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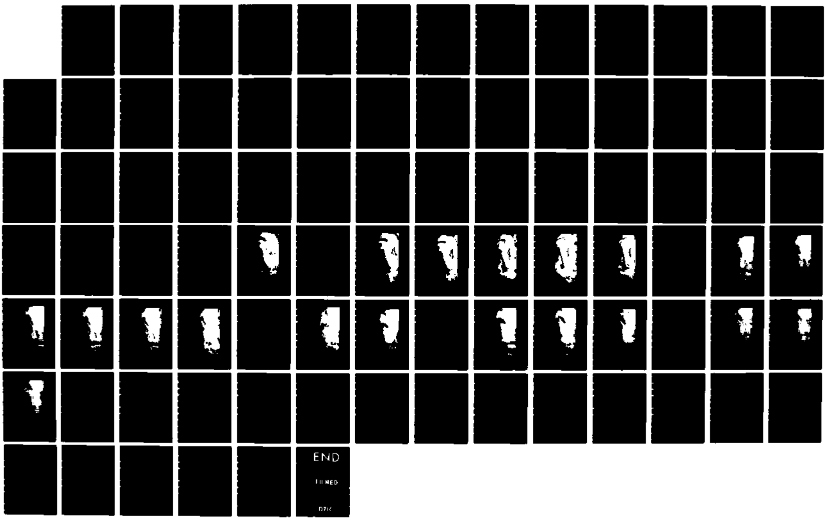

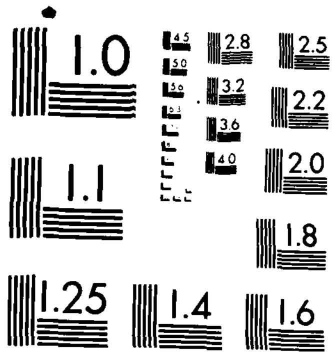

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Monterey, California

THESIS

UTILIZATION OF SATELLITE-OBSERVED CLOUD PATTERNS TO IMPROVE ANALYSES OF EXPLOSIVE EXTRATROPICAL MARITIME CYCLOGENESIS

by

Dock D. Williams, Jr.

September 1985

Thesis Advisor: C. H. Wash

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(3) objective evaluations of usage potential. Specific findings include: (1) a high number of dual cloud element storms; (2) distinct developmental segments in pressure fall rates of the storms; (3) varying degrees of reliability for the designated cloud patterns and (4) discussion of the practicability of formulating a storm developmental analog from the designated cloud patterns.

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Utilization of Satellite-Observed Cloud Patterns to Improve Analyses of Explosive Extratropical Maritime Cyclogenesis

by

Dock David Williams, Jr.
Lieutenant Commander, United States Navy
B.S., University of Utah, 1975

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
September 1985

Author: ______________________
Dock D. Williams, Jr.

Approved by: ______________________
Carlyle H. Wash, Thesis Advisor

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Robert J. Renard, Second Reader

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Robert J. Renard, Chairman of Meteorology

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John N. Dyer, Dean of Science and Engineering

ABSTRACT

On the basis of analysis of satellite imagery, a set of designated cloud patterns is explored to evaluate their potential for improving the forecasts of explosively deepening extra-tropical cyclones. An analysis of 23 western Atlantic Ocean cases included correlation of infrared satellite imagery with derived pressure diagrams and synoptic data. The study includes: (1) quantitative pattern definition, (2) frequency of occurrence statistics and (3) objective evaluations of usage potential. Specific findings include: (1) a high number of dual cloud element storms; (2) distinct developmental segments in pressure fall rates of the storms; (3) varying degrees of reliability for the designated cloud patterns and (4) discussion of the practicability of formulating a storm developmental analog from the designated cloud patterns.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Oceanic cyclogenesis is a key research area for the improvement of maritime prediction. Sanders and Gyakum (1980) provide a study of a particular subset of cyclogenesis cases which undergo deepening at a rate which exceeds that of the normal cyclogenetic process. They define a "bomb" as an extratropical surface cyclone whose central pressure fall averages at least 1 mb/h (a correction is applied for latitude) for 24 consecutive hours. In a more detailed study for the 1978-1979 season, they utilized a twelve-hour developmental criterion which is used in this study to insure inclusion of more cases which might escape detection under the less stringent twenty-four hour criterion.

