution of the cyclone from three features: a MCS at (M), an upper level system at (U-U'), and a squall line at (S) to a mature comma head (C) and comma tail (T) by December 15, 1200 GMT. The surface low deepened 27 mb in 18 hours. Surface low positions are plotted on the December 15, 1301 GMT satellite picture. The surface analysis for December 15, 1200 GMT appears in Figure 24. Low, middle and upper level forcing and moisture analyses are presented in Figures 25, 26, 27, and 28, respectively. The 850 mb TEA fields are shown in Figures 25a,b,c,d. The advection field in Figure 25c (December 15, 0600 GMT) is an interpolated field between Figure 25b (December 15, 0000 GMT) and Figure 25d (December 15, 1200 GMT). Often the 850 mb TEA field will correspond to the maximum advection of unstable air as given by the NGM Lifted Index (LI) and the 850 mb height contour analysis. Such is the case for December 15, 1200 GMT where the maximum TEA (Figure 25d) and the maximum advection of unstable air (Figure 25e) are quite similar in pattern and location. Twelve-hour, heavy-snowfall analyses (4 or more inches) appear in Figures 29a,b,c and 24 hour observed precipitation is shown in 30a,b,c. Note that the maximum positive TEA at 850 mb is a very conservative feature that can be tracked from northern Arkansas to southern Michigan. Also, the TEA analysis is oriented in a similar pattern as the heavy snowfall. Heavy snow fell 1-3° latitude north of the axis of maximum TEA. From the theta-e maximum southward, locally heavy rain occurred. It has been our experience that in frontogenetic and cyclogenetic situations (such as this case), the axis of maximum TEA often locates the transition zone between snow and rain; rain is often moderate to heavy along and just south of the axis. The December 15, 0600 GMT advection field (Figure 25c) was produced because the TEA field between December 15, 0000 GMT and 1200 GMT moved quite rapidly. During this same time, the surface low moved and deepened rapidly. The snowstorm and accompanying rapidly deepening surface low were associated with:

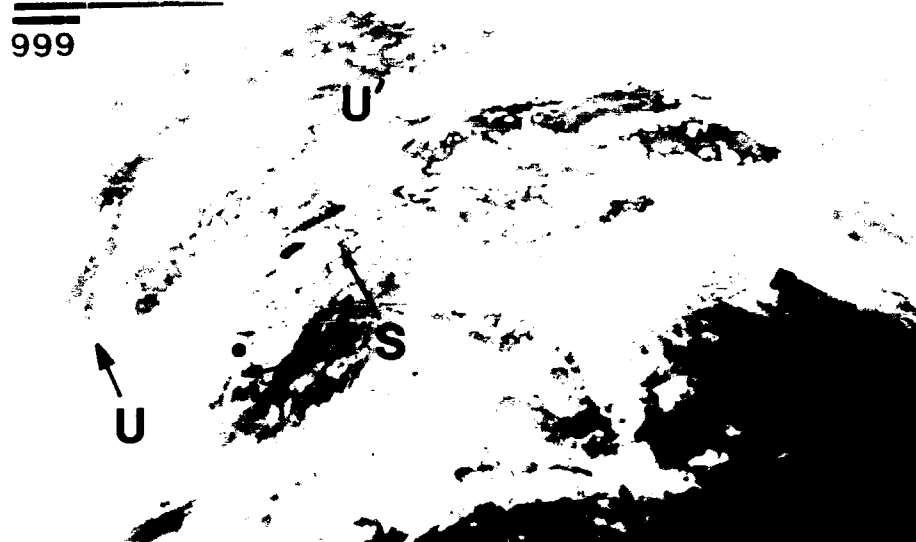
- (1) A MCS/baroclinic leaf type feature in the satellite imagery that evolved into a comma head/comma tail (squall line) and finally into a "hooked-shaped" cloud pattern (Figure 22);
- (2) Low level forcing mechanisms as shown by the strong positive TEA fields and the development of a pronounced north-south oriented TEA couplet (Figure 25);

14 DEC 87

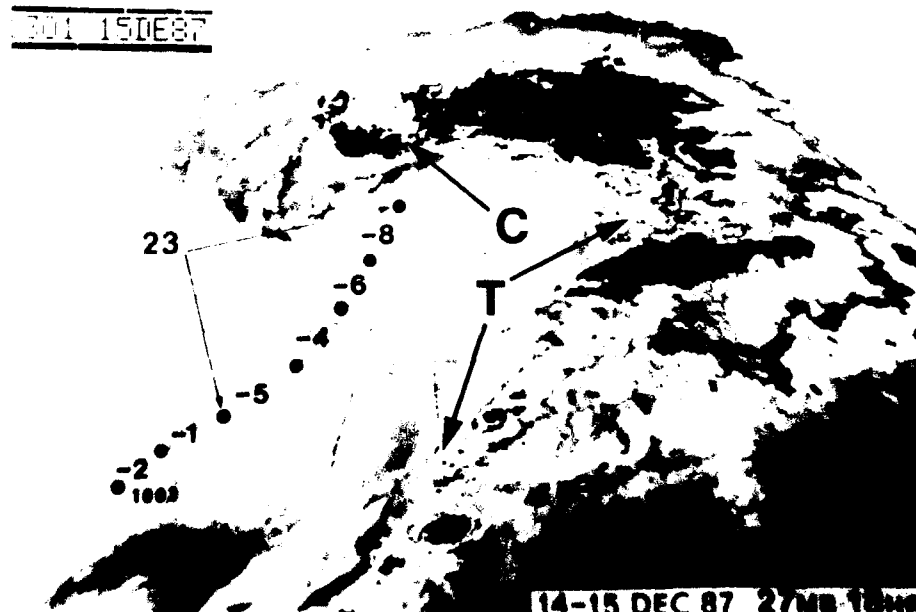


0031 15 DEC 87

999



001 15 DEC 87



14-15 DEC 87 27MB 10HR

Figure 22. Extratropical Cyclone Systems (ECSSs) over the midwest; enhanced IR imagery (CC Curve), December 14-15, 1987; dots locate position of surface low and the numbers are in units of millibars.

-

42

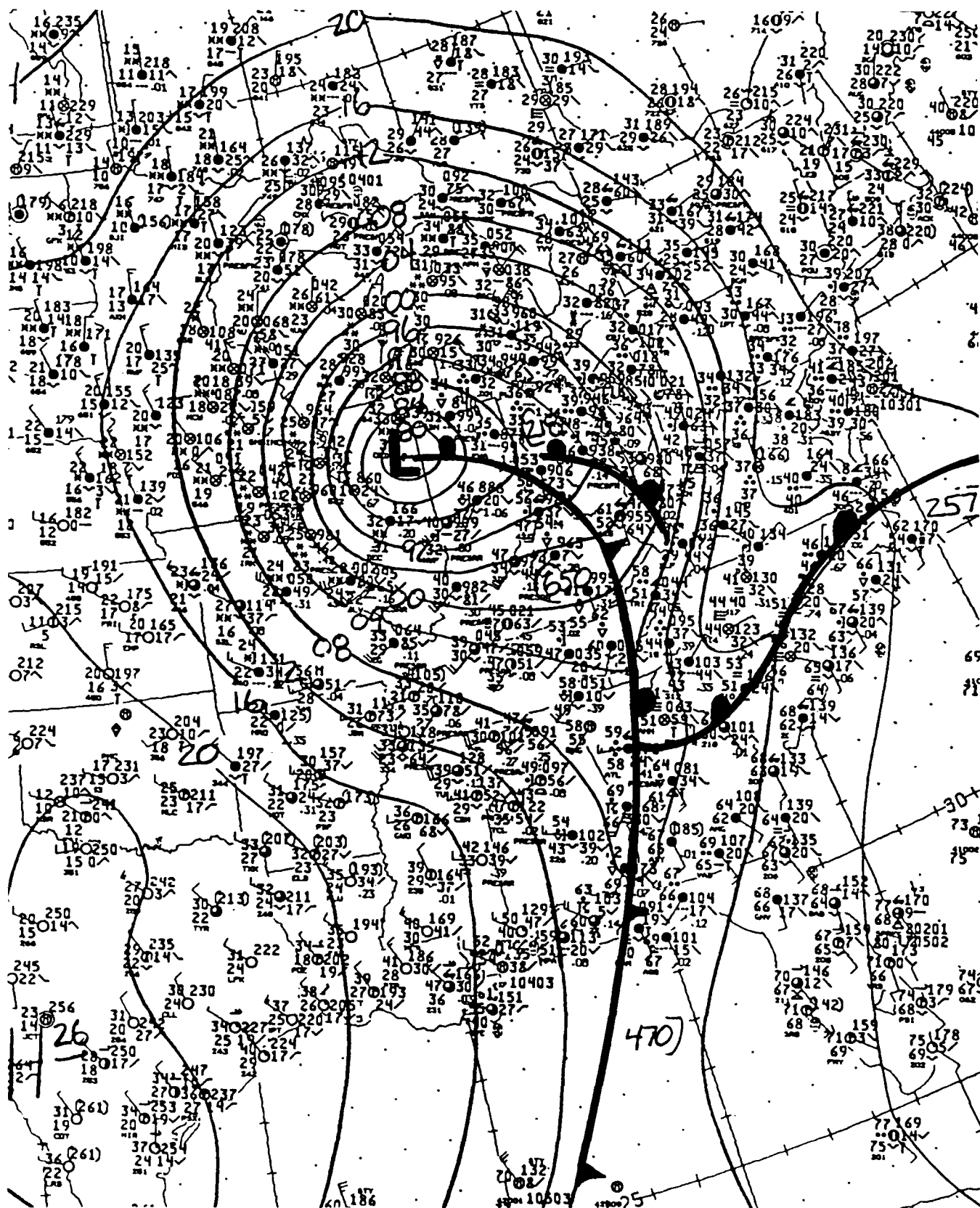


Figure 24. Surface analysis for December 15, 1987, 1200 GMT.

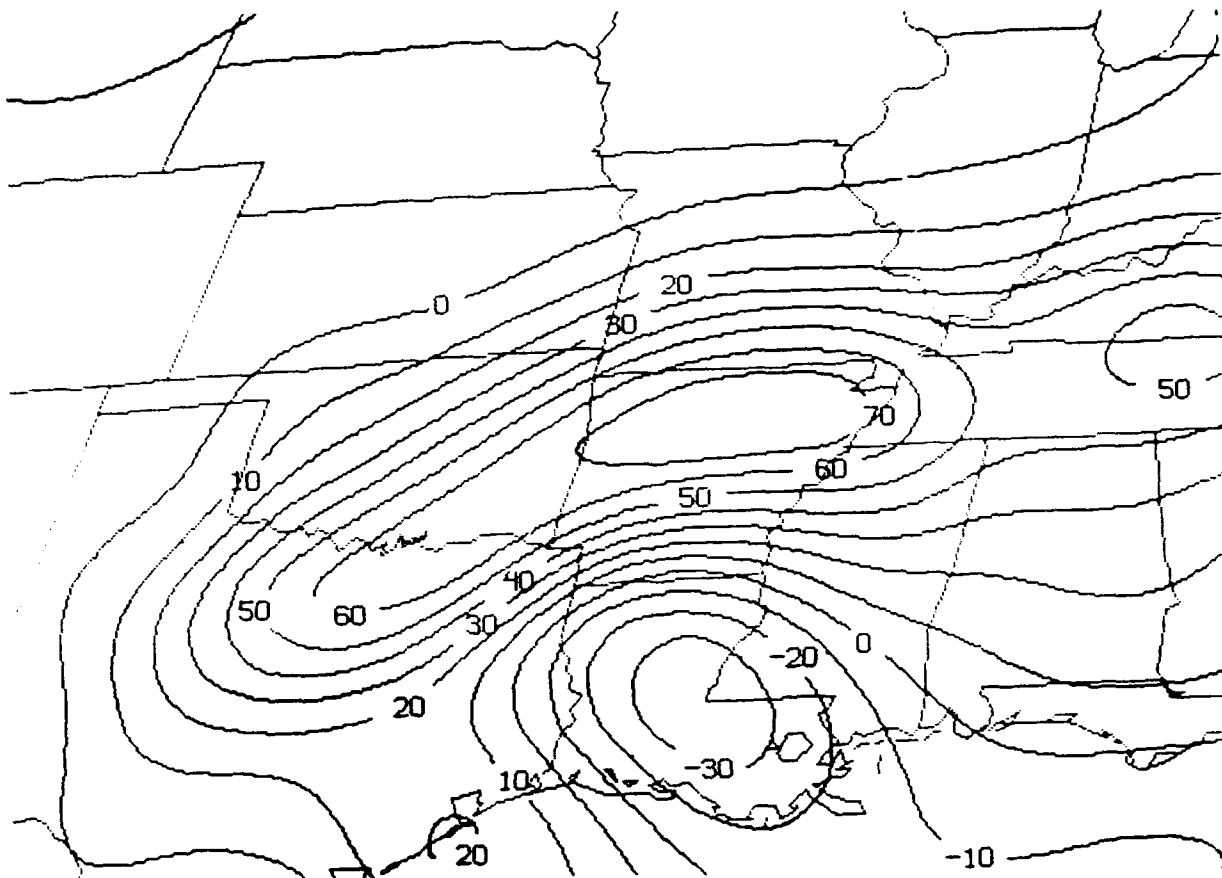


Figure 25a. 850 mb theta-e advection (degrees/day), December 14, 1987, 1200 GMT.

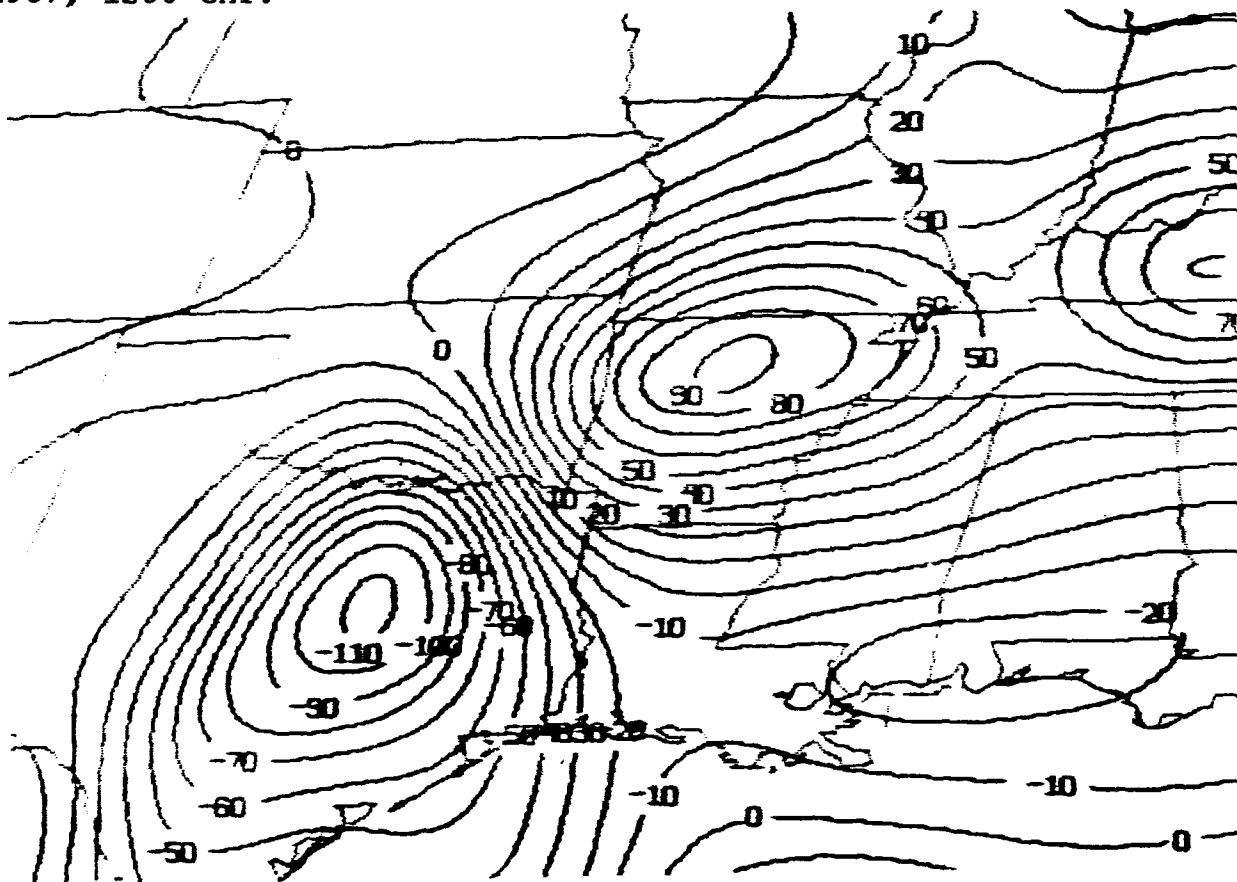


Figure 25b. 850 mb theta-e advection (degrees/day), December 15, 1987, 0000 GMT.

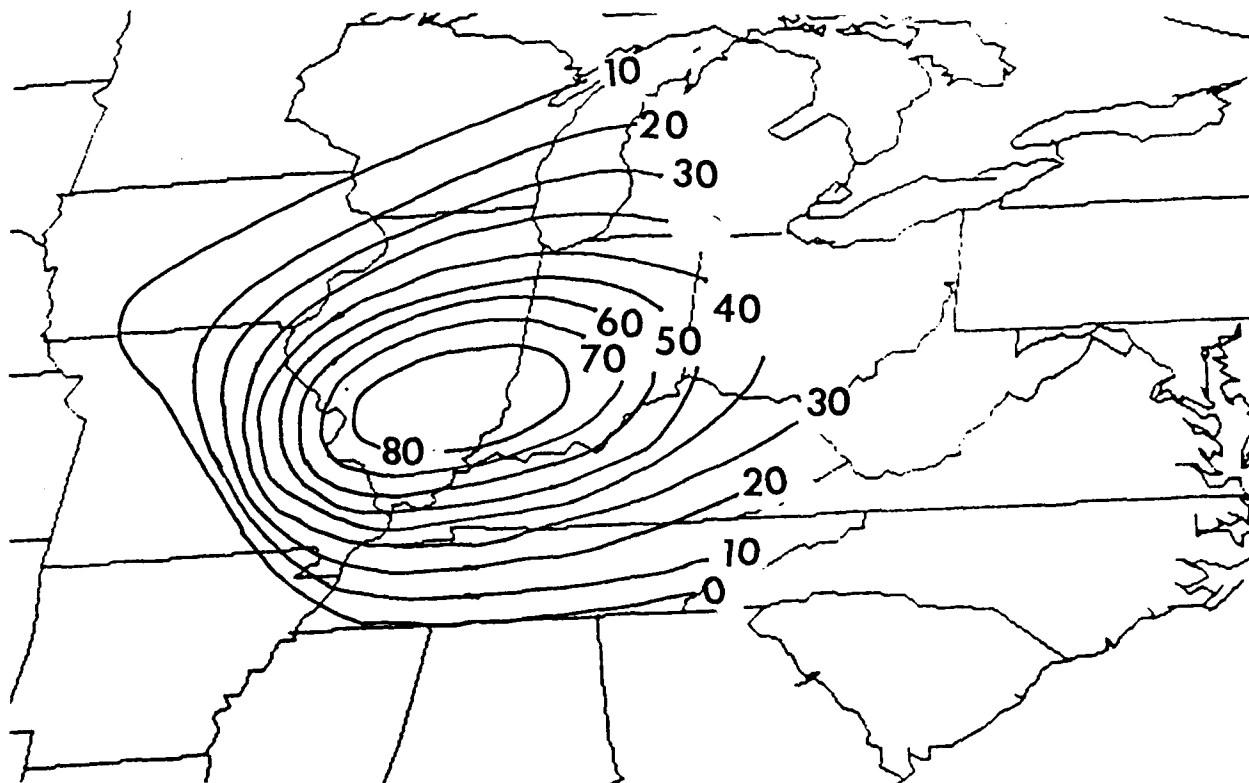


Figure 25c. Interpolated 850 mb theta-e advection (degrees/day) December 15, 1987, 0600 GMT.

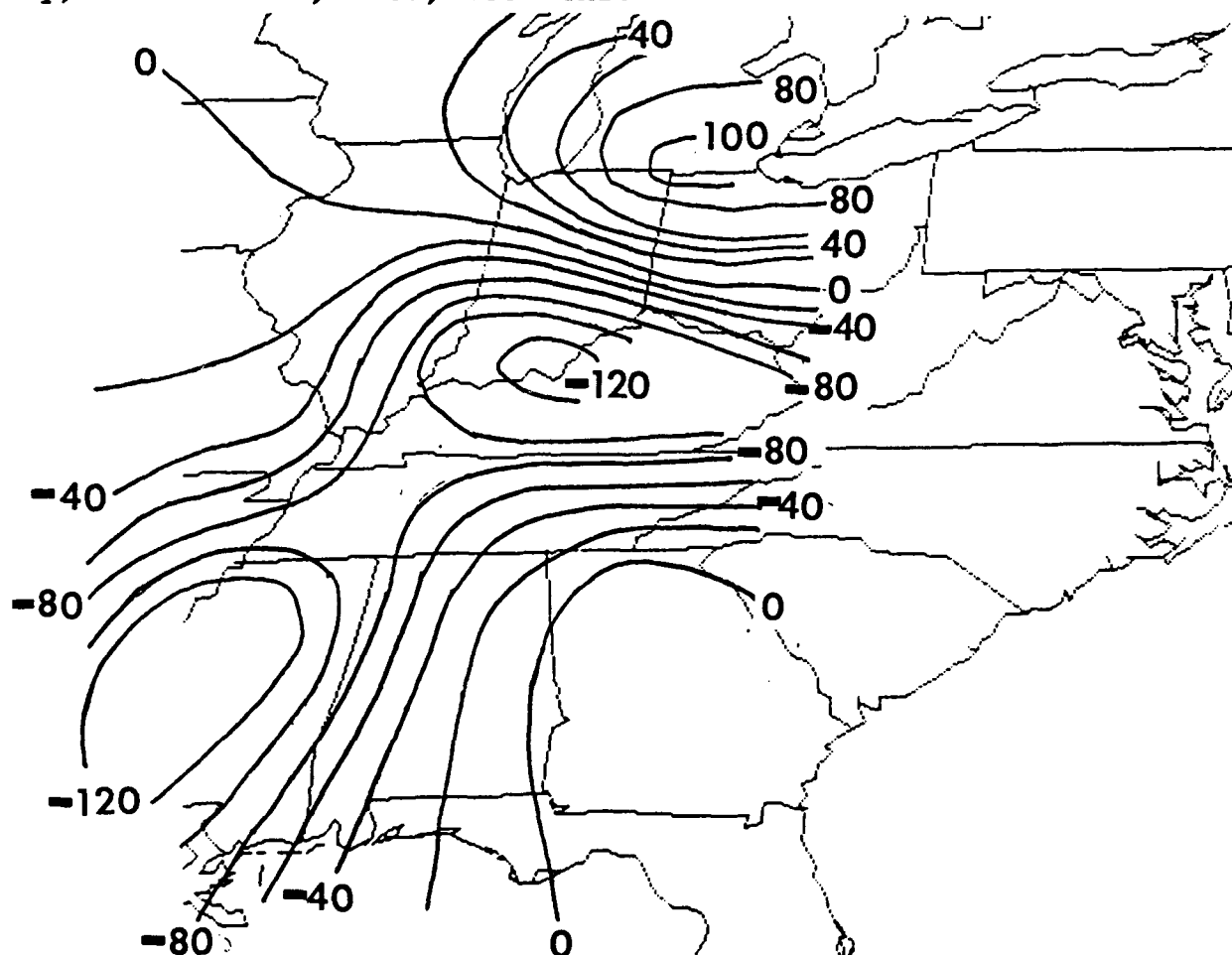


Figure 25d. 850 mb theta-e advection (degrees/day), December 15, 1987, 1200 GMT.