Sanders and Gyakum describe the "bomb" as a predominantly maritime, cold season event. It is usually found to occur approximately 400 n mi downstream from a mobile trough, within or poleward of the maximum westerlies and within or ahead of the planetary scale trough. The mobile trough typically migrates for several days across the upwind continent before triggering the explosive surface event. They show that the cold season, extending from September until early April, includes the majority of such events and cite statistical data which indicate a peak frequency during the months of December and February. This frequency varies over the world's oceans but is considered to be applicable for the western North Atlantic Ocean Basin. The geographical distribution for the western North Atlantic Ocean places nearly all occurrences between 40° and 75°W with a significant decrease for latitudes north of 50°N. In testing the hypothesis that most of the hemisphere's deepest cyclones have deepened explosively, Sanders and Gyakum found that out of 37 deep lows (960 mb or lower) during the nine-month period following 1 September 1978, 31 qualified as a bomb during their development. Therefore, they conclude: "Explosive deepening is a characteristic of the vast majority of the deepest cyclones."

The damaging potential of this type of cyclogenesis is a major concern of forecasters in near-coastal regions and an ultimate source of danger for vessels traversing open oceans in extratropical latitudes. Recent examples are provided by the tragic disruption and subsequent loss of life during the 1979 Fasnet Yacht Race (Rice, 1979) and the total paralysis of the Nation's Capitol, as a result of a record snowfall associated with the President's Day Cyclone of February 1979 (Bosart, 1980 and Uccellini et al., 1984).

The inability of current atmospheric numerical models to predict explosive cyclogenesis is discussed by Sanders and Gyakum (1980), Uccellini et al. (1981) and others. Sanders and Gyakum state that it seems unlikely that further improvements can be achieved simply by increasing the horizontal resolution. They suggest that important physical processes are missing. Likely candidates are inadequate representation of the bulk effects of cumulus convection and the planetary boundary layer. Uccellini et al. (1981) analyzed the LFM-II predictions of the President's Day Cyclone. They found poor prediction of the pre-cyclogenesis mass-momentum adjustments associated with the supergeostrophic subtropical jet and development of the low-level jet off the east coast of the United States.

The removal of ocean weather ships has additionally weakened the probability of timely detection through the loss of consistent oceanic observations (Bottger et al., 1975). The authors discuss the current trend toward the use of satellite imagery as an additional aid in prognosis. They state: "It is fortunate that satellite imagery has proven to be of direct assistance for predicting the onset of deepening."

However, the utilization of satellite imagery has its inherent problems for locations which lack high resolution, direct readout capabilities. The relative mediocrity of landline facsimile satellite products produces degradations in clarity and resolution. These deficiencies limit the user to larger scale patterns which are readily discernible in the available imagery products.

The primary purpose of this thesis is to improve the quality and timeliness of forecasts for explosive cyclogenetic events which occur over the nearshore waters of the western Atlantic Ocean. The use of meteorological satellite imagery as a prognostic tool is addressed as an important element for improvement in the existing level of meteorological forecast expertise in conjunction with these events. The objectives for this study are designed to develop a framework to aid in the satellite-imagery detection of cloud patterns or individual signatures which can be associated with explosive cyclogenesis.

The study objectives are as follows:

1. The designation of cloud patterns which could be associated with explosive cyclogenesis.
2. To quantitatively define these cloud patterns.
3. To provide the frequency of occurrence statistics for a number of documented cases.
4. To evaluate the usage potential of these patterns.
5. To organize these patterns into a developmental analog(s).
6. To describe additional synoptic implications and provide documentation where possible.

Chapter 2 describes the variety of cloud patterns associated with cyclogenesis. Data for this study and analysis techniques are presented in Chapters 3 and 4 followed by results (Chapter 5) and conclusions (Chapter 6).