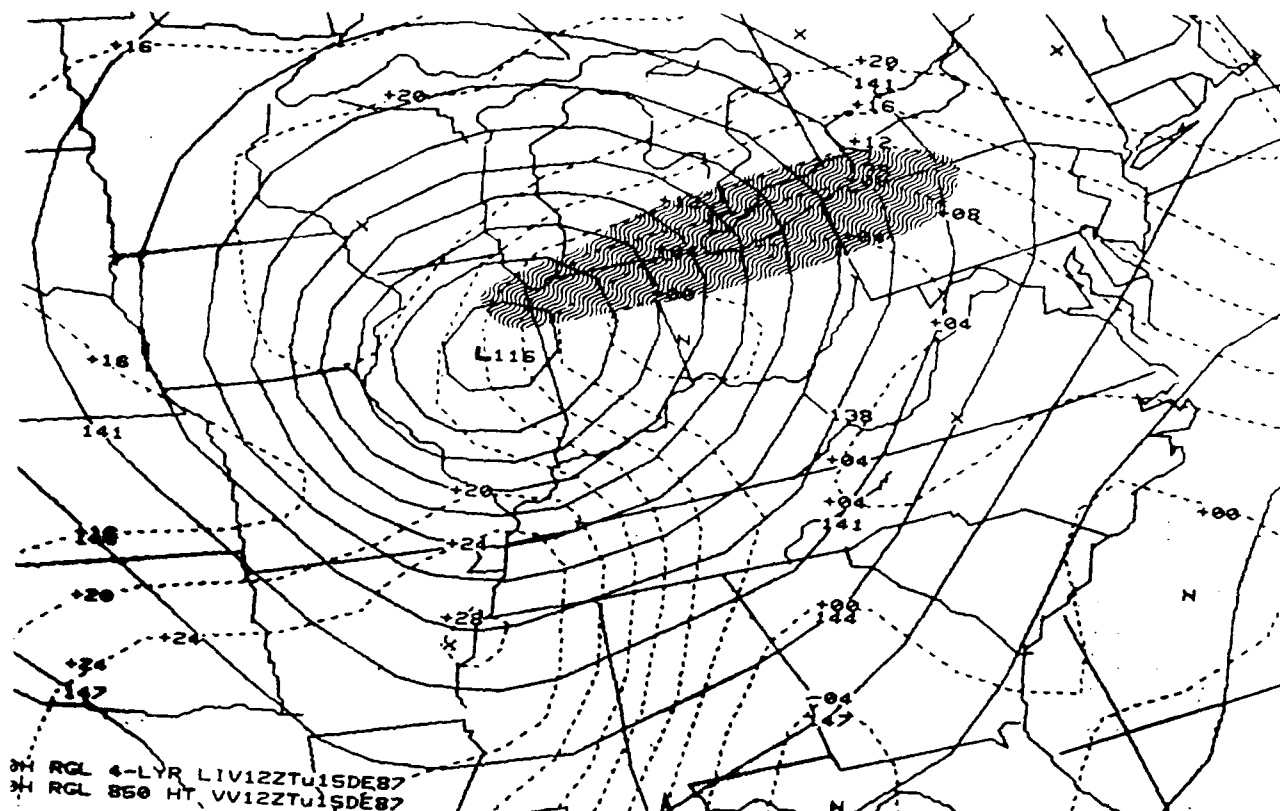


Figure 25e. Nested Grid Model (NGM) Lifted Index (dashed) and 850 mb contour analysis (solid) for December 15, 1987, 1200 GMT; shaded area locates the Instability Burst associated with the maximum advection of unstable air.

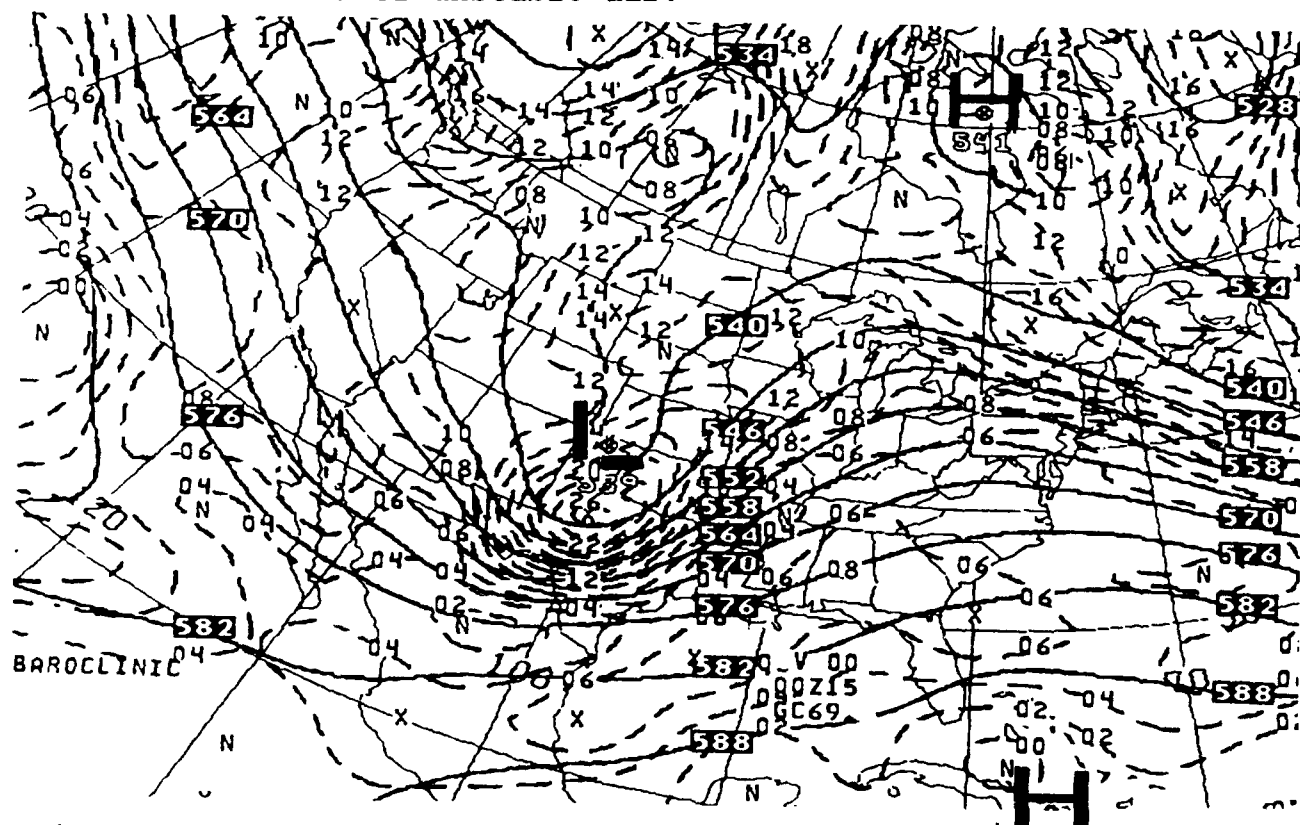


Figure 26. 500 mb heights/vorticity analysis, December 15, 1987, 0000 GMT.

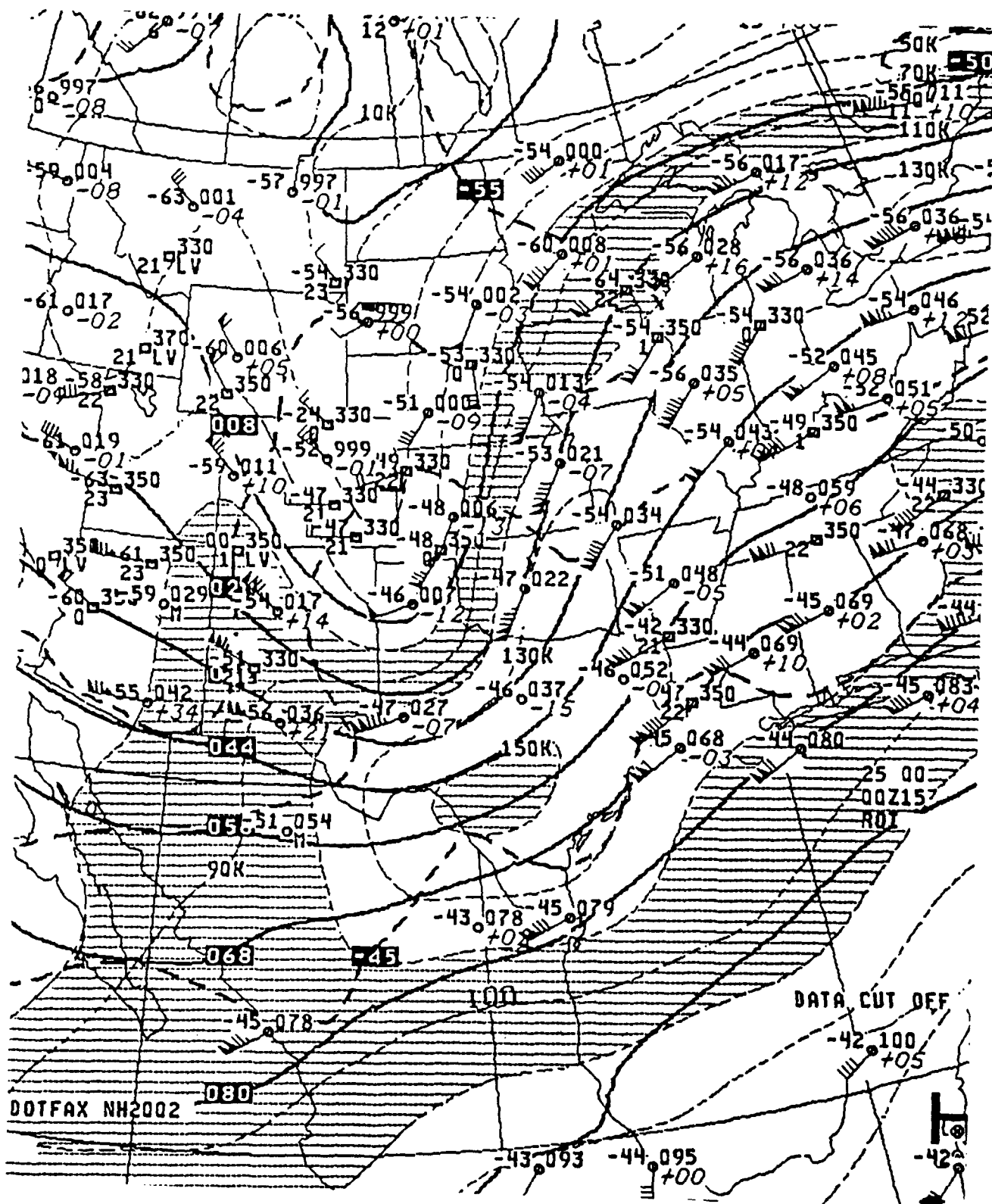


Figure 27. 250 mb heights/isotachs analysis, December 15, 1987, 0000 GMT.

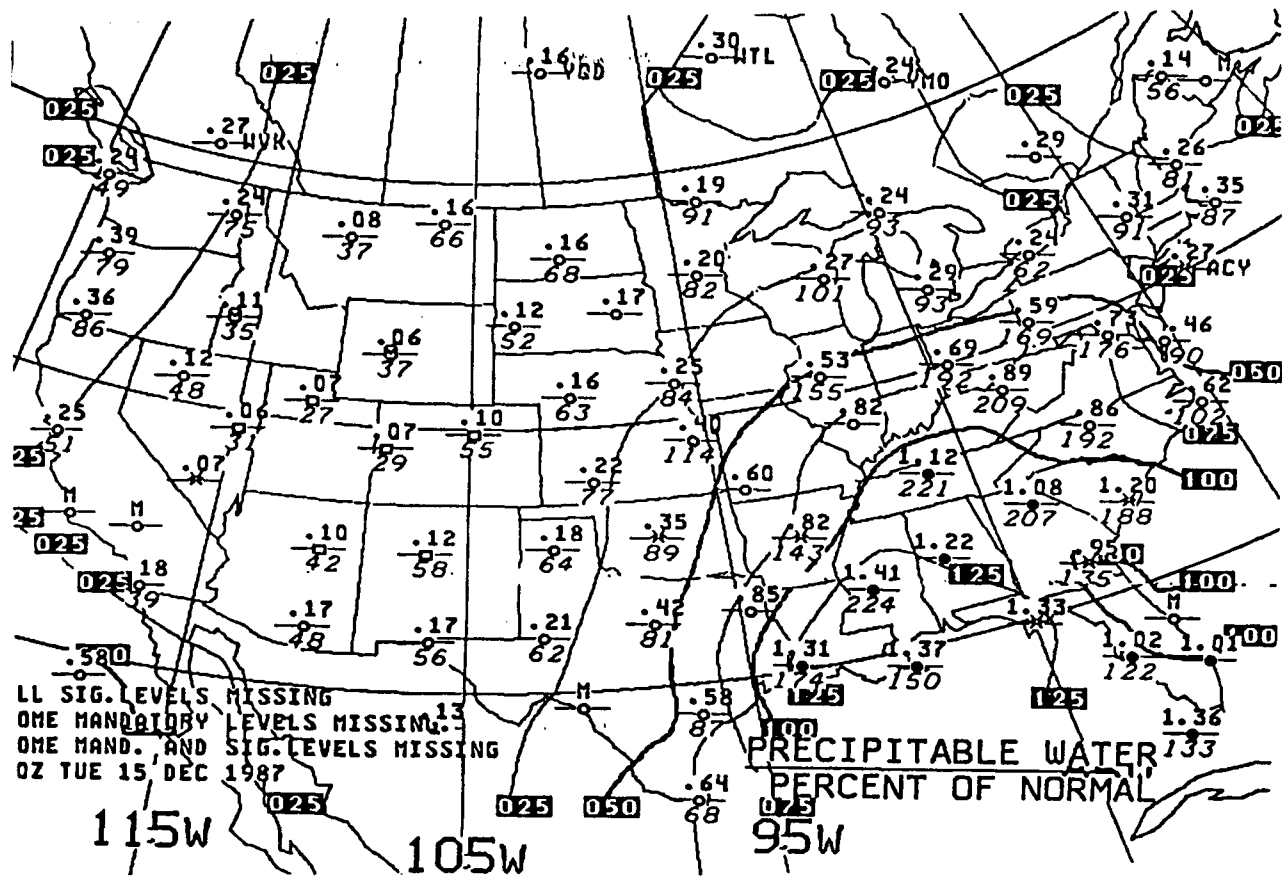


Figure 28a. 1000-500 mb precipitable water analysis, December 15, 1987, 0000 GMT.

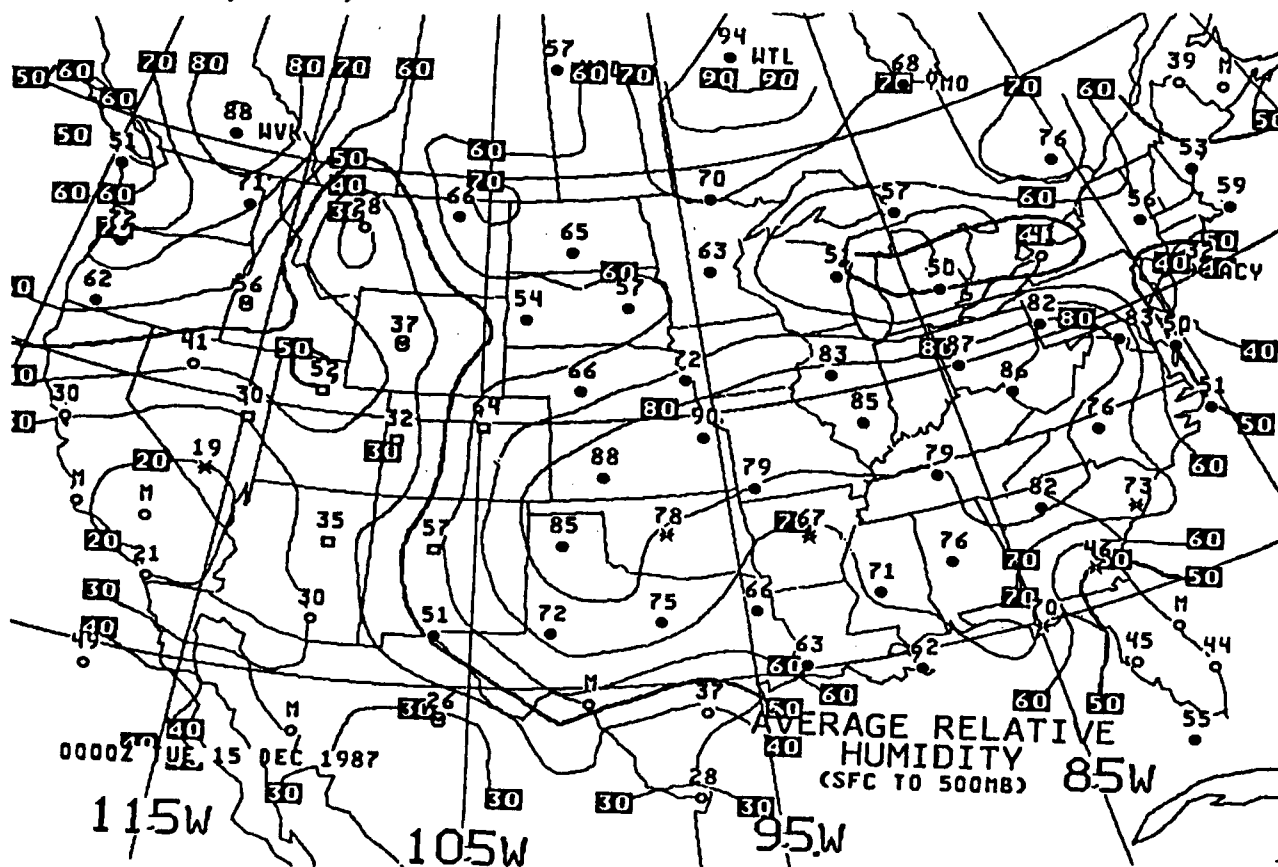


Figure 28b. 1000-500 mb relative humidity analysis, December 15, 1987, 0000 GMT.

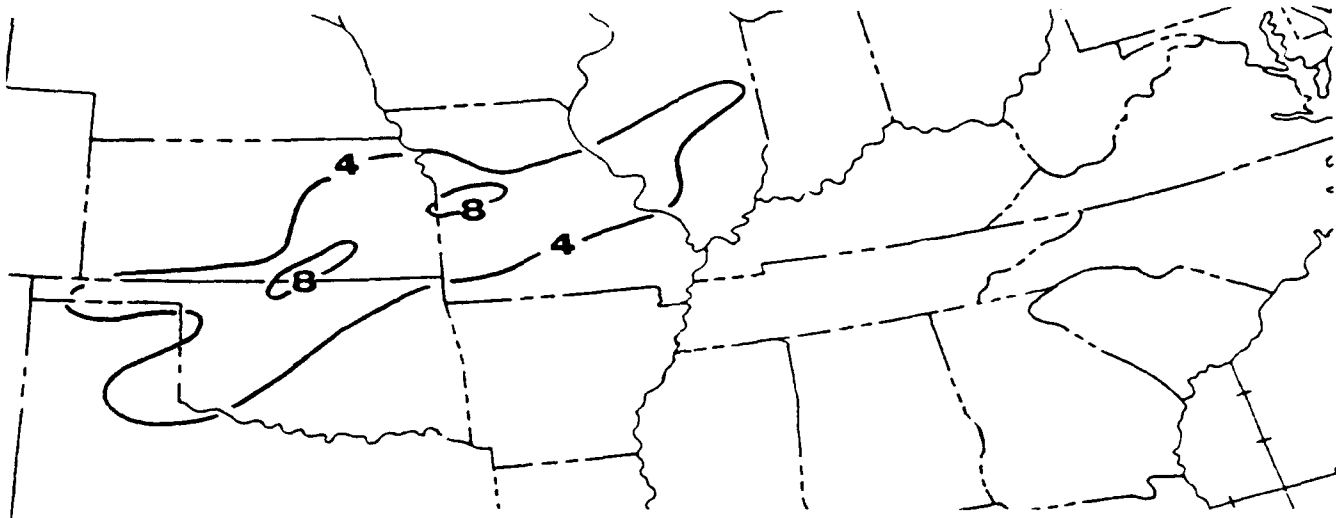


Figure 29a. Twelve hour heavy snowfall (inches) ending at December 15, 1987, 0000 GMT.

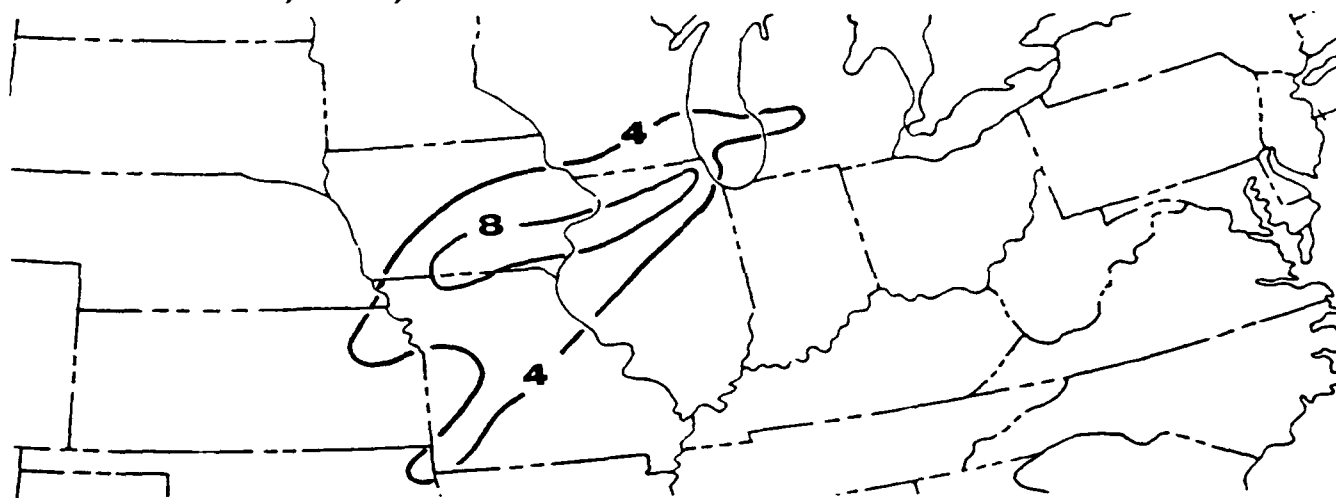


Figure 29b. Twelve hour heavy snowfall (inches) ending at December 15, 1987, 1200 GMT.

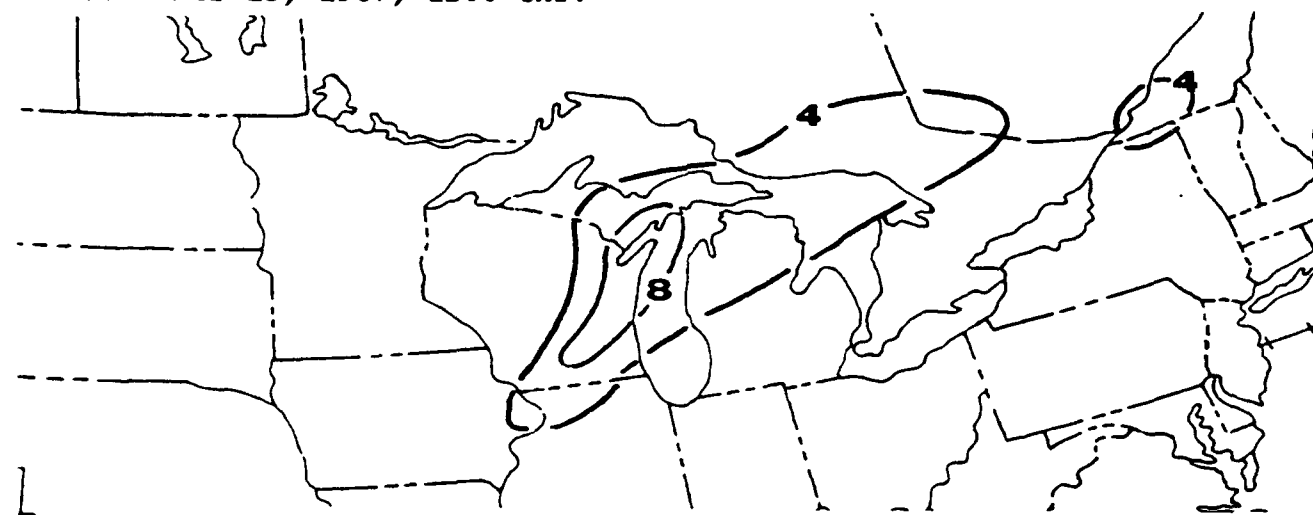


Figure 29c. Twelve hour heavy snowfall (inches) ending at December 16, 1987, 0000 GMT.

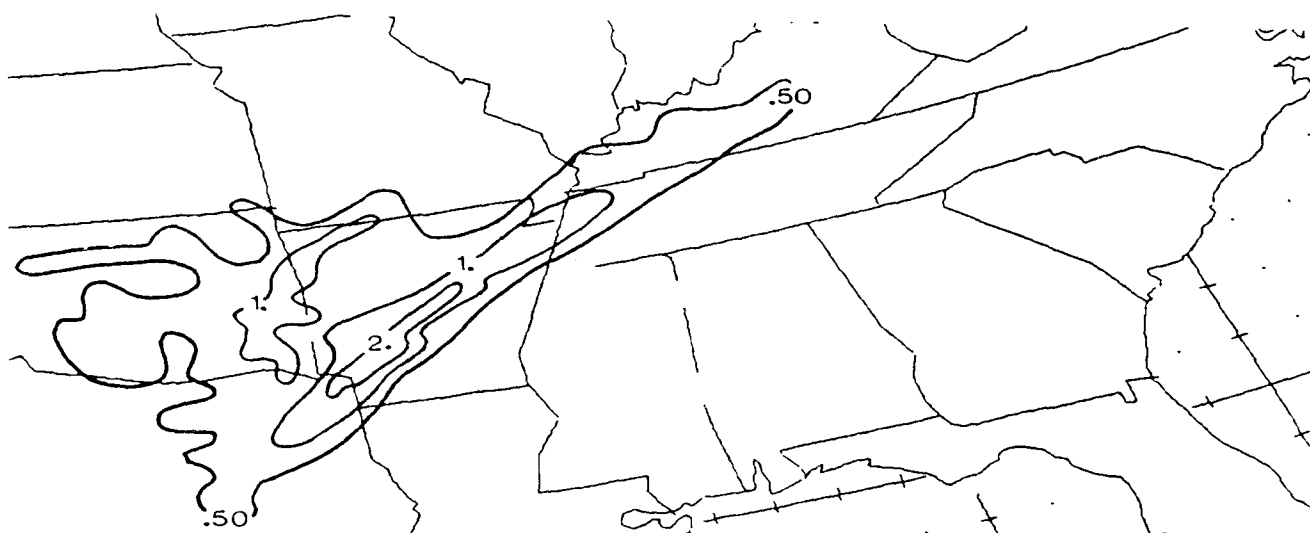


Figure 30a. Twenty-four hour observed precipitation (inches) ending at December 14, 1987, 1200 GMT.

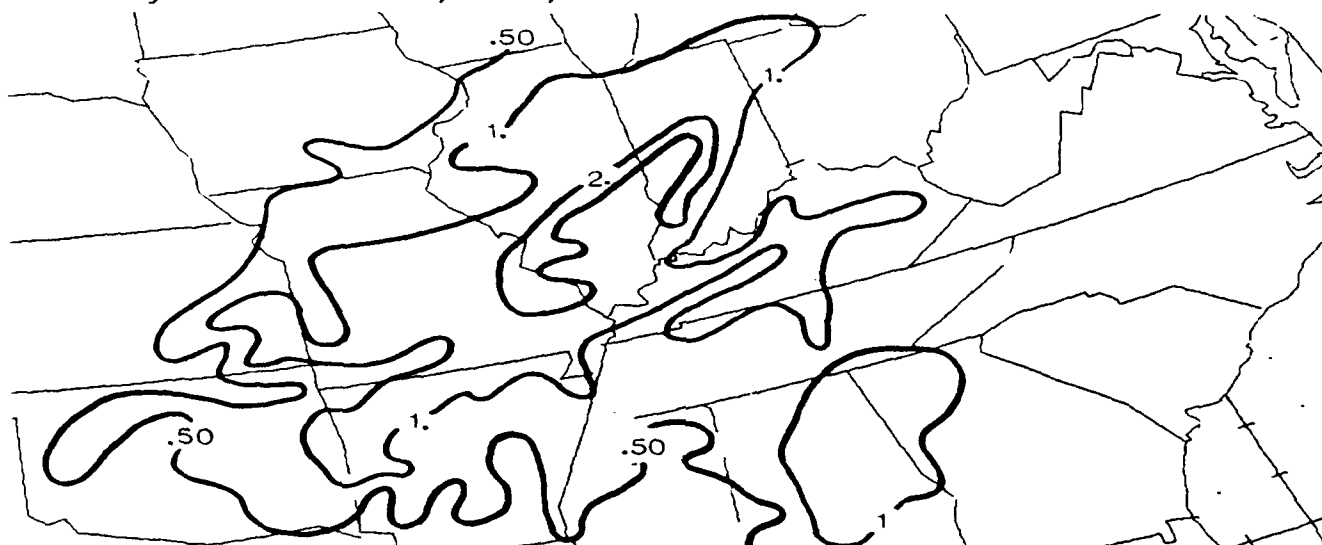


Figure 30b. Twenty-four hour observed precipitation (inches) ending at December 15, 1987, 1200 GMT.

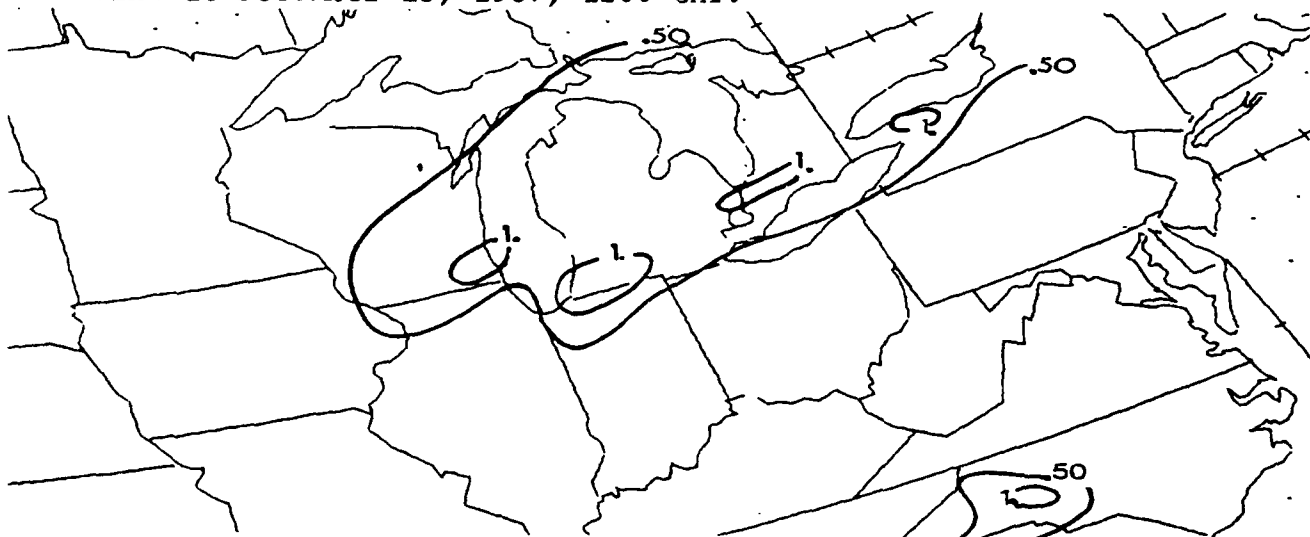


Figure 30c. Twenty four hour observed precipitation (inches) ending at December 16, 1987, 1200 GMT.

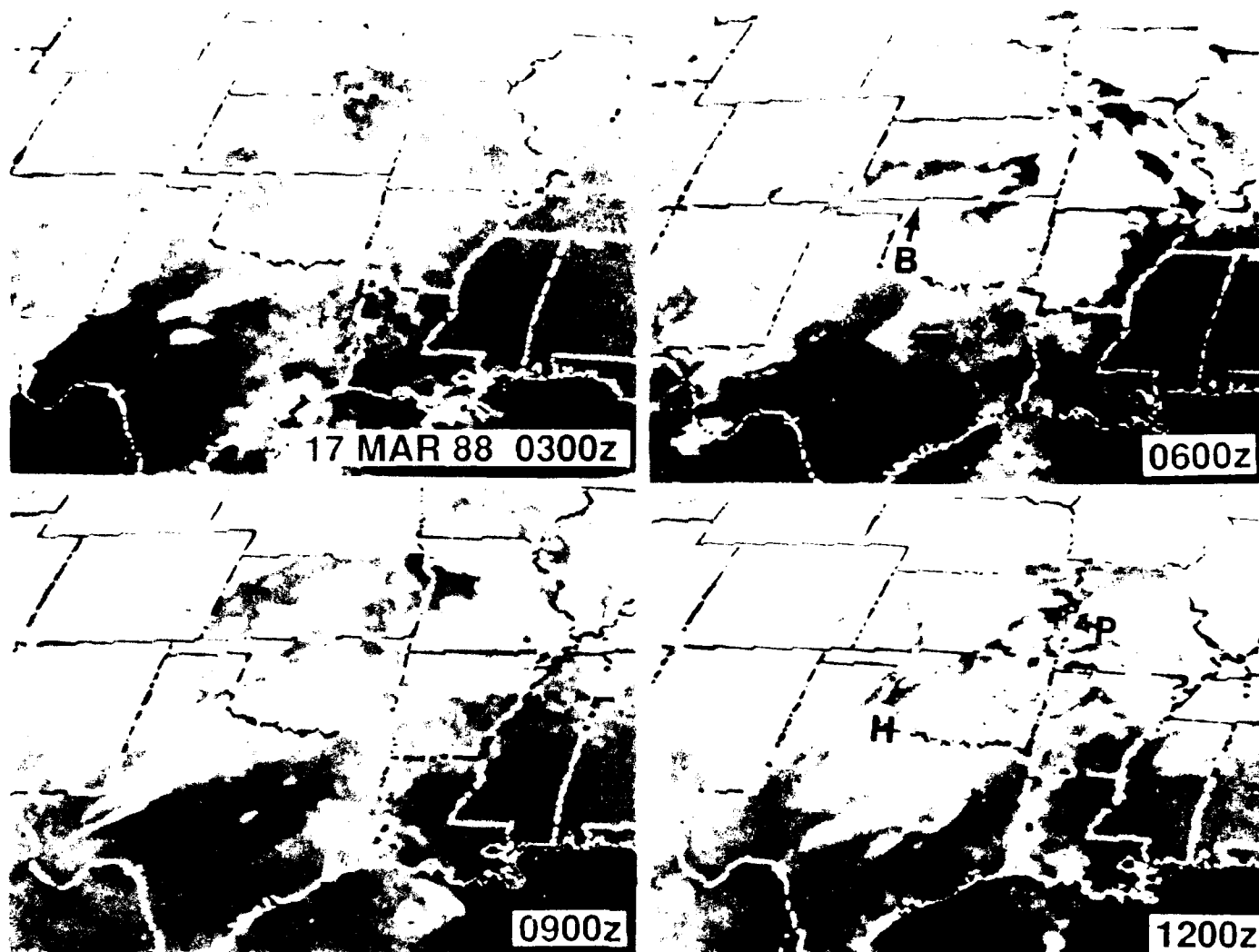


Figure 31. A Baroclinic Leaf; enhanced IR imagery (MB Curve), March 17, 1988.

Southern Region Snowstorm of March 17 and 18, 1988

On-March 17 and 18, 1988, heavy snow, produced by IBs, fell from the Texas Panhandle through Oklahoma, southern Kansas and northern Arkansas. The enhanced IR imagery (Figure 31) shows the development of a baroclinic leaf (at B). As is characteristic of most baroclinic leaves, the heaviest precipitation (in this case SNOW) occurs in the southern part of the leaf (H-P) where new cloud developments are occurring. In noncyclogenetic situations, baroclinic leaves will move from west to east with the heaviest precipitation occurring in the extreme southern part of the leaf. Such is the case in this situation (Figure 32) as the leaf moved eastward and dissipated. A "ragged" comma head/comma tail (at C) developed along the Gulf Coast and moved eastward out to the Atlantic Ocean. In cyclogenetic situations, baroclinic leaves will transform into comma heads and hooked shaped cloud patterns and move rapidly northeastward. The water vapor imagery (Figure 33) clearly shows the jet streak (dark boundary between J-S) at the base of the trough. In addition, the imagery indicates that a cyclonic surge (development of a pronounced dark slot) was not taking place east of the trough (Texas Panhandle area). As shown

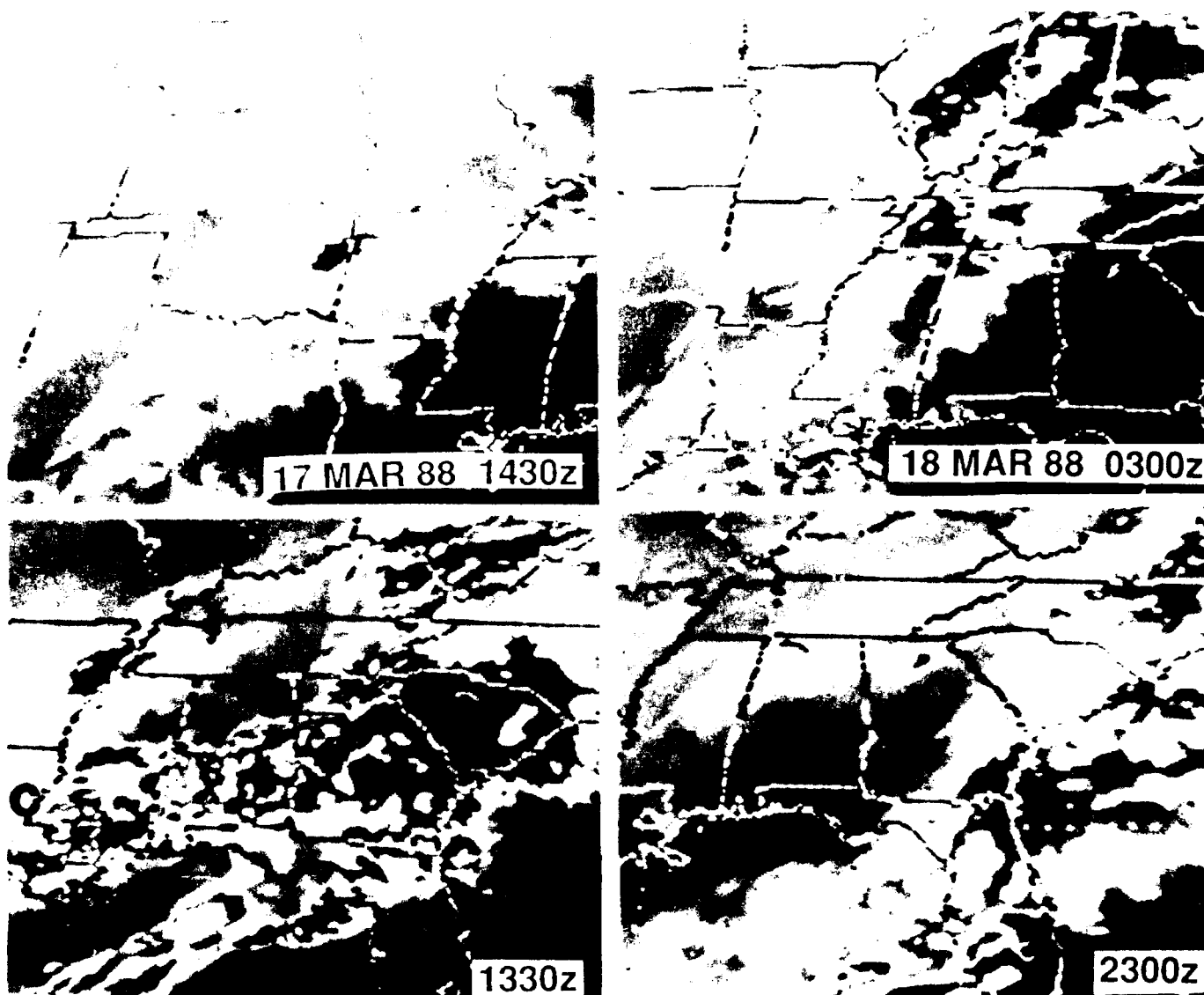


Figure 32. A ragged comma head and comma tail; enhanced IR imagery (MB Curve), March 17-18, 1988.

by Weldon and Holmes (1990), this is indicative that cyclogenesis will NOT TAKE PLACE. The NGM surface and 1000-500 mb thickness analysis for March 17, 1200 GMT is shown in Figure 34. A weak low is positioned over southwest Texas and cold air is located over the Texas Panhandle, Oklahoma and Arkansas. Analyses of low, middle and upper level forcing and moisture are presented in Figures 35, 36, 37, and 38, respectively. The 850 mb TEA fields are shown in Figures 35a,b,c,d,e; the K index analysis field with the maximum 850 mb winds superimposed is depicted in Figure 35f for March 17, 1200 GMT. Maximum 850 mb flow from higher to lower K index values is occurring from northern Texas into Oklahoma. Twelve hour heavy snowfall analyses (4 or more inches) are illustrated in Figures 39a,b and 24 hour observed precipitation is shown in Figures 40a,b. The positive 850 mb TEA fields (Figures 35a-e) occurred from northern Texas and Oklahoma to the Gulf Coast and then eastward out to the Atlantic Ocean. Most of these TEA fields were quite conservative and trackable. However, the southward shift in the TEA pattern from March 17, 1200 GMT (Figure 35b) to March 18, 0000 GMT (Figure 35c) is difficult to anticipate or predict. As dis-