II. BACKGROUND

The commonly accepted association between extratropical cyclones and jet streams dictates a necessity to search for cloud patterns which might be related to either or both phenomena. Thus, the majority of studied patterns are associated with upper-level cloud manifestations of jet streams or individual signatures of cyclogenetic events. These patterns are also among the easiest to detect since their relative height precludes obscuration by higher clouds and their extensive coverage nullifies the adverse affects of low quality landline facsimile satellite imagery.

An extensive search of available literature provides six potential patterns and one set of four cloud models which have been linked with cyclogenesis and its associated jet streams:

1. "Jet Stream Cirrus Patterns"; Kadlec (1964).
2. The "Baroclinic Leaf"; Weldon (1977).
3. The "Comma Cloud"; Weldon (1979).
4. The "Cloud Head Formation"; Bottger et al. (1975).
5. The "Cloud Tip and Slot"; Weldon (1979).
6. The "Enhanced Cumulus Wedge"; Fett (1981).
7. The "Polar Low"; Reed (1979) and Mullen (1979).

A. JET STREAM CLOUD PATTERNS

The inclusion of jet stream cloud patterns was found to be practical for at least two reasons: (1) they are large scale patterns which are easily recognized in satellite imagery and

(2) a large part of the research of associated cloud patterns for "bomb" occurrences linked these patterns to the characteristic deepening. Kadlec (1964), McLean (1957), Conover (1960) and others determined that an extensive cloud shield exists to the south of a jet stream core. These early works describe the presence of a sharp northern edge which is found within 400 n mi of the jet stream core on the warm side in the entrance or neutral region. Kadlec (1964) associates three basic requirements with the formation of cirrus: (1) a widespread area of ascending motion or lift in the upper wind field (2) static air temperatures of 38°C or colder and (3) a wind velocity of 40 kt or greater.

Whitney et al. (1966) discuss a theoretical model proposed by Riehl which relates to the dynamics of the jet stream in the area of a wind maximum and its relationship to high level clouds. The horizontal divergence in the entrance region on the tropical side and on the polar side in the exit area are proposed to provide the ascending motion for cirrus formation. In the ensuing discussion they also point out alteration of the divergence pattern by jet stream curvature, low moisture in the polar exit region and frequent observations of cirrus in areas of positive vorticity advection.

McLean (1957) discusses the frequency of occurrence of cloud types in the vicinity of jet streams. He concludes that a maxima of cloud occurrence are found in the upper troposphere four to five degrees north of the core and immediately above the jet stream front four to six degrees south of the core. McLean points to a minimum of cloudiness north of the jet stream at the core level. He also indicates that on the basis of study cloud observations, where the cirrus extended to the north of the core, there is often a narrow break in the cirrus at the core itself.

1. Jet Stream Cirrus Patterns

Kadlec (1964) expanded his original study to a data base of 607 flights. He redefined the original study and formulated four cloud patterns which describe the areas of occurrence, thickness and horizontal extent of cirrus. Type A through C are models of jet stream cirrus which are associated with the polar front jet stream, subtropical jet stream and a combination of the influence of both jet streams. Type D is primarily a jet situation that produces little if any significant cirrus.

The Type A and C models formulate the basic characteristics for the polar front and subtropical jet stream cloud patterns. In the Type A model the polar jet stream is in a trough-to-ridge configuration (Fig. 1). The average distance across the cirrus shield is 600 to 800 n mi. The cirrus occurs south of the jet stream and clear skies are observed in the trough area. The Type C model is illustrated by Fig. 2. This situation produces a thick cirrus layer when the jet stream is oriented in an anticyclonic arch. The width of the pattern is about 600 n mi in the area of maximum curvature and diminishes to approximately 400 n mi in areas of formation and dissipation. This model includes both the polar front and subtropical jet streams and produces extensive cirrus. The polar front jet stream is in a Type A trough to ridge configuration and the subtropical jet is in an anticyclonic configuration. The pattern width varies from 400 n mi in areas of formation to between 1,000 and