17 MAR 88

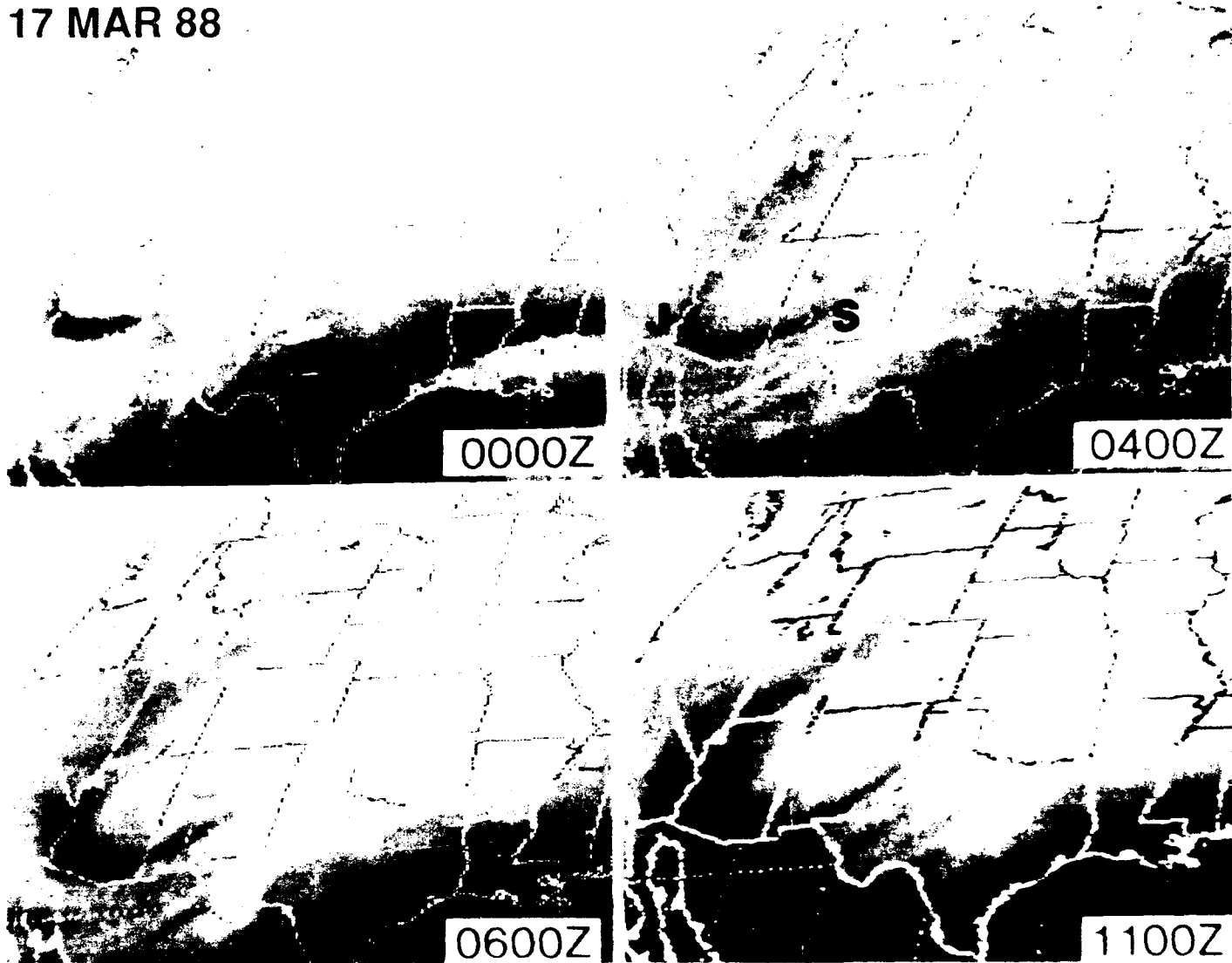


Figure 33. Water vapor imagery (6.7 m), March 17, 1988.

cussed in Section I, TEA fields are primarily controlled by synoptic scale features. In this case, there was a shift in the synoptic scale dynamics (and positive TEA field) from northern Texas and Oklahoma to the Gulf Coast by March 18, 0000 GMT. Heavy snow fell along and north of the axis of maximum TEA (Figures 35a,b). Very heavy rain of 2 to 6 inches occurred in southeast Texas as the TEA field moved to the Texas Gulf Coast on 0000 GMT, March 18. The TEA field formed a west-east oriented couplet BUT the couplet never became oriented north-south and even weakened after March 18, 0000 GMT. During this same time, a weak surface low and inverted trough moved along the Gulf Coast and out to sea. The snowstorm, heavy rain and nondeveloping surface low were associated with:

- (1) A baroclinic leaf in the enhanced IR satellite imagery (Figure 31); however, no cyclonic surge was observed in the water vapor imagery to indicate cyclogenesis (Figure 33);
- (2) Low level forcing mechanisms as shown by the strong positive TEA fields and a maximum 850 mb flow from higher to lower K index values into the area of heavy snow (Figure 35);

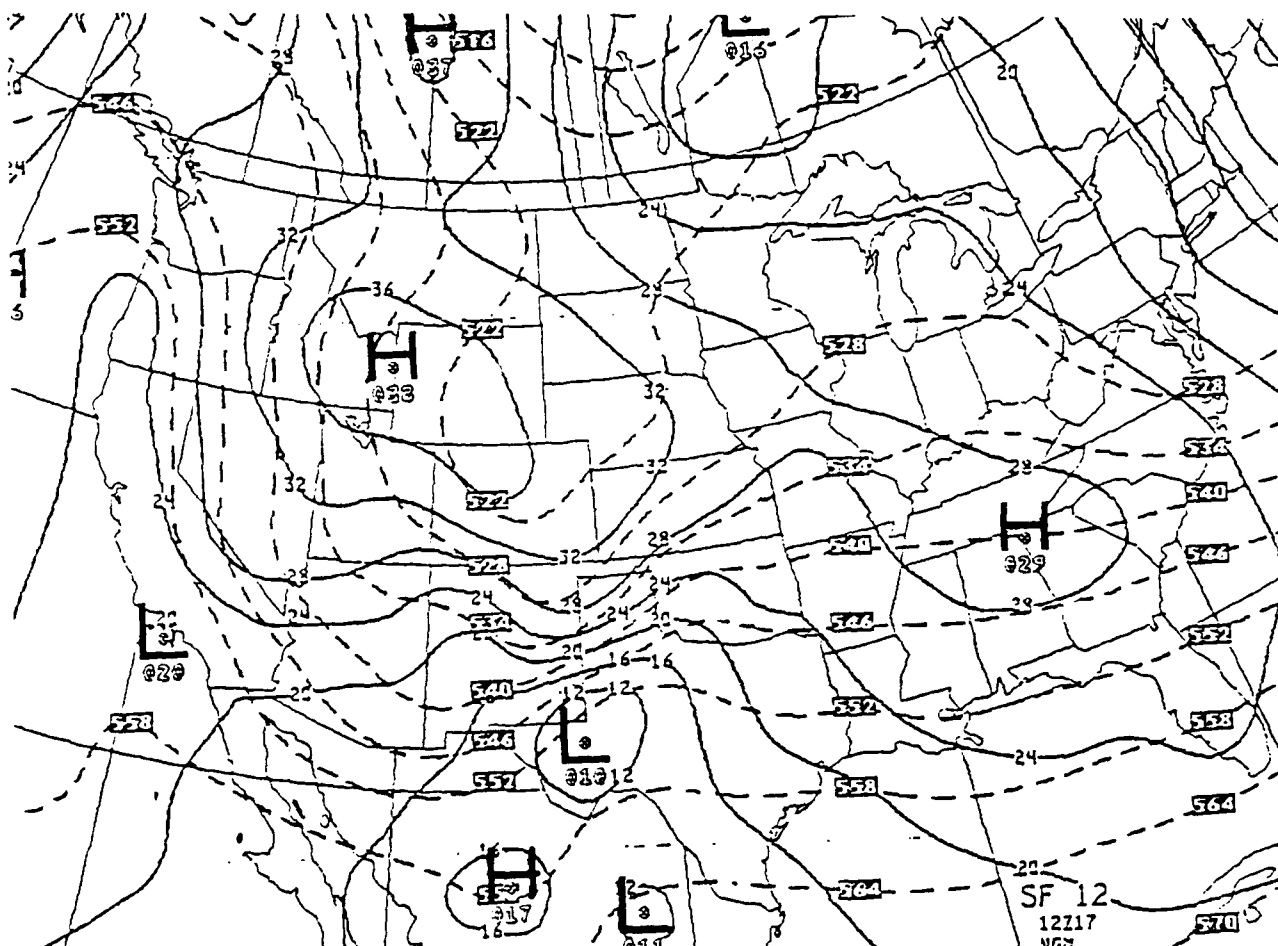


Figure 34. NGM surface/1000-500 mb thickness analysis, March 17, 1988, 1200 GMT.

- (3) Middle level forcing mechanisms as shown by an intense vorticity center (over New Mexico) and accompanying PVA; also, the synoptic pattern is a split flow situation (often associated with nondeveloping baroclinic leaves) and not a "full" meridional trough (Figure 36);
- (4) Upper level forcing mechanisms as depicted by a 125 knot jet, a split flow pattern and a somewhat diffluent jet stream pattern (Figure 37);
- (5) Significant moisture over Texas, Oklahoma, and Arkansas as indicated by the 1000-500 mb precipitable water (almost 150% of normal for Oklahoma) and relative humidity analyses (Figure 38).

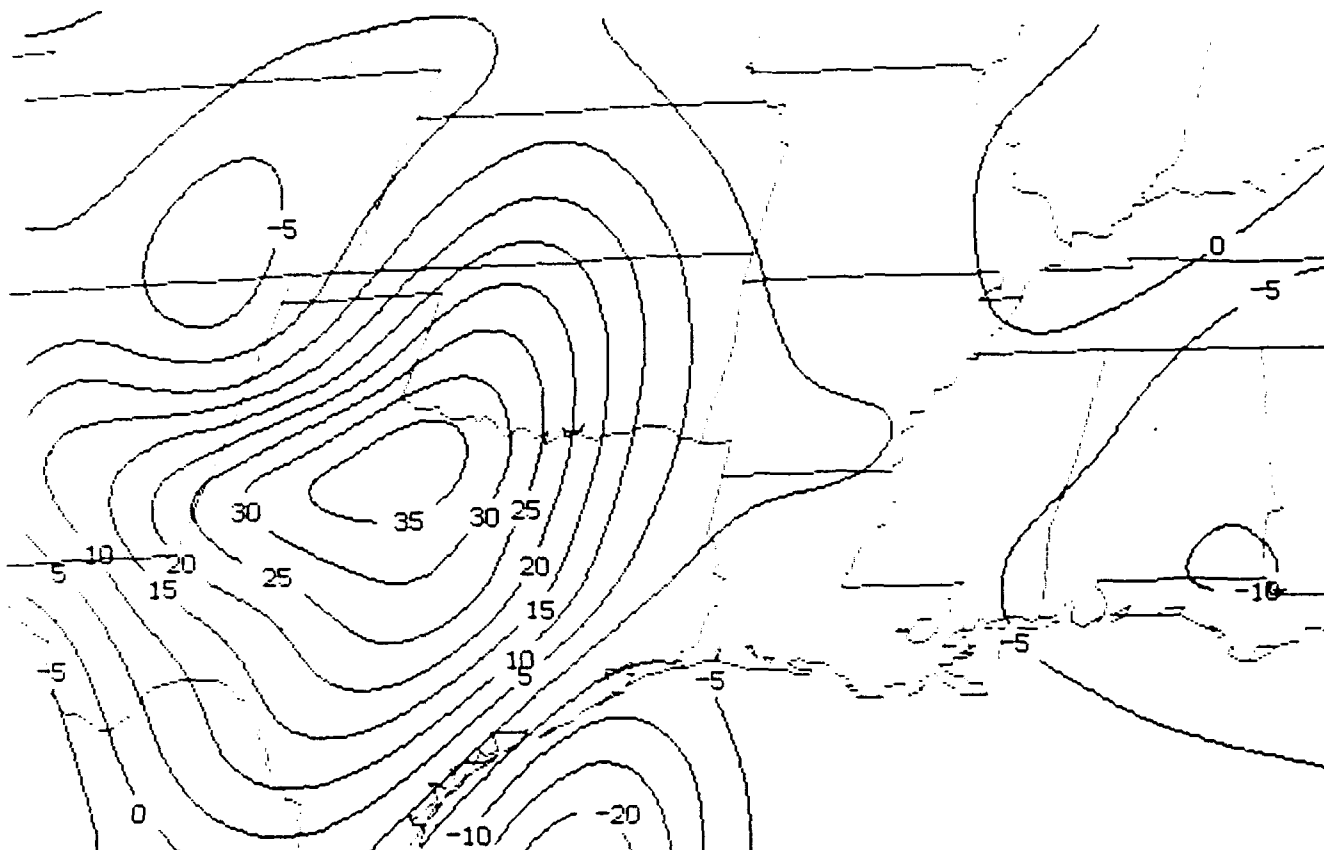


Figure 35a. 850 mb theta-e advection (degrees/day), March 17, 1988, 0000 GMT.

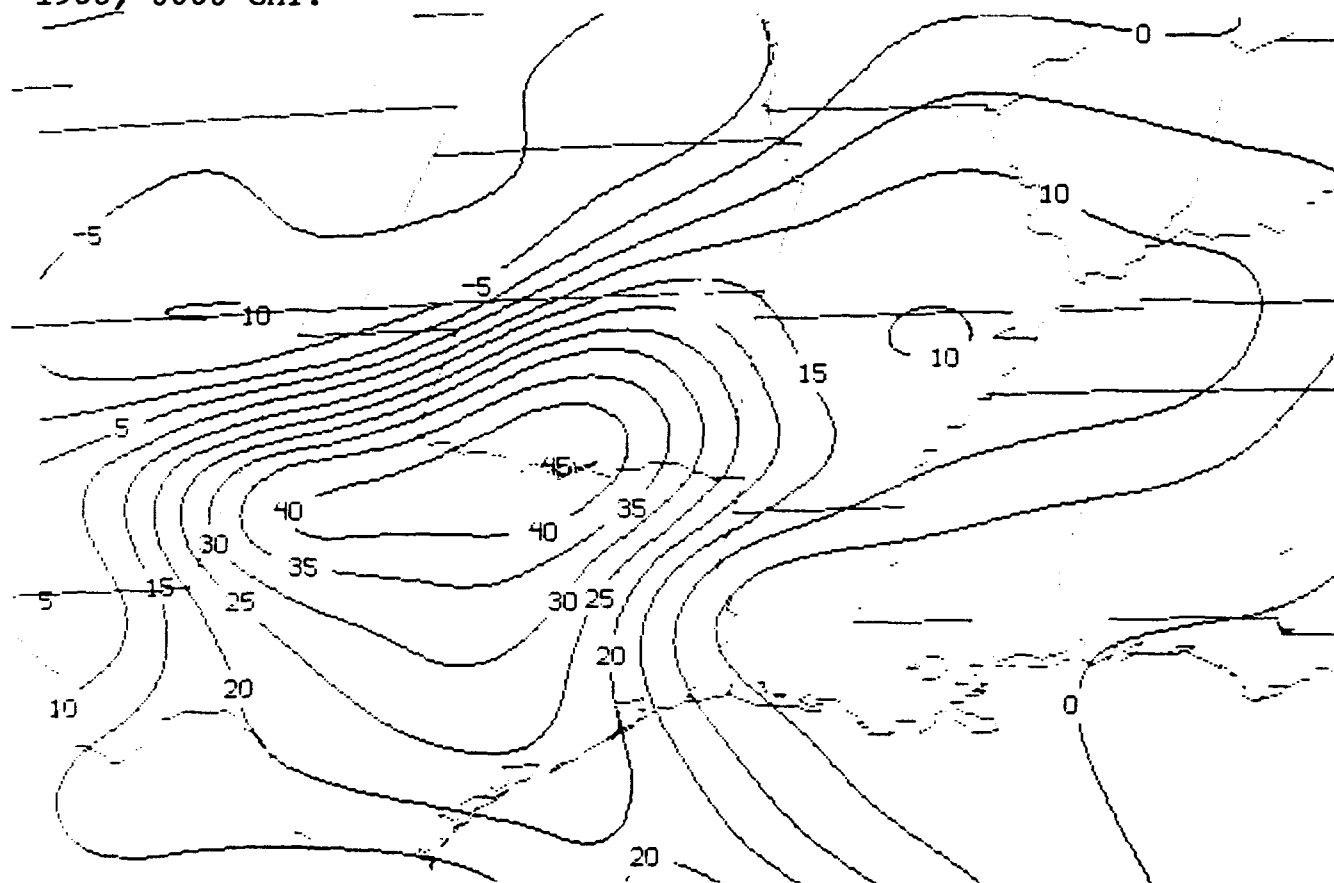


Figure 35b. 850 mb theta-e advection (degrees/day), March 17, 1988, 1200 GMT.

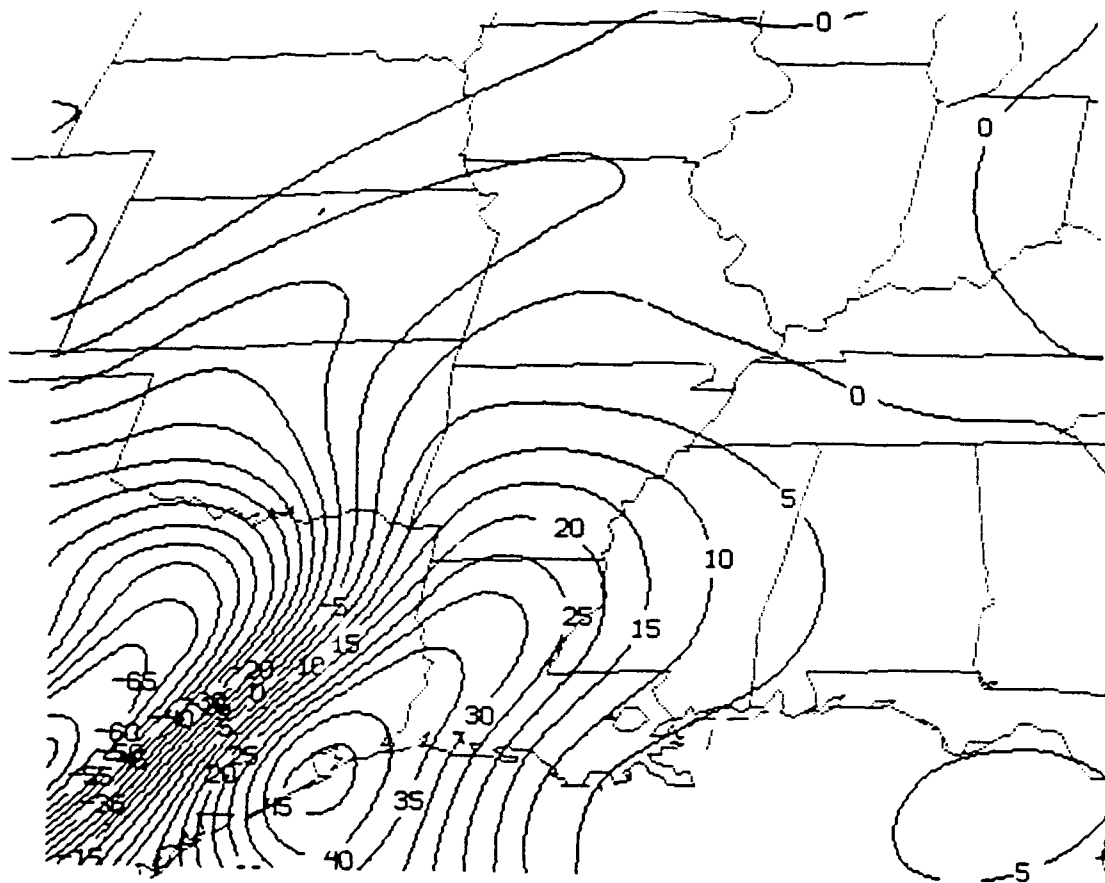


Figure 35c. 850 mb theta-e advection (degrees/day), March 18, 1988, 0000 GMT.

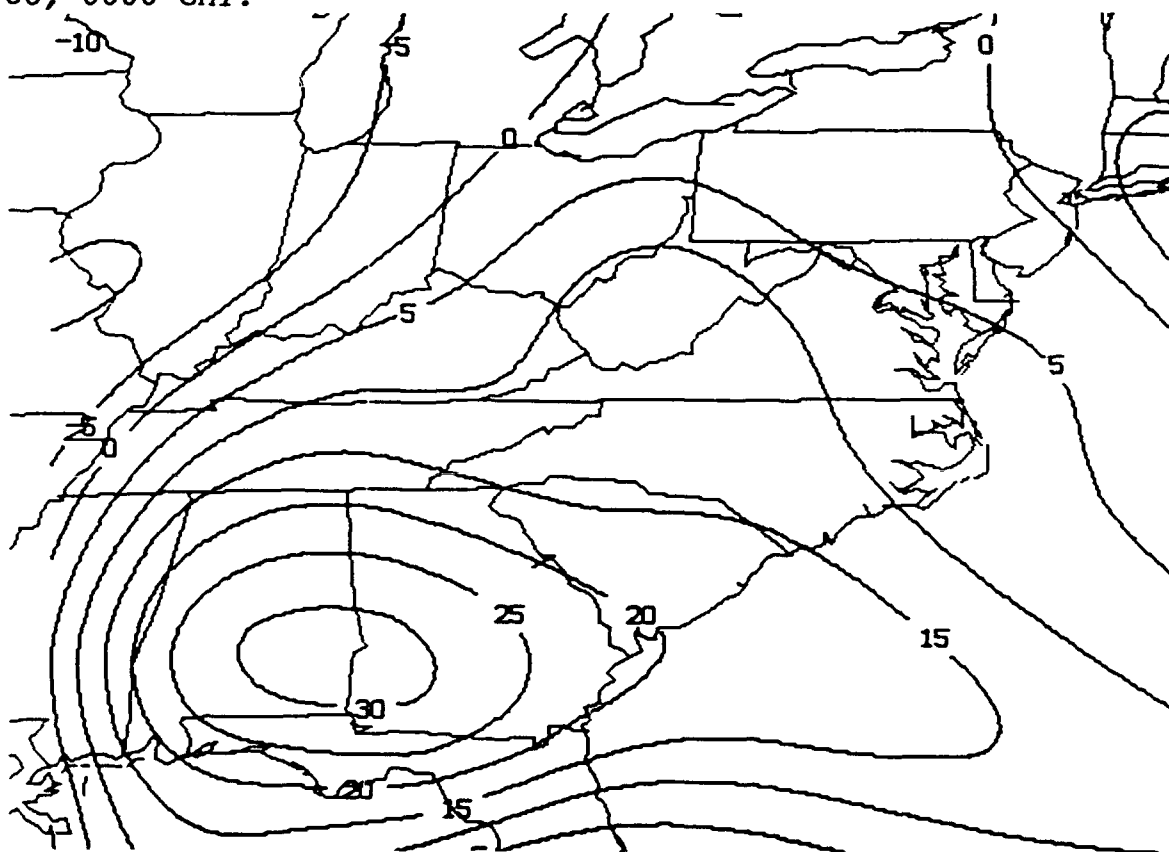


Figure 35d. 850 mb theta-e advection (degrees/day), March 18, 1988, 1200 GMT.

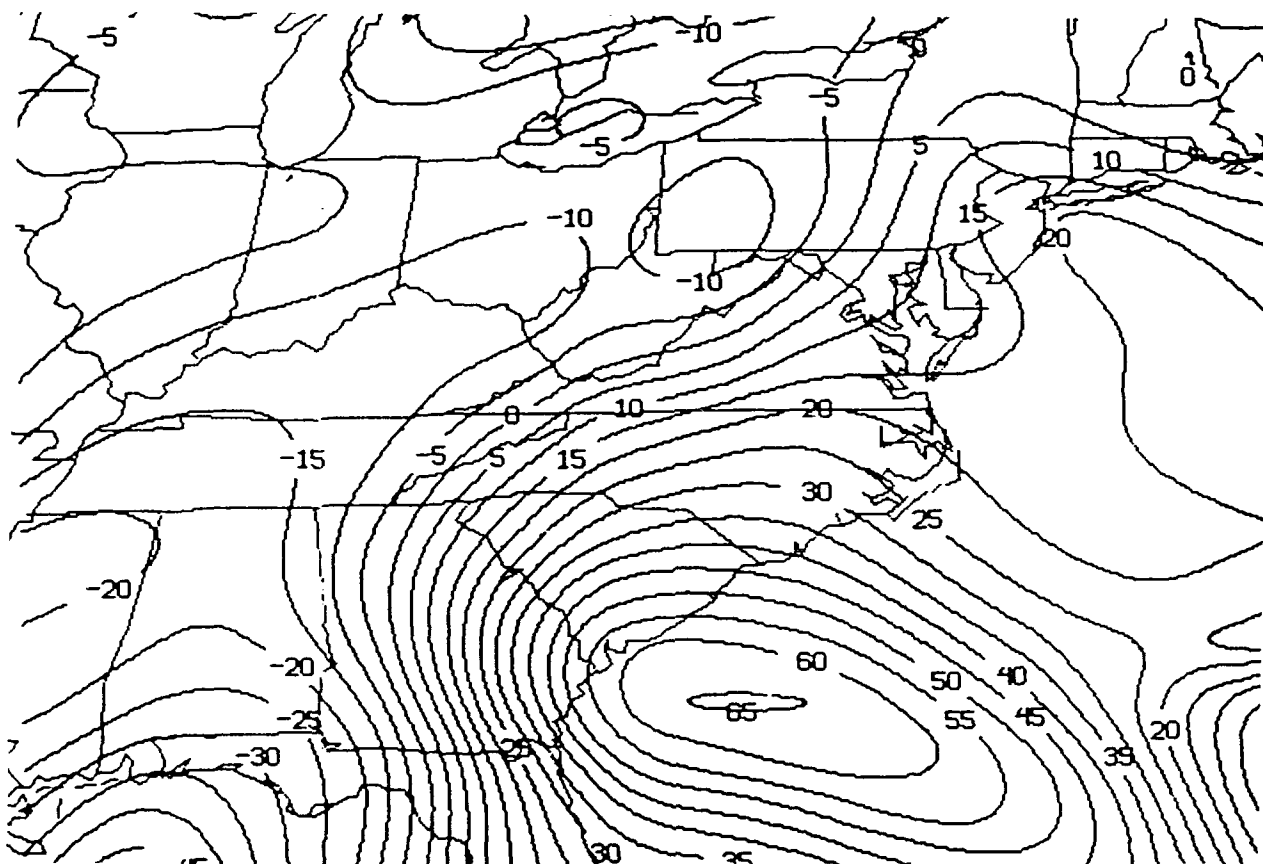


Figure 35e. 850 mb theta-e advection (degrees/day), March 19, 1988, 0000 GMT.

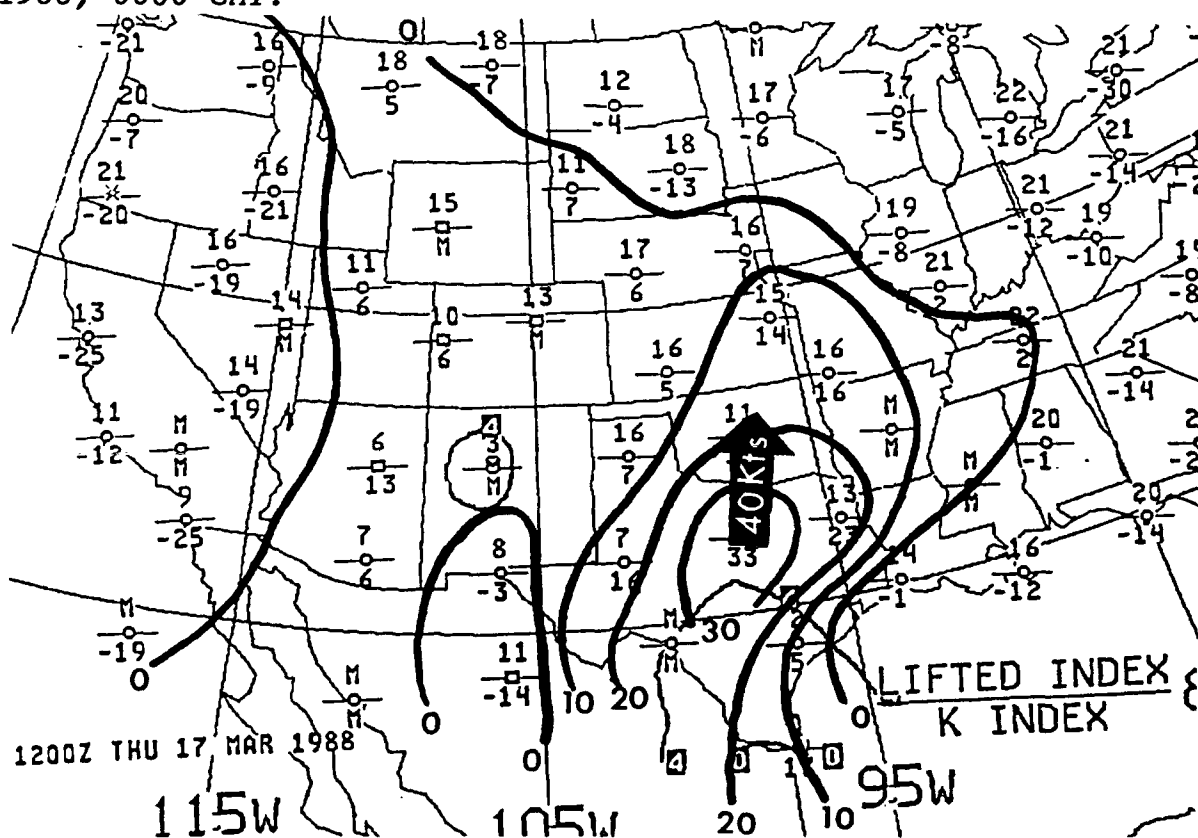


Figure 35f. K Index analysis with 850 mb maximum winds indicated by an arrow, March 17, 1988, 1200 GMT.

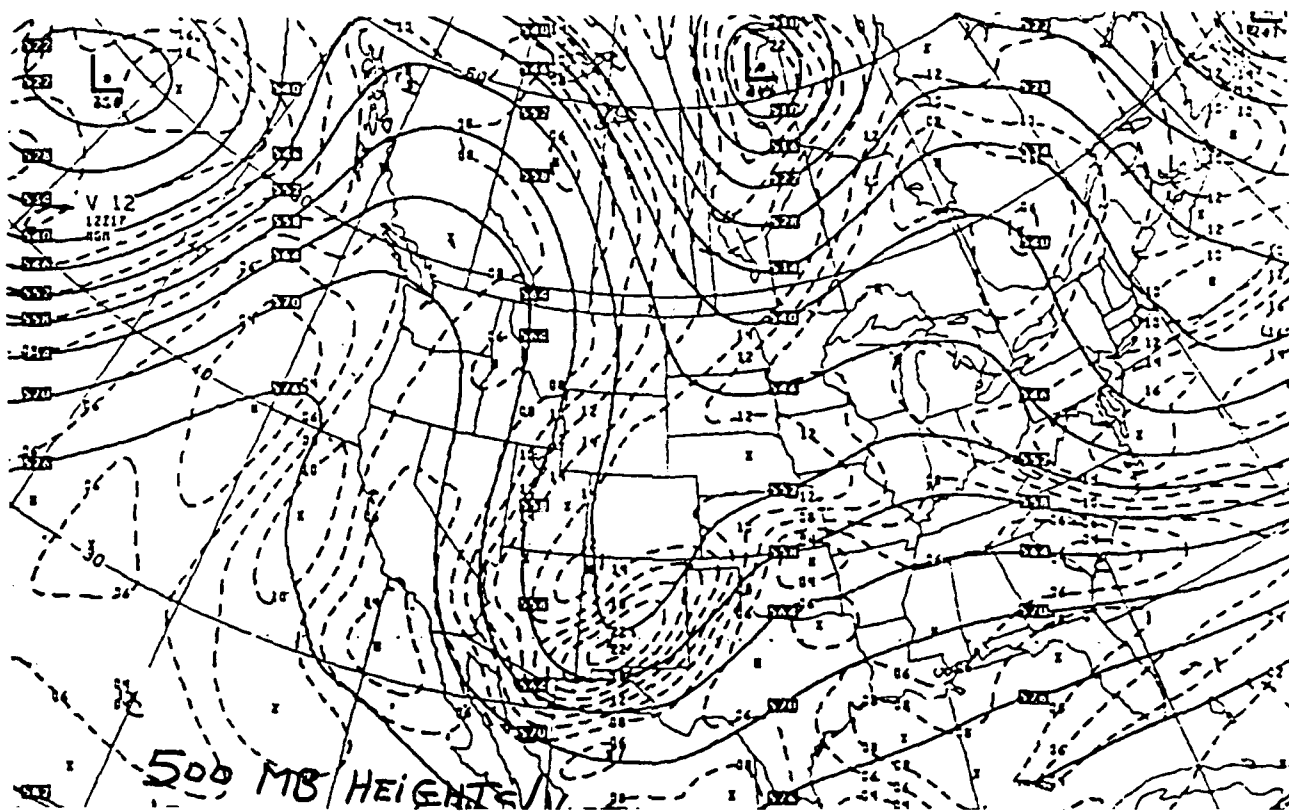


Figure 36. 500 mb heights/vorticity analysis, March 17, 1988, 1200 GMT.

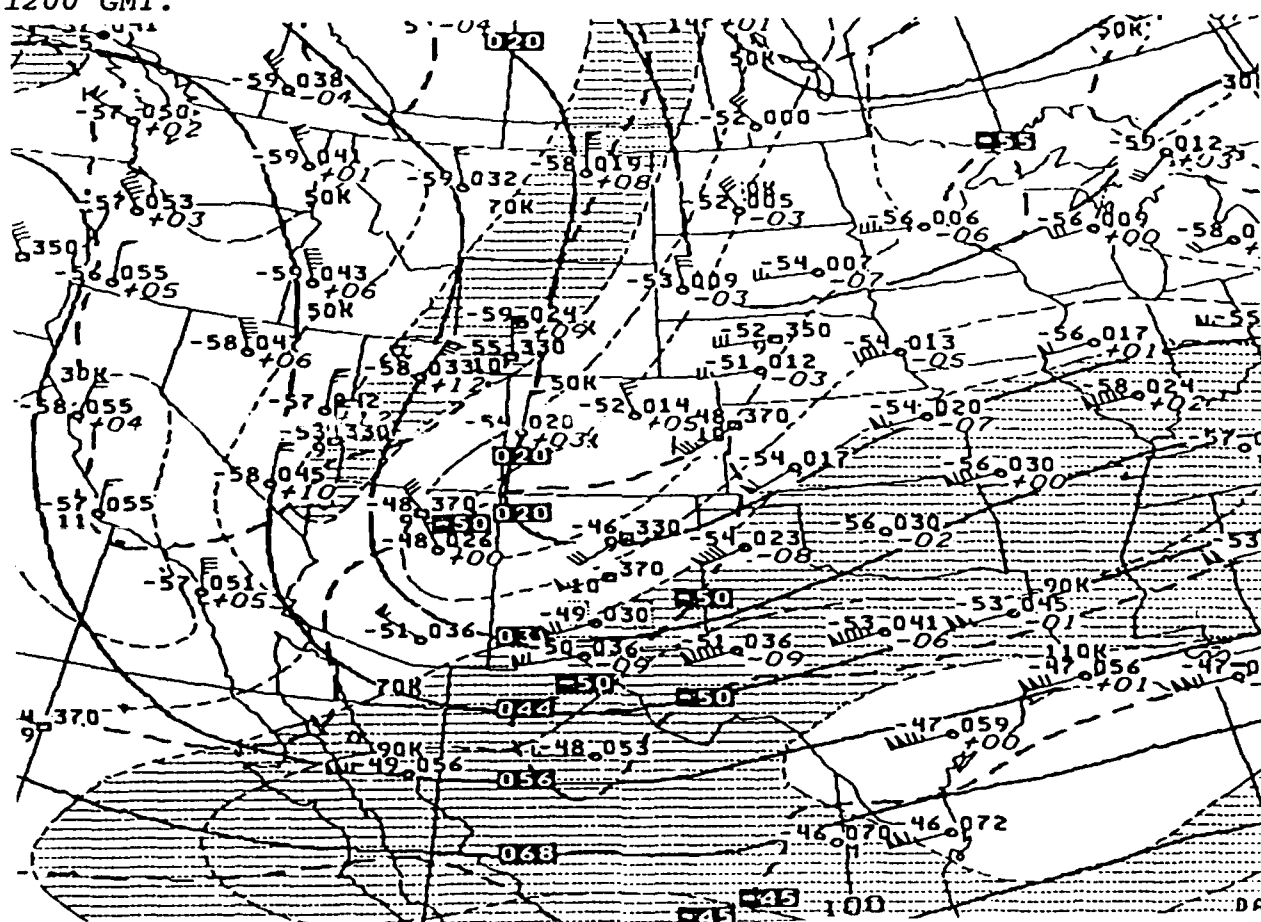


Figure 37. 250 mb heights/isotachs analysis, March 17, 1988, 1200 GMT.

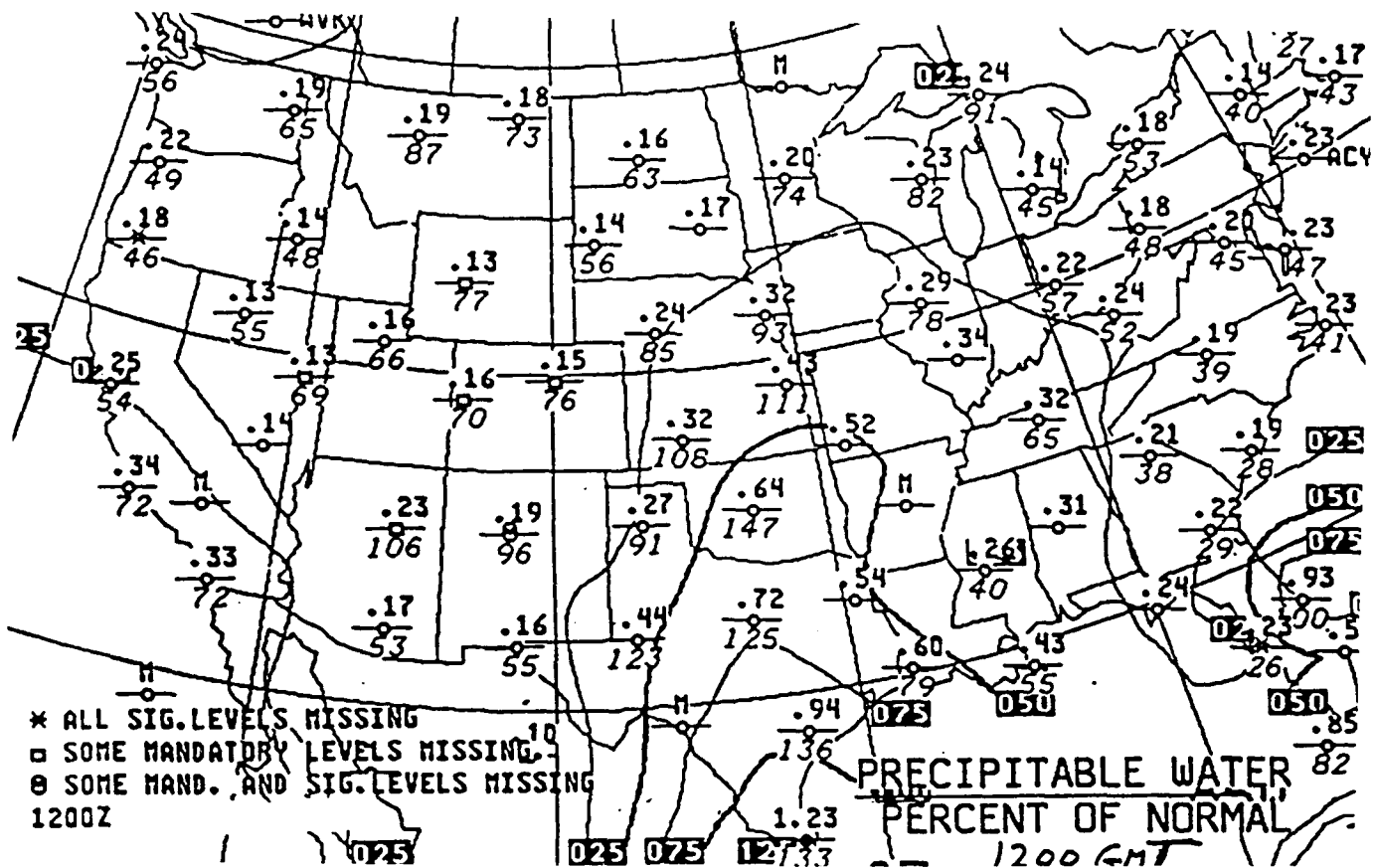


Figure 38a. 1000-500 mb precipitable water analysis, March 17, 1988, 1200 GMT.

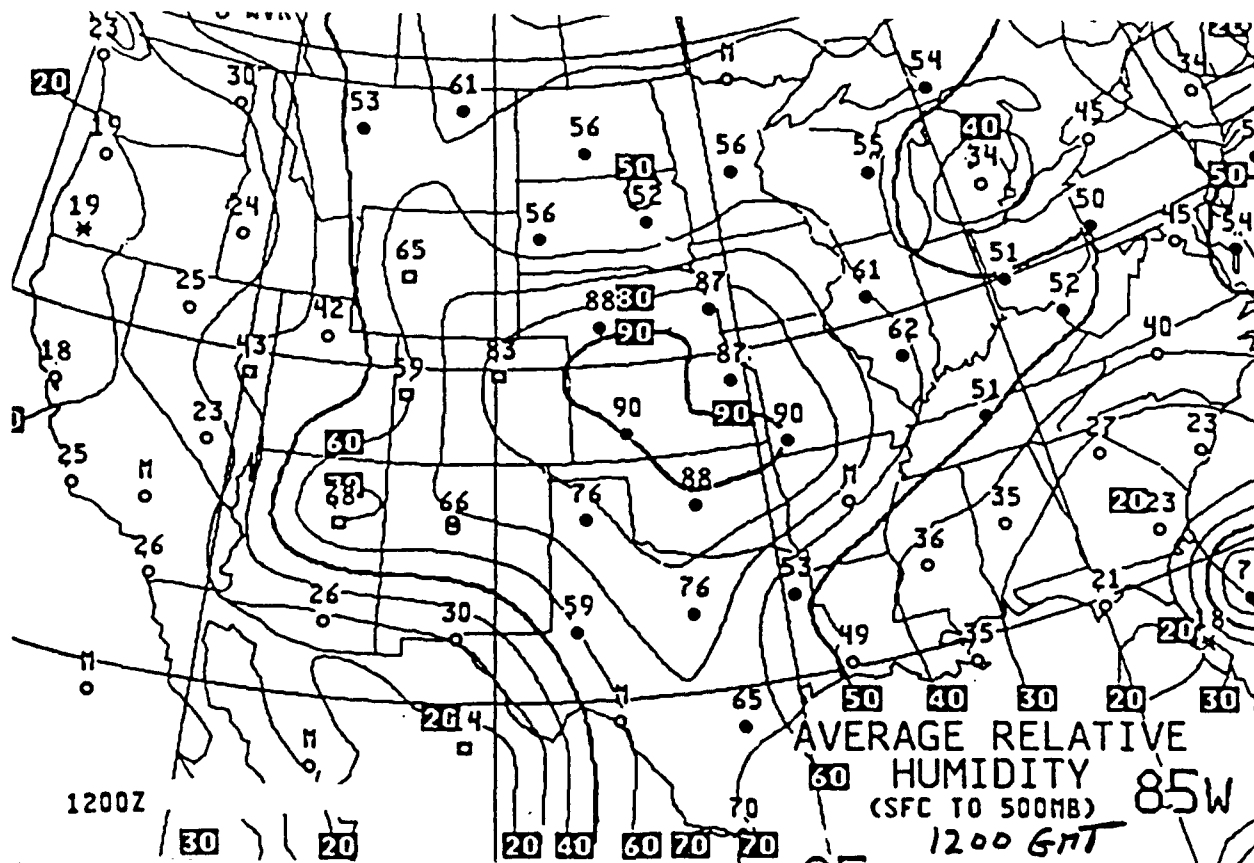


Figure 38b. 1000-500 mb relative humidity analysis, March 17, 1988, 1200 GMT.



Figure 39a. Twelve hour heavy snowfall (inches) ending at March 17, 1988, 1200 GMT.