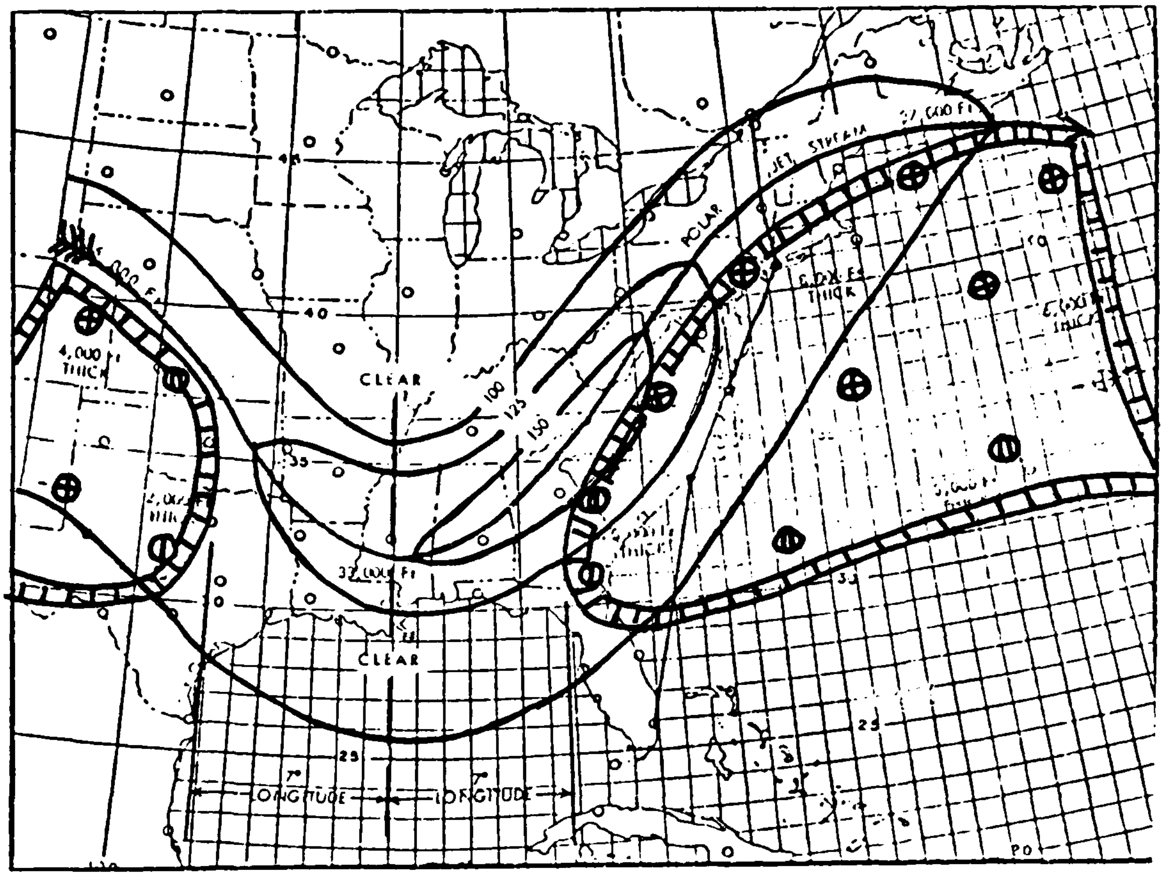

Figure 1. Plan View of Polar Jet Stream and Cirrus Pattern Model Type A. (from Kadlec, 1964)