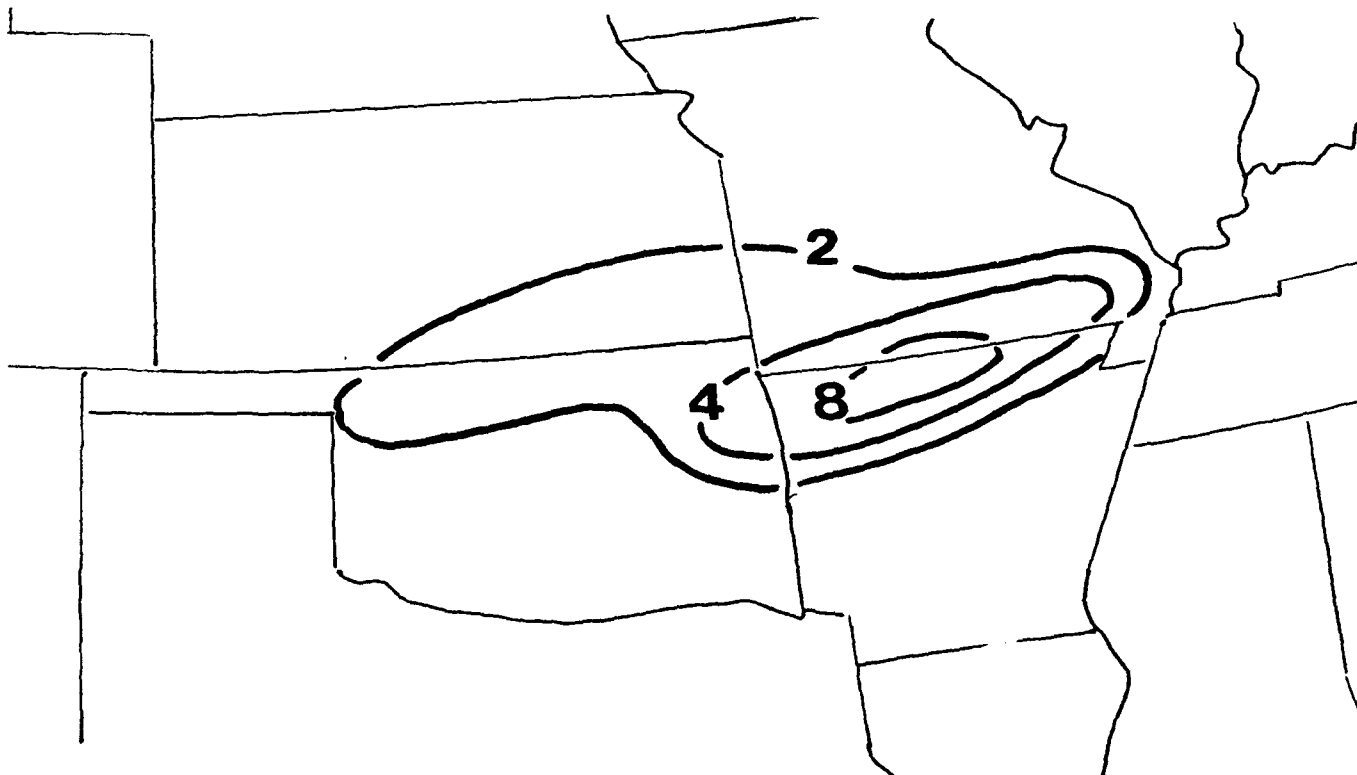


Figure 39b. Twelve hour heavy snowfall (inches) ending at March 18, 1988, 0000 GMT.

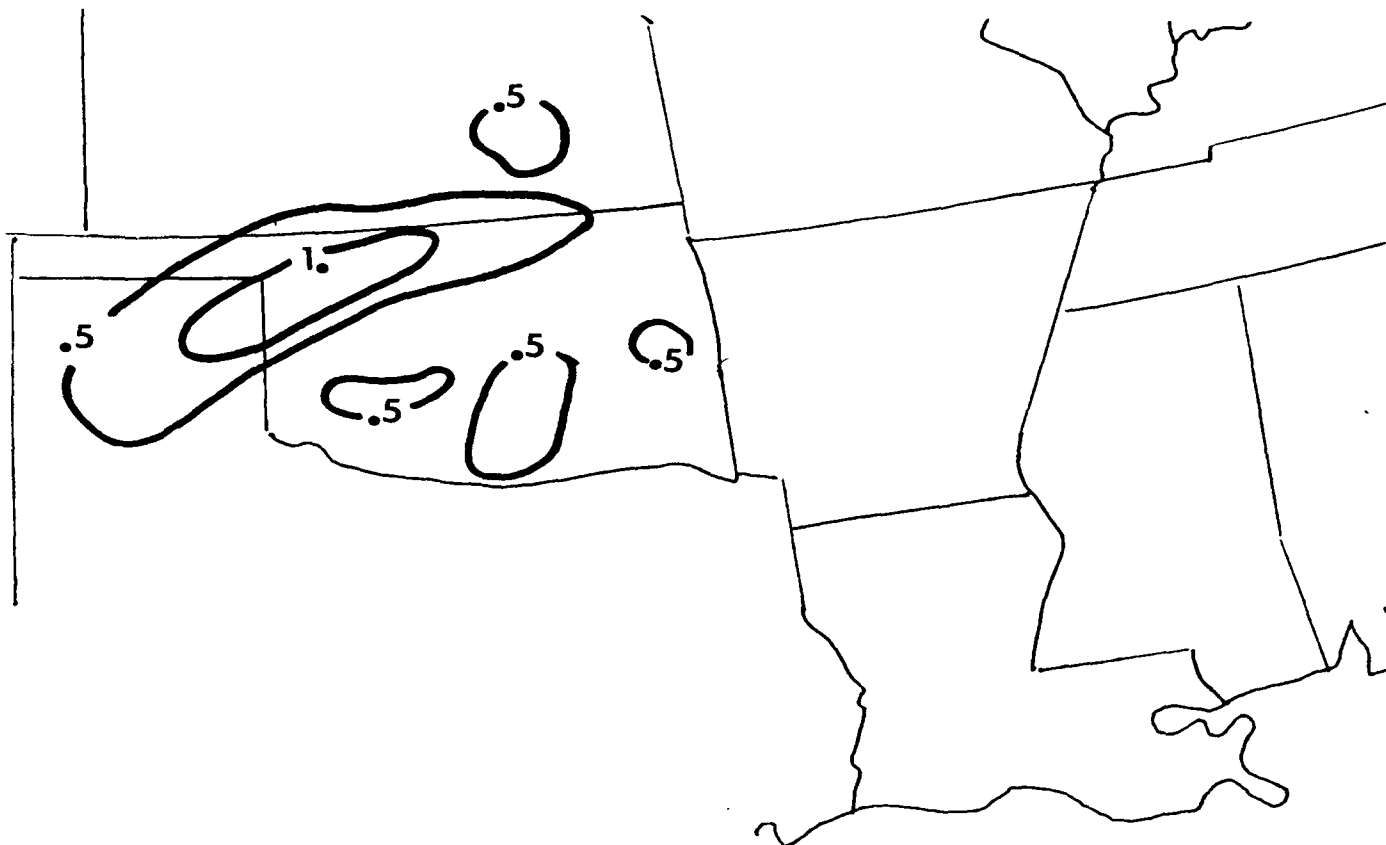


Figure 40a. Twenty-four hour observed precipitation (inches) ending at March 17, 1988, 1200 GMT.



Figure 40b. Twenty-four hour observed precipitation (inches) ending at March 18, 1988, 1200 GMT.

Eastern Region "Veterans Day" Snowstorm of November 11, 1987

On November 11 and 12, 1987, heavy snow occurred in the middle Atlantic states and in extreme eastern New England. The enhanced IR imagery (Figure 41) shows a north-south cloud band (C-B) from northern Pennsylvania to southern Virginia. VIS imagery at 1330 GMT (Figure 41) indicates that there are several cloud bands embedded within this enhanced IR cloud band (C-B). One pronounced band in the VIS imagery at 1330 GMT is located over the Washington, DC metropolitan area. These multiple cloud bands were convective and produced thunder and heavy snow over the metropolitan area of Washington, DC. The enhanced IR imagery in Figure 42 shows the cloud band associated with the heavy snow over eastern New England. In addition, over the Atlantic Ocean, rapid deepening of the surface low is occurring as indicated by the enhanced IR, hook-shaped cloud pattern. By 1430 GMT, November 12, the VIS imagery (Figure 42) shows a pronounced

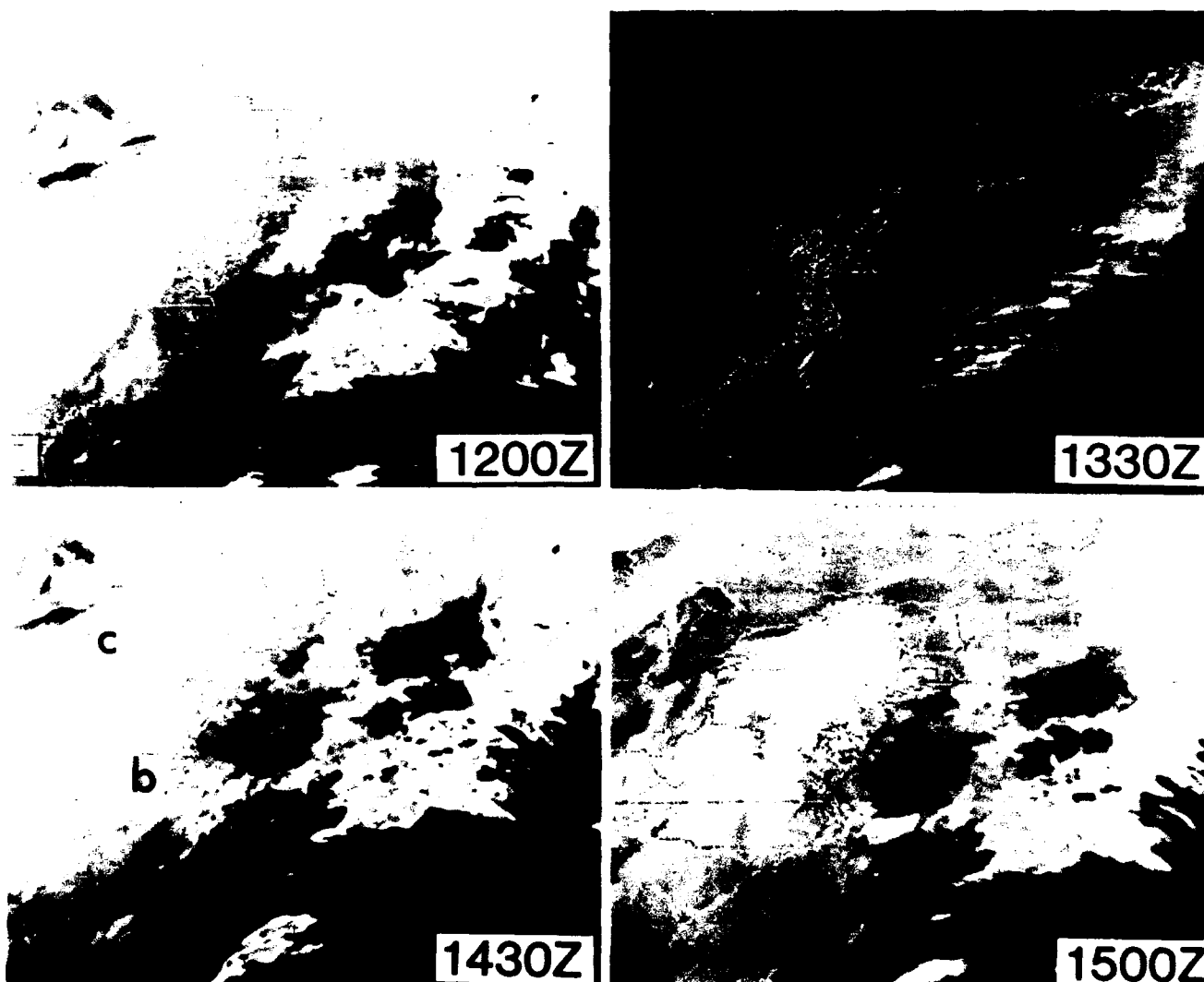


Figure 41. A cloud band; enhanced IR (Mb Curve) and VIS imagery (1330 GMT), November 11, 1987.

cyclonic circulation. The water vapor imagery in Figure 43 clearly shows the cyclogenesis that occurred over the ocean. A plot of surface low positions and intensities indicated (Figure 44) that the low deepened rapidly between 0000 and 1200 GMT on November 12. In fact, the pressure fell 18 mb during this 12 hour period. Low, middle and upper level forcing and moisture analyses are presented in Figures 45, 46, 47 and 48, respectively. The 850 mb TEA fields are shown in Figures 45a, b, c. Twelve hour heavy snowfall analyses (4 or more inches) are illustrated in Figures 49a, b and 24 hour observed precipitation (of 0.5 inches or greater) in Figure 50. Heavy snow fell near the axis of maximum TEA; the axis is indicated by a dashed line in Figure 45a and 45c. The maximum TEA and axis were also associated with the heaviest 24 hour amounts (Figure 50). Moderate to heavy rainfall occurred just south of the TEA axis in south-central and southeast Virginia. A TEA couplet oriented north-south is depicted in Figure 45a; the couplet moves out to sea after 1200 GMT (November 11) and cannot be accurately analyzed (due to lack of upper air sounding data).

The snowstorm and rapidly deepening surface low were associated with:

- (1) A convective cloud band in the enhanced IR and VIS satellite imagery (Figure 41) that evolved into a pronounced cyclonic circulation over the ocean (Figure 42 and 43);

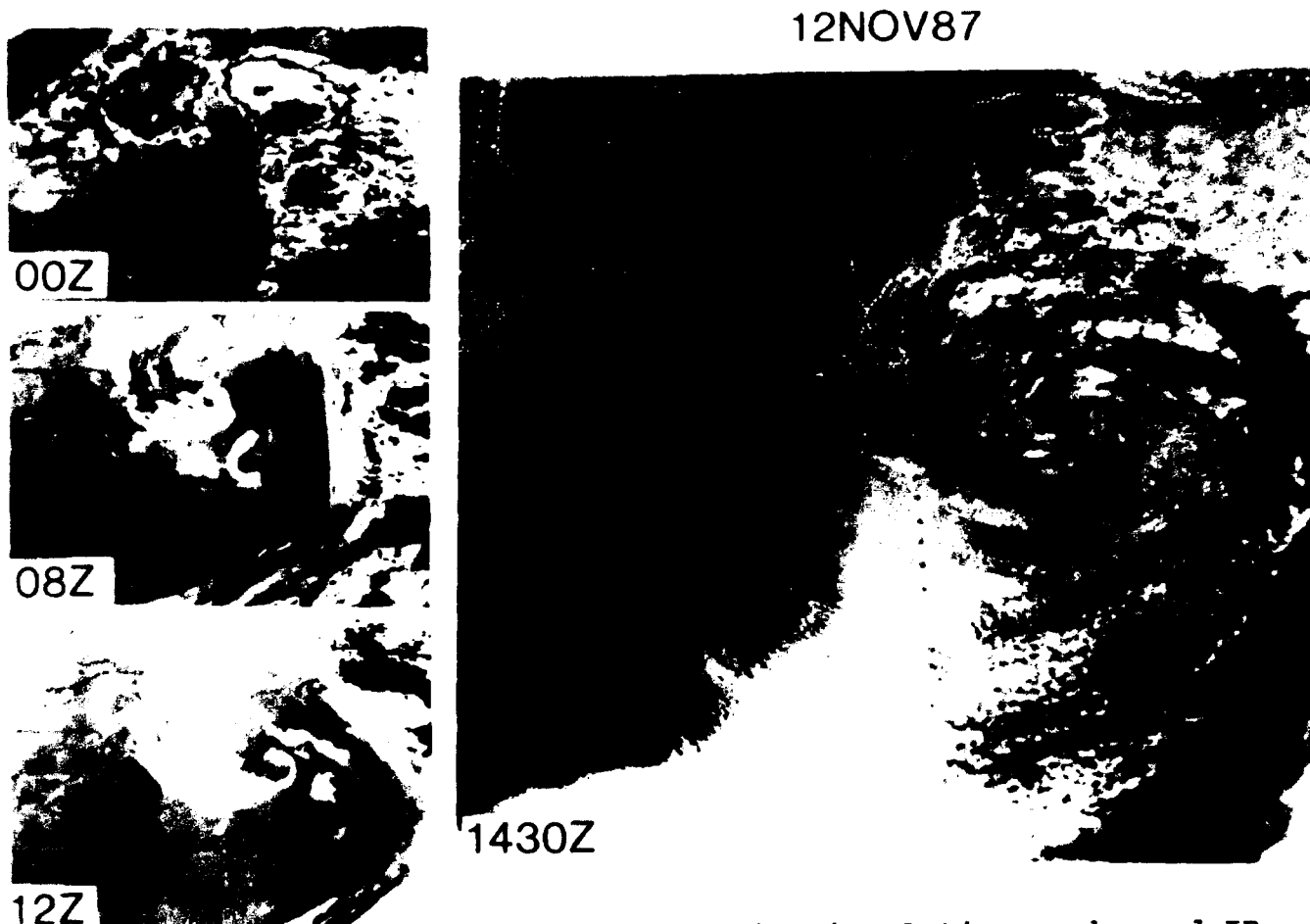


Figure 42. A rapid deepening cyclonic circulation; enhanced IR (Mb Curve) and VIS (1430 GMT) imagery, November 12, 1987.

- (2) Low level forcing mechanisms (Figure 45) as shown by the existence of positive TEA fields; these fields were also associated with the heaviest precipitation;
- (3) Middle level forcing mechanisms (Figure 46) as shown by two intense vorticity centers (Ohio and Georgia) and PVA over the middle to southern Atlantic coastal states;
- (4) Upper level forcing mechanisms (Figure 47) as depicted by a 150 knot jet streak near the base of the trough and a diffluent jet stream pattern;
- (5) The development of a "full" meridional trough as a vorticity center to the northwest (north of Lake Superior) of the centers over Ohio and Georgia (Figure 46) came into phase;
- (6) An abundance of moisture along the Atlantic coastal states as indicated by the 1000-500 mb precipitable water (125-150% of normal) and relative humidity analyses (> 90%).

This snowstorm and cyclogenesis "fits" the check list developed by Auciello (1988) for predicting meteorological "bombs" in the western north Atlantic Ocean.

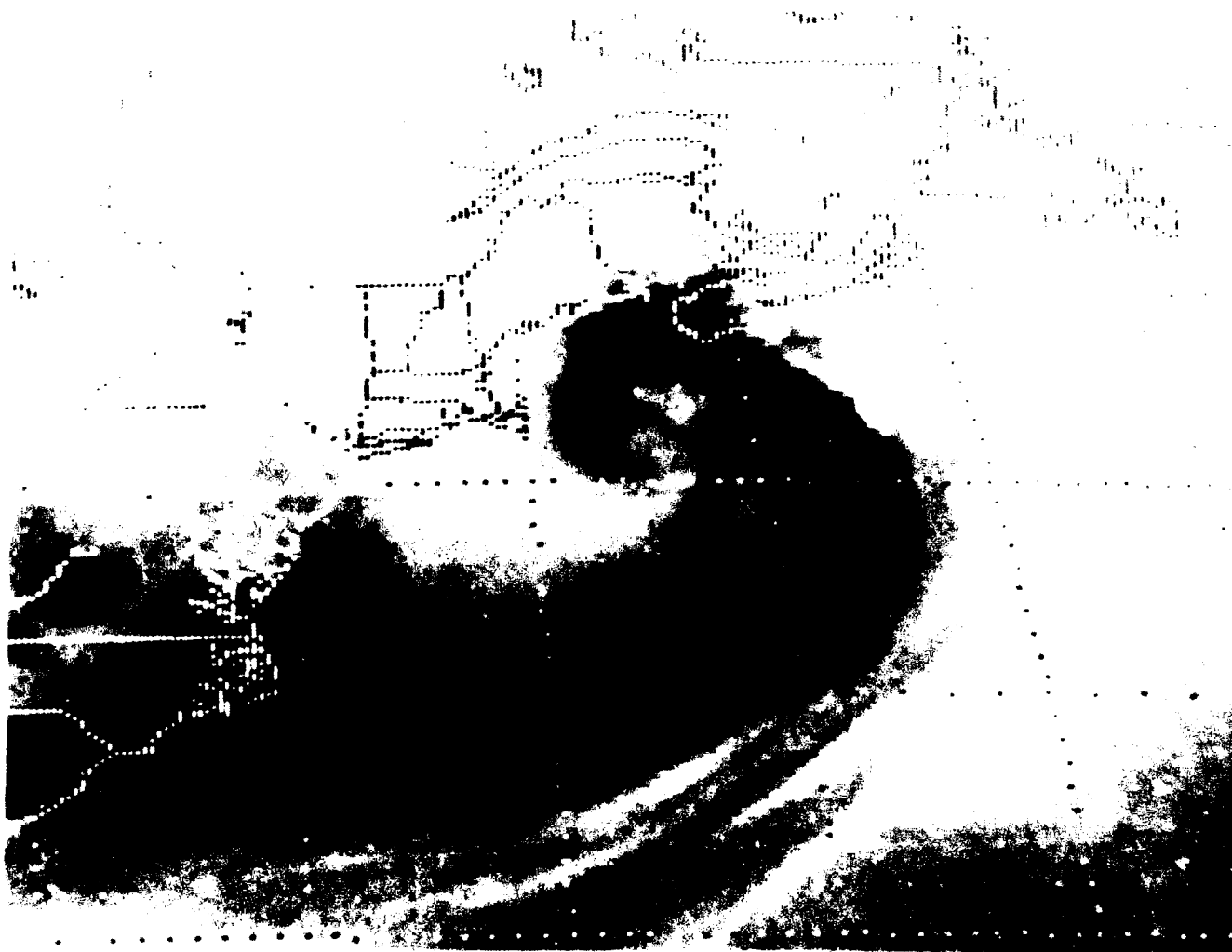


Figure 43. Water vapor imagery (6.7 m), November 12, 1987, 1200 GMT.

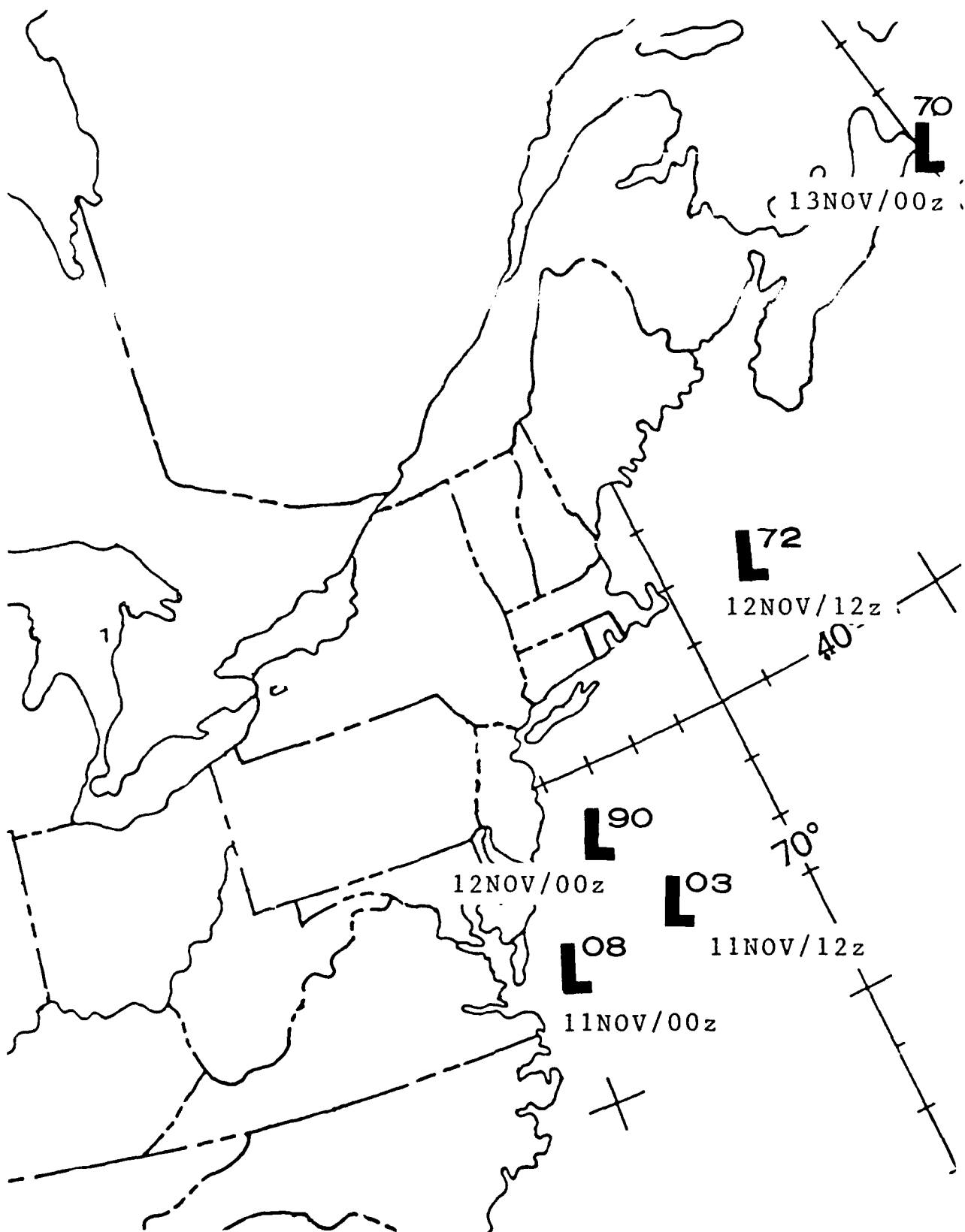


Figure 44. A plot of surface low positions and intensities, November 11 and 12, 1987.

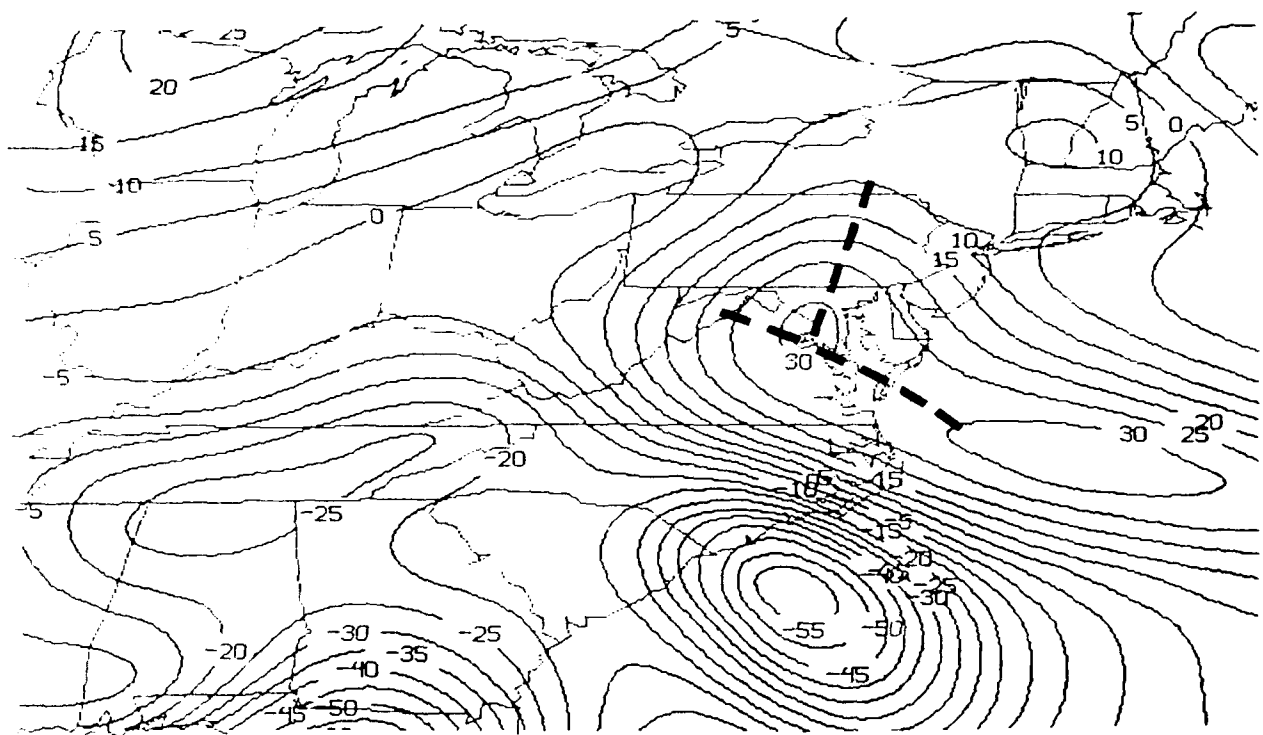


Figure 45a. 850 mb theta-e advection (degrees/day), November 11, 1987, 1200 GMT.

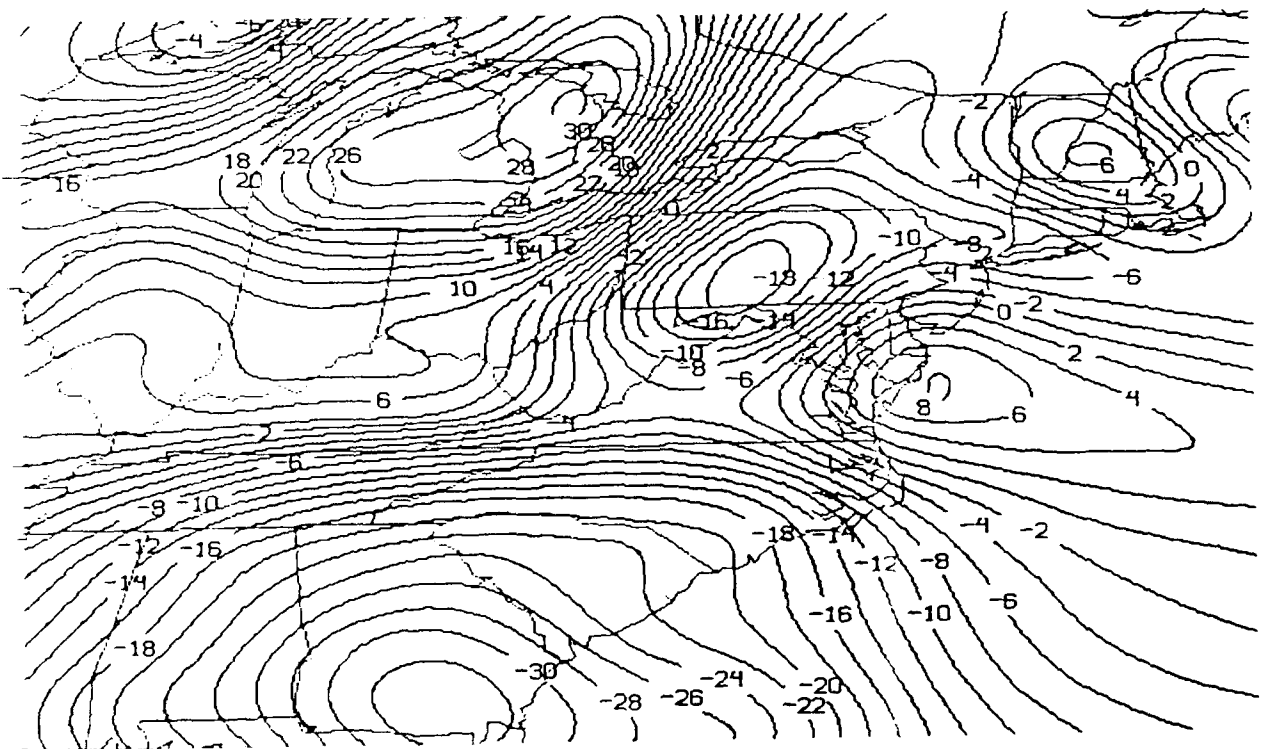


Figure 45b. 850 mb theta-e advection (degrees/day) November 12, 1987, 0000 GMT.

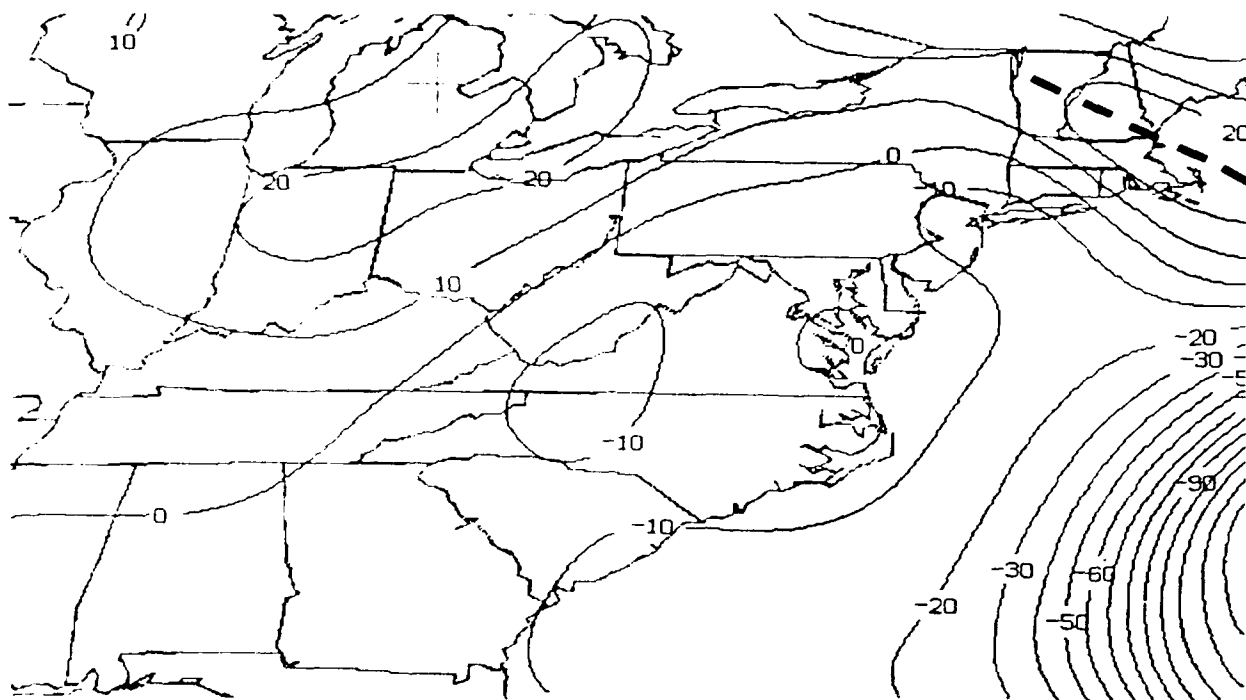


Figure 45c. 850 mb theta-e advection (degrees/day), November 12, 1987, 1200 GMT.

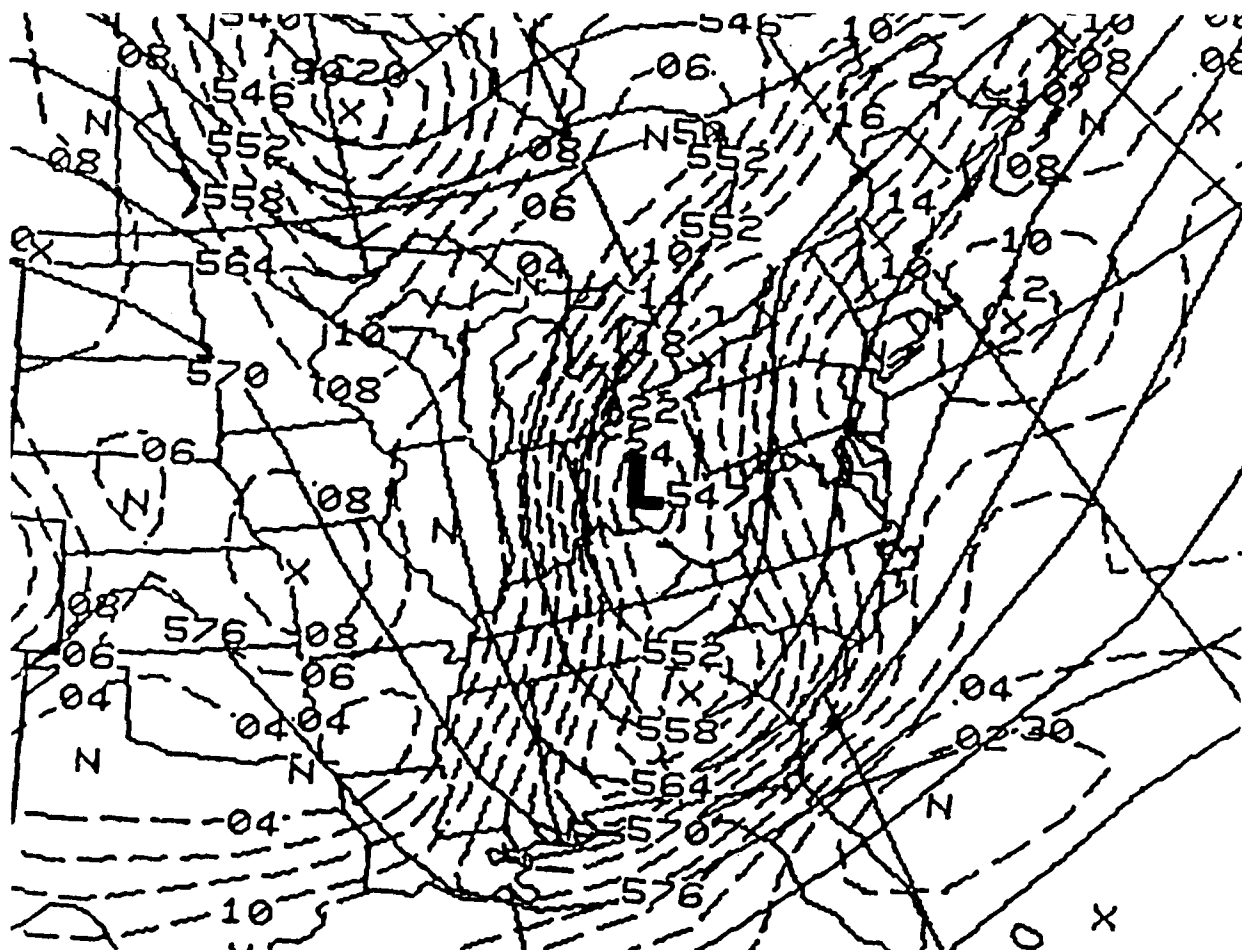


Figure 46. 500 mb heights/vorticity analysis, November 11, 1987, 1200 GMT.

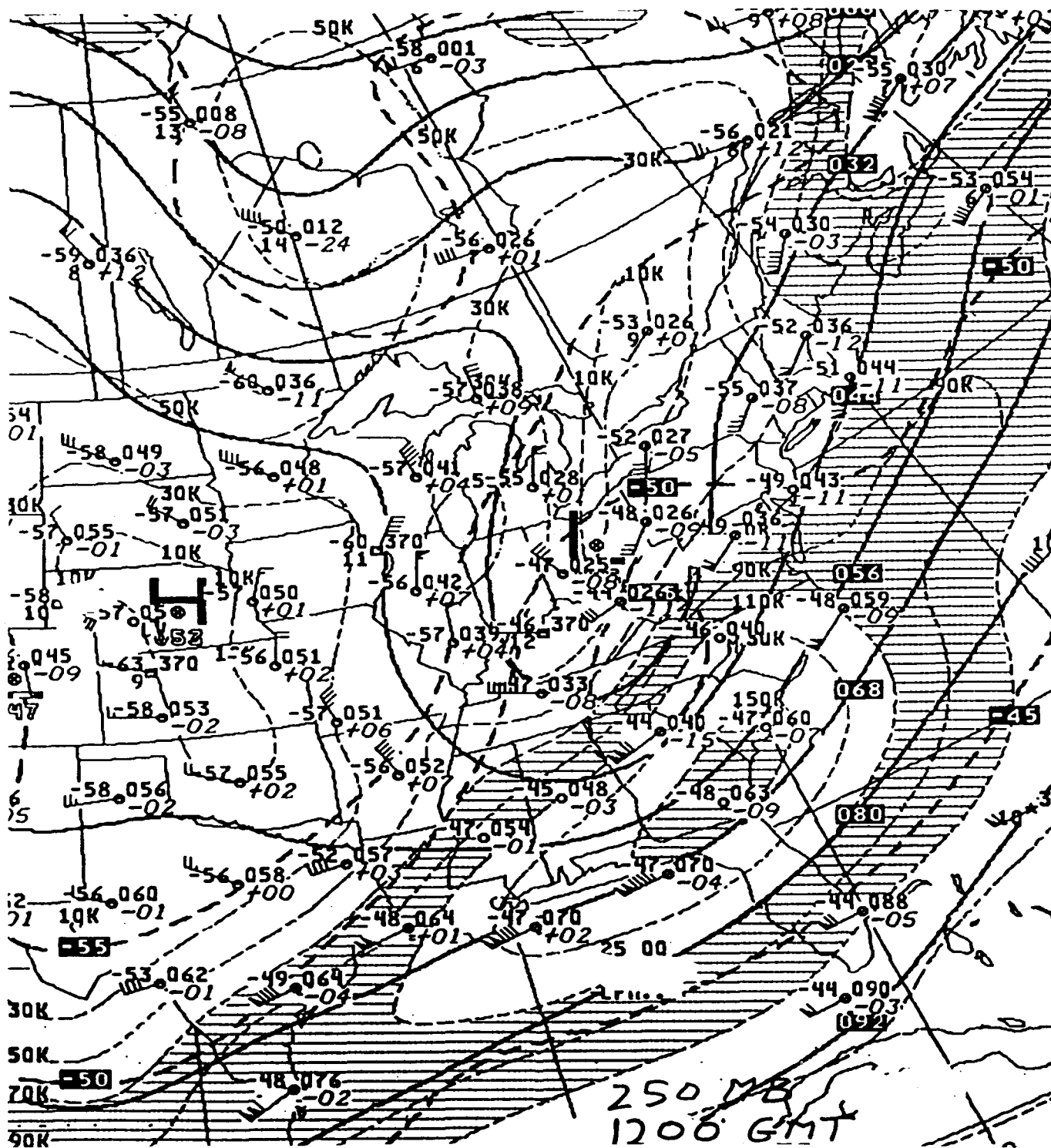


Figure 47. 250 mb heights/isotachs analysis, November 11, 1987, 1200 GMT.

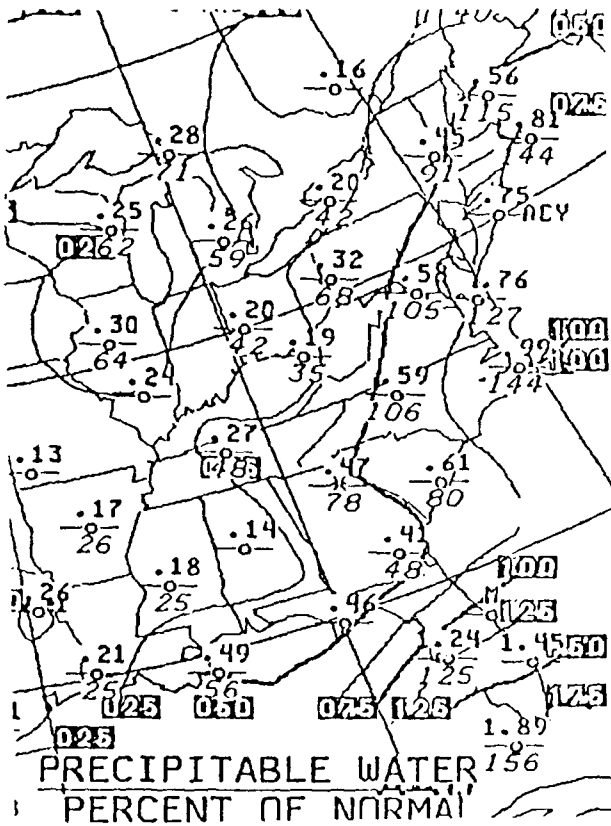


Figure 48a. 1000-500 mb precipitable water analysis, November 11, 1987, 1200 GMT.

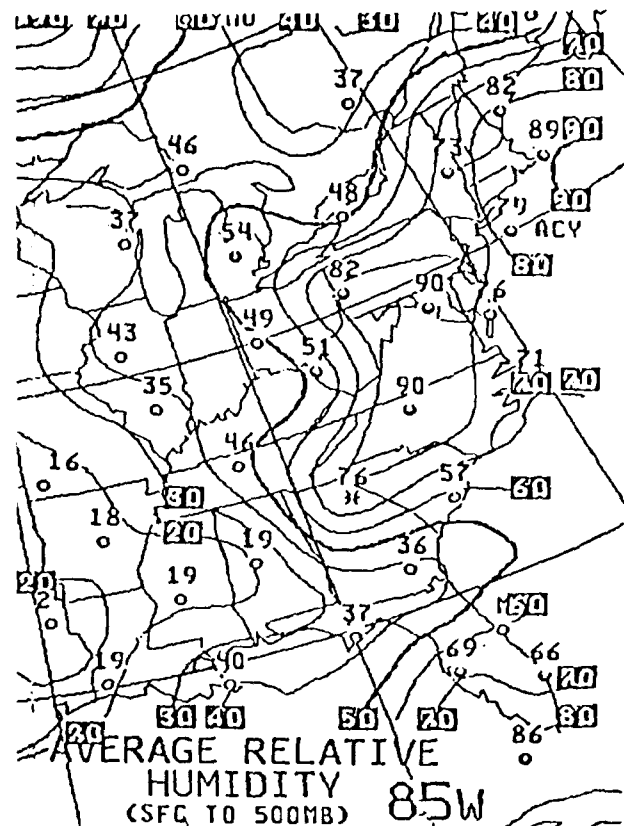


Figure 48b. 1000-500 mb relative humidity analysis, November 11, 1987, 1200 GMT.

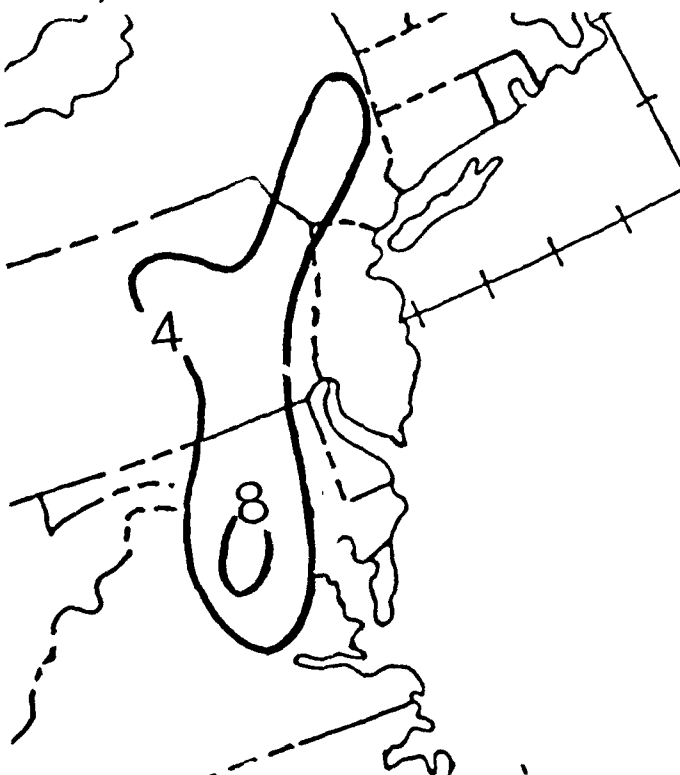


Figure 49a. Twelve hour heavy snowfall (inches) ending at November 12, 1987, 0000 GMT.

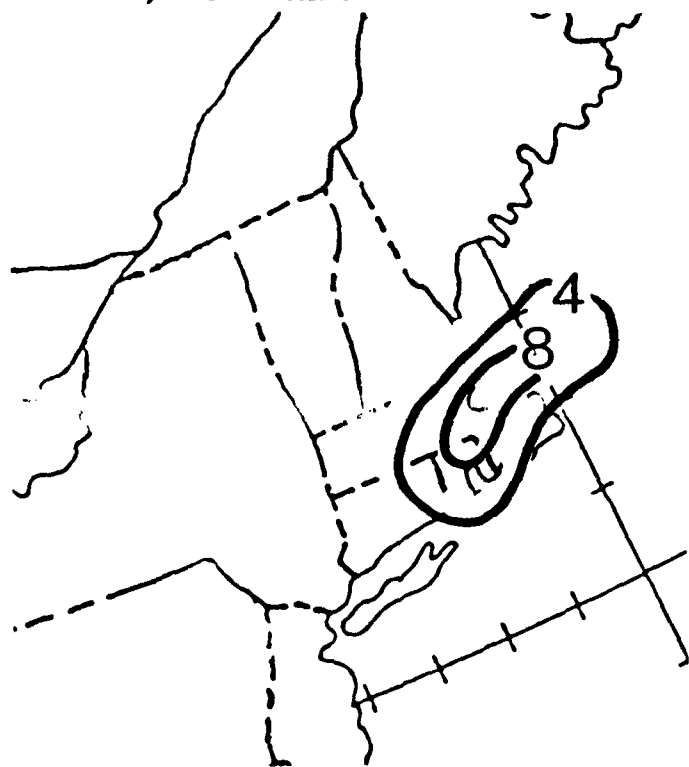


Figure 49b. Twelve hour heavy snowfall (inches) ending at November 12, 1987, 1200 GMT.

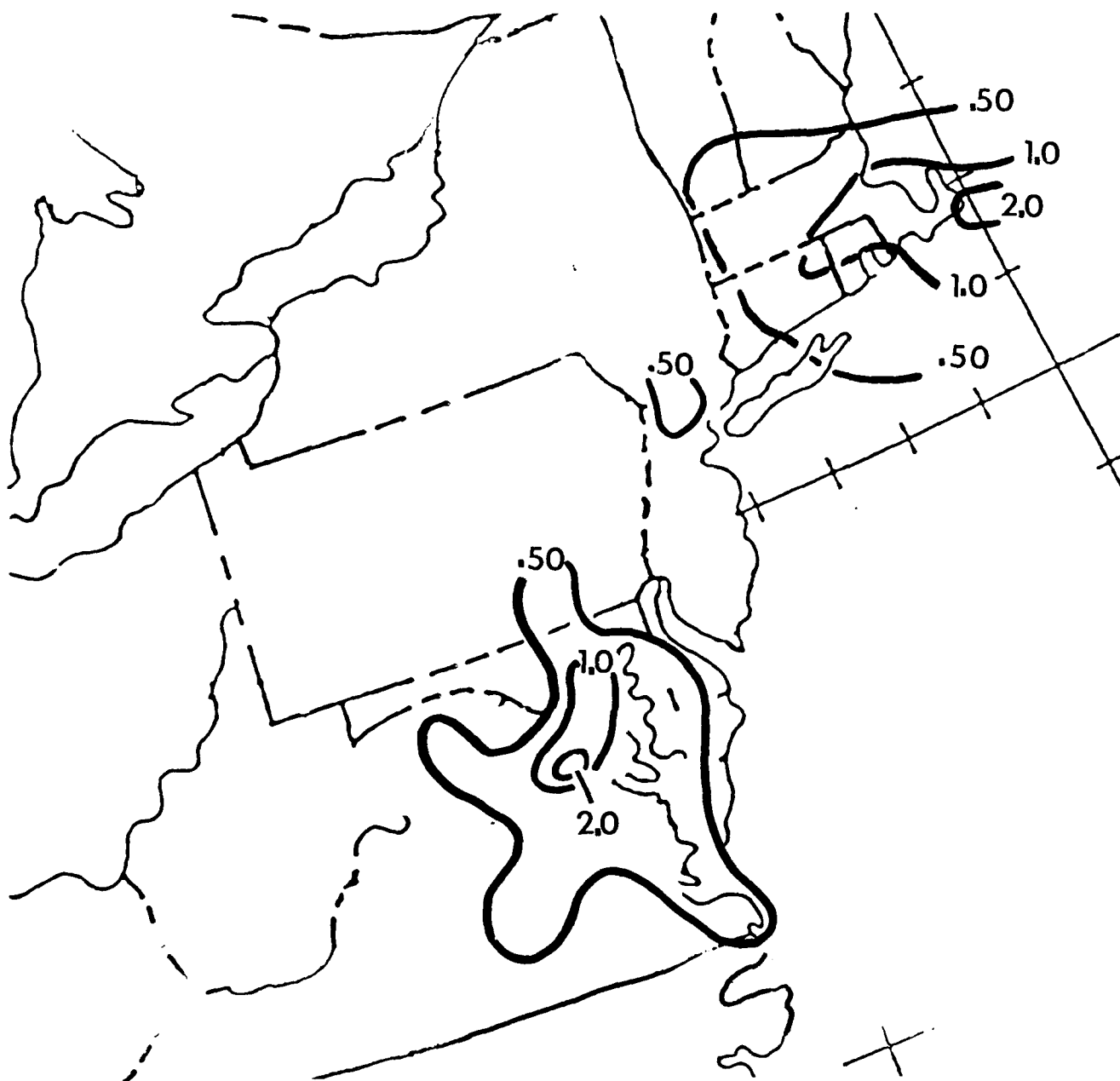


Figure 50. Twenty-four hour observed precipitation (inches) ending at November 12, 1987, 1200 GMT.

THE CONNECTING LINK

MCSs

ECSs

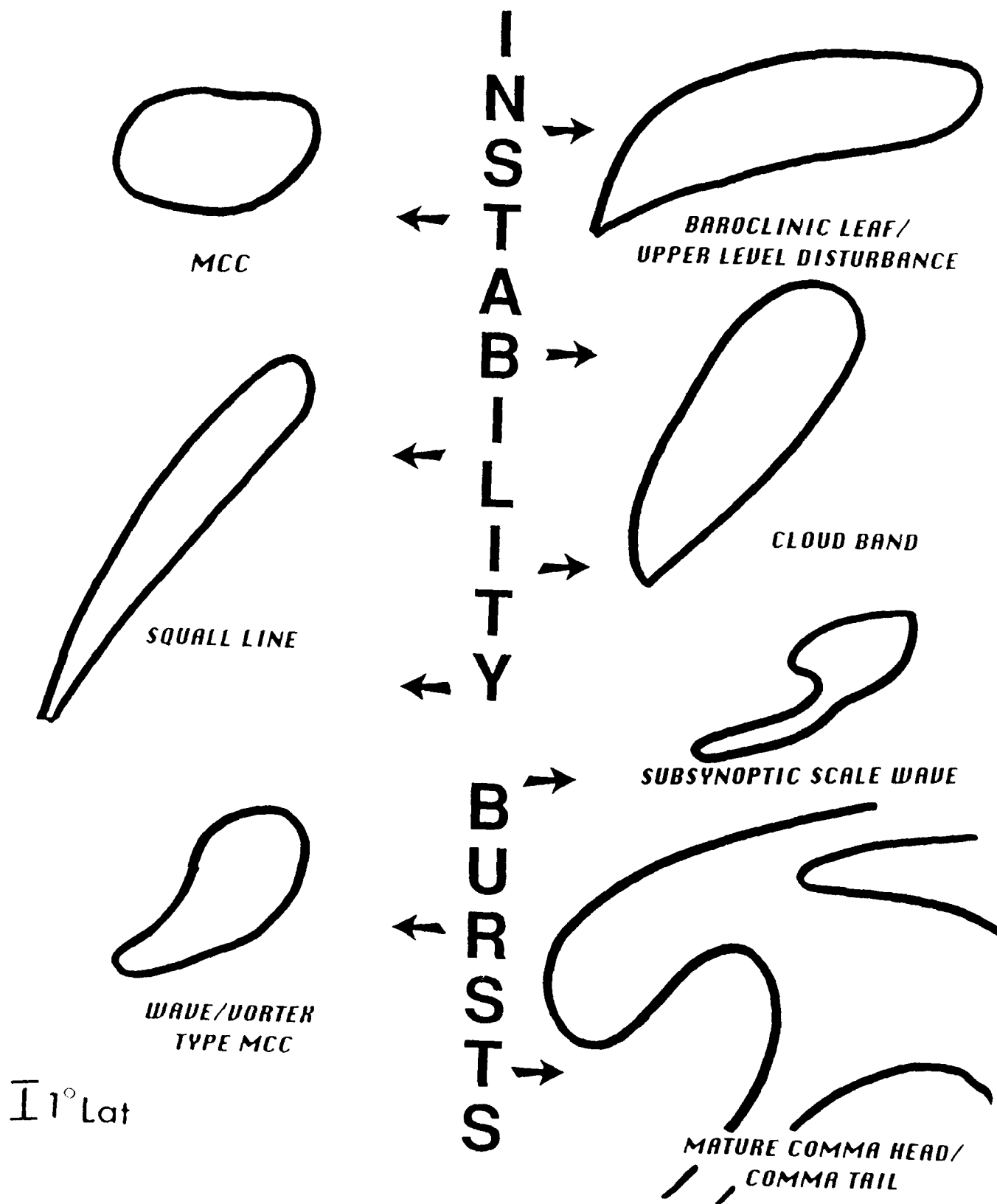


Figure 51. The connecting link between MCSs and ECS

VI. SUMMARY

The relationship between IBs, moisture, ECSs and heavy precipitation is given by the following formulations:

INSTABILITY BURST + MOISTURE = HEAVY PRECIPITATION

INSTABILITY BURST = CONVECTIVE CLOUD AREAS OR BANDS
EMBEDDED WITHIN ECSs
(DETERMINED FROM SATELLITE IMAGERY)

+

INSTABILITY ADVECTION

OR

LIFTING OF UNSTABLE AIR
(DETERMINED FROM SURFACE/UPPER AIR DATA
AND
NGM ANALYSES/FORECASTS)

Scofield and Robinson (1990) have shown that the heavier the precipitation the:

- o more significant the satellite signatures of heavy precipitation;
- o larger the values of maximum TEA (this results in a tighter gradient);
- o more pronounced the TEA ridge axis;
- o greater the available moisture.

As shown in this Tech Memo, IBs are readily detectable in the TEA fields, especially at 850 and 700 mbs. The following summarizes the uses of TEA (850/700 mb) for analyzing and short-range forecasting of heavy precipitation from ECSs:

1. Analyses of TEA must be used with satellite imagery to determine if heavy precipitation is present or anticipated; in the satellite imagery, look for:
 - o baroclinic leafs and upper level systems;

- o convective cloud bands or convective areas embedded within the ECS (especially along and south of the "comma head" and baroclinic leaf edges);
 - o subsynoptic scale wave patterns;
2. Usually the heaviest snow occurs along and north of the axis of maximum TEA and especially in the area of tight gradients (where low level forcing (see "MECHANISMS" in Figure 21b) is important);
 3. The heaviest snow occurs further north where TEA varies from slightly < 0 to slightly > 0 in the presence of middle and upper level forcing (see "MECHANISMS" in Figure 21b);
 4. In frontogenetic and cyclogenetic situations, rule 2 above will often locate the transition zone between snow and rain; rain is often moderate to heavy along and south of the axis of maximum TEA;
 5. TEA advection areas are often conservative (can be analyzed and followed in the 12 hour sounding data); however, they are primarily controlled by the synoptic scale features;
 6. Positive TEA areas increasing with time and becoming better organized are often associated with heavier precipitation; the reverse is associated with lighter precipitation;
 7. A pronounced couplet of positive and especially negative TEA becoming larger (in magnitude) and better organized with time are associated with cyclogenesis and heavy precipitation. Usually the couplet evolves from a west orientation (negative advection) to east orientation (positive advection) (with an incipient surface low) to a north orientation (positive advection) to south orientation (negative advection) (with an occluding surface low);

CAUTIONS: When NO satellite precipitation signatures are present:

8. Positive TEA can be present but precipitation does not occur with this advection area (often associated with a warm air advection ridge and subsidence ahead of a trough);
9. However, sometimes, especially in the plains states, positive TEA occurs 12-24 hours before the precipitation breaks out (a pre-conditioning of the environment);
10. Positive TEA can be present but there is a lack of moisture and upward vertical motion ("Lifting Mechanisms") --- subsidence prevails.

As shown in Figure 25e, IBs are also found by using a combination of the NGM Lifted Index analysis and the 850 mb height contour analysis. IBs are associated with the maximum advection of unstable air. The NGM Lifted Index is a "best" Lifted Index which is a measure of the most unstable air between the Earth's surface and approximately 850 mb. The NGM Lifted Index is especially useful in locating unstable air in overrunning situations. Additional ways to detect IBs operationally include analyzing: (1) maximum 850 mb flow from higher to lower K index values ($K = 10$ or greater) and upward vertical motion (location of "Lifting Mechanisms") associated with relatively high K index values and (2) cross sections of theta-e and momentum on AFOS.

As shown in Figure 51, IBs are a connecting link between MCSs and ECSs. The: (1) Mesoscale Convective Complex (MCC) and Baroclinic Leaf or upper level disturbance, (2) squall line and cloud band, and (3) wave/vortex type of MCC and subsynoptic scale wave all have similar appearances in the satellite imagery. In addition, the above are associated with heavy precipitation and IBs are a principal mechanism for their initiation. Perhaps, the mature comma head/tail could be considered as the ultimate, "IB-produced", ECS storm structure as it evolves from: baroclinic leaves, cloud bands and subsynoptic scale waves.

A 3-12 hour ECS forecast index is presented in the form of a five step decision tree. The five steps require the determination of:

- (1) the presence (or expectation) of satellite signatures and mechanisms of heavy precipitation;
- (2) the presence (or expectation) of moisture;
- (3) the type (or expectation) of ECS movement;
- (4) the location and estimation (amount) of the heaviest precipitation within the ECS;
- (5) the potential for a rapidly deepening surface low.

VII. OUTLOOK

More events must be studied in order to better understand the evolution and characteristics of precipitation within the ECS. This will lead to improvements in the Forecast Index of 3-12 Hour Heavy Precipitation for ECSs. It has been suggested by Moore and Blakley (1988) that thickness fields should also be used in the analysis of heavy precipitation embedded within ECSs. Mesoscale heavy precipitation bands often line up with the 850-700 mb thickness contours. GOES-VIS and IR spin scan radiometer atmospheric sounder (VAS) sounding will be available on the VAS Data Utilization Center (VDUC) system. As a result, TEA, thickness, moisture, and other products derived from three hourly VAS data plus conventional data products will be an excellent

source of data to study the evolution and precipitation characteristics of ECSs. Thus, future efforts will involve archiving ECS events and performing analyses (both in real time and with the archived data) on the VDUC system.

Additional research will concentrate on:

- (1) defining better the threat area of heavy precipitation within the 850/700 mb TEA pattern by using satellite imagery, radar, Q-VECTORS (Barnes, 1987) and surface observations;
- (2) testing the applicability of NGM-derived analysis and forecast fields of TEA to the short range prediction of heavy precipitation;
- (3) developing a better understanding of how TEA patterns relate to mesoscale and synoptic scale features observed in the satellite, surface and upper air data and numerical forecast data.

VIII. ACKNOWLEDGMENTS

The author thanks Frances Holt and Don Miller of the Satellite Applications Laboratory of NESDIS and Sam Beckman of the National Severe Storms Forecast Center of NWS for their constructive criticism in the preparation of this manuscript, Tina Cashman for typing, John Shadid and Phil Golden for the preparation of illustrations and layout.

IX. REFERENCES

- Auciello, E.R., 1988: A method for predicting meteorological bombs in the western North Atlantic Ocean. Published in NOAA Technical Memorandum NWS ER-82: Postprints from the Second National Winter Weather Workshop, conducted by the National Weather Service-Eastern Region, Raleigh, North Carolina, 26-30, September, 1988.
- Baldwin, T., 1988: Unpublished technique used by the Synoptic Analysis Branch of NESDIS.
- Barker, T., 1987: Convective spatial cross sections AFOS program note. National Weather Service Western Region Headquarters, Salt Lake City, Utah.
- Barnes, S.L., 1987: Analysis of quasi-geostrophic forcing during the AIMCS project, Volume I: discussion. NOAA Tech Memo ERL ESG-27, vol I, U.S. Dept. of Commerce, Washington DC, 31 pp.
- Beckman, S.K., 1987: Use of enhanced IR and visible satellite imagery to determine heavy snow areas. Mon. Wea. Rev., **115**, 2060-2087.

- Bennetts, D.A. and B.J. Hoskins, 1979: Conditional symmetric instability - A possible explanation for frontal rainbands. Quart. J. R. Met. Soc., 105, 945-962.
- Fleming, E.L. and L.E. Spayd, Jr., 1986: Characteristics of western region flash flood events in GOES imagery and conventional data. NOAA Tech Memo NESDIS 13, 82 pp.
- Funk, T.W., 1986: The use of water vapor imagery in the analysis of the November 1985 middle Atlantic states record flood event. Nat. Wea. Dig., 11, 12-19.
- Heppner, P.O.G., 1988: Differential ridge-axis displacement: Applications to forecasting the onset of precipitation. Nat. Wea. Dig., 13, 5-14.
- Herzogh, P.H. and P.V. Hobbs, 1980: The mesoscale and microscale structure and organization of clouds and precipitation in mid-latitude cyclones. II: Warm frontal clouds. J. Atmos. Sci., 37, 597-611.
- Houze, R.A., Jr., S.A. Rutledge, T.J. Matejka, and P.V. Hobbs, 1981: The mesoscale and microscale structure and organization of clouds and precipitation in mid-latitude cyclones. III: Air motion and precipitation growth in a warm-frontal rainband. J. Atmos. Sci., 38, 639-649.
- Jiang, Shi and R.A. Scofield, 1987: Satellite observed Mesoscale Convective System (MCS) propagation characteristics and a 3-12 hour heavy precipitation forecast index. NOAA Technical Memo NESDIS 20, U.S. Dept. of Commerce, Washington, DC, 43 pp.
- Moore, J.T. and P.D. Blakely, 1988: The role of frontogenetical forcing and conditional symmetric instability in the midwest snowstorm of January 30-31, 1982. Mon. Wea. Rev., 116.
- Moore, J.T., 1986: Isentropic analysis and interpretation: Operational applications to synoptic and mesoscale forecast problems. Printed by the NWS Training Center, 617 Hardesty St., Kansas City, MO 64124, 116 pp.
- Sanders, F., 1984: Slantwise convection in the megalopolitan snowstorm of February 11-12, 1983. Preprints, 10th Conf. on Weather Forecasting and Analysis, Clearwater Beach, FL, Amer. Meteor. Soc., 602-607.
- Scofield, R.A. and J. Robinson, 1990: Using instability bursts and satellite imagery to analyze and NOWCAST heavy snow. Satellite Applications Information Note 90/1, NESDIS, Washington, DC.

Scofield, R.A. and J. Robinson, 1989: Instability bursts and mesoscale convective system development and propagation. Satellite Applications Information Note 89/2, NESDIS, Washington, DC.

Scofield, R.A., 1989a: Instability bursts associated with extratropical cyclone systems (ECSs) and a 3-12 hour heavy precipitation forecast index --- an extended abstract. Published in NOAA Technical Memorandum NWS WR-206: "A Collection of Papers Related to Heavy Precipitation Forecasting."

Scofield, R.A., 1989b: Instability bursts and heavy precipitation from extratropical cyclone systems (ECSs). Published in NOAA Technical Memorandum NWS ER-82: Postprints from the Second National Winter Weather Workshop, conducted by the National Weather Service-Eastern Region, Raleigh, North Carolina, 26-30, September, 1988.

Scofield, R.A. and Jiang Shi, 1987: Evolutionary "satellite" characteristics of mesoscale convective systems and extratropical cyclone systems. Proc. from the Workshop on Satellite and Radar Imagery Interpretation, Reading, England, July 20-24, 1987.

Scofield, R.A. and T.W. Funk, 1986: The use of water vapor imagery in the analysis and forecasting of heavy precipitation. NWS Southern Region Quantitative Precipitation Forecasting Workshop, February 3-5, 1986, Houston, TX, NOAA Tech Memo NWS SR-117, 77-82.

Scofield, R.A. and L.E. Spayd, Jr., 1984: A technique that uses satellite, radar, and conventional data for analyzing precipitation from extratropical cyclones. NOAA Tech Memo NESDIS 8, 51 pp.

Weldon, R. and S. Holmes (1990): Water vapor imagery; to be published in 1990.

Xie Juying and R.A. Scofield, 1989: Satellite-derived rainfall estimates and propagation characteristics associated with Mesoscale Convective Systems (MCSs). NOAA Technical Memorandum NESDIS 25, U.S. Dept. of Commerce, Washington, DC, 49 pp.