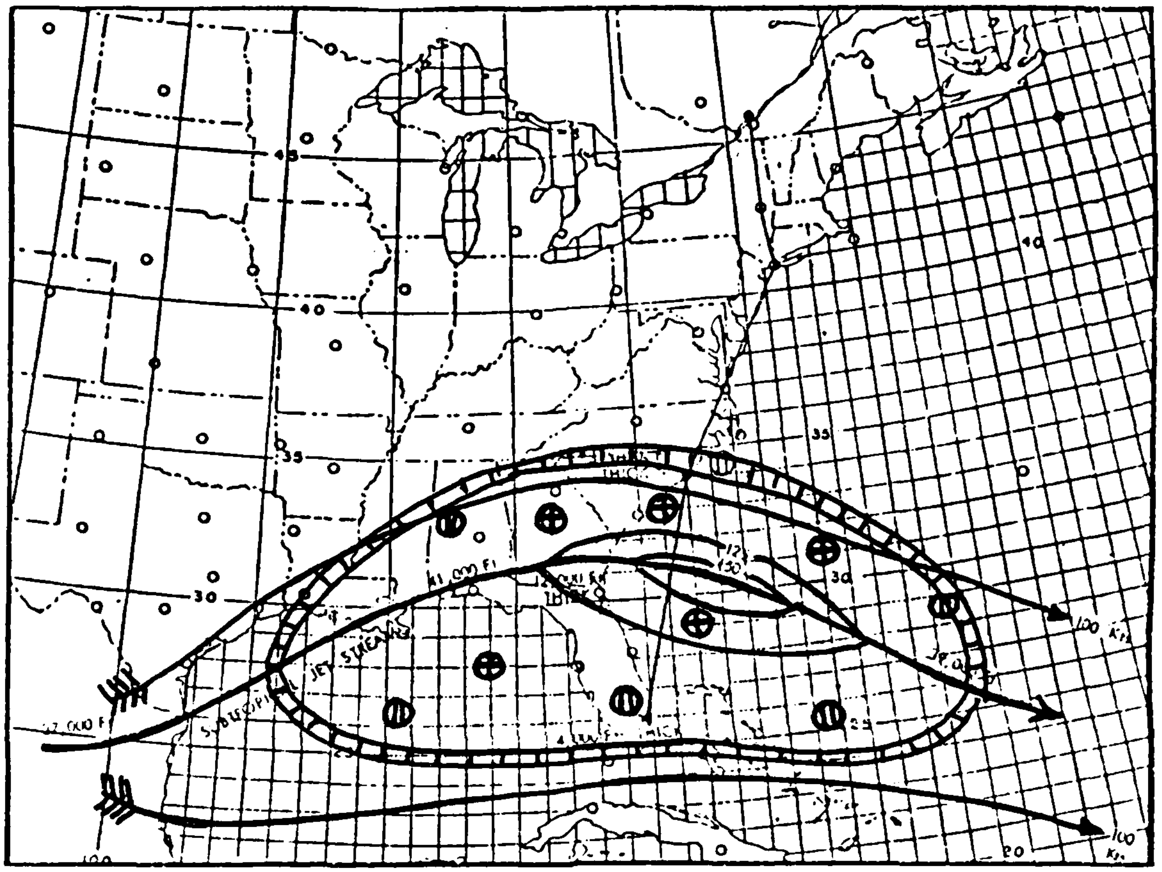

Figure 2. Plan View of Subtropical Jet Stream and Cirrus Pattern Model Type C. (from Kadlec, 1964)

1,500 n mi in the ridge. This extensive coverage occurs when two jet streams converge to within 300 n mi in the trough area. The Type B (Fig. 3) model provides for clear skies in the trough area north of the polar front jet stream and between the polar front and subtropical jet stream in the area of convergent flow upwind of the trough. This clear area between the two jet streams is recognized as Kadlec's "Dual Jet Split."

2. Baroclinic Leaf

Weldon (1979) provides an excellent discussion on the use of satellite imagery in conjunction with cyclogenesis forecasting. He utilizes three major cloud development types to formulate a basis for imagery analysis in cyclogenetic events: (1) baroclinic zone cirrus, (2) the baroclinic leaf and (3) the comma cloud. He provides guidance for developmental cloud sequences and well-illustrated examples of numerous configurations that these basic elements may assume. Weldon (1977) discusses the cloud pattern evolution for oceanic cyclogenesis. He refers to the earliest detectable characteristic of this pattern as a "baroclinic leaf" (Fig. 4). Weldon indicates that the baroclinic leaf is a cloud pattern which is associated with frontogenesis aloft within a westerly wind field. Usually the system is vertically deep and surface frontogenesis is also occurring. The ensuing cloud pattern is normally elongated with relatively well-defined borders on both sides. The equatorward side may be well defined along its entire distance, or it may be more distinct along its western or upstream end. The distinct southern border and tip are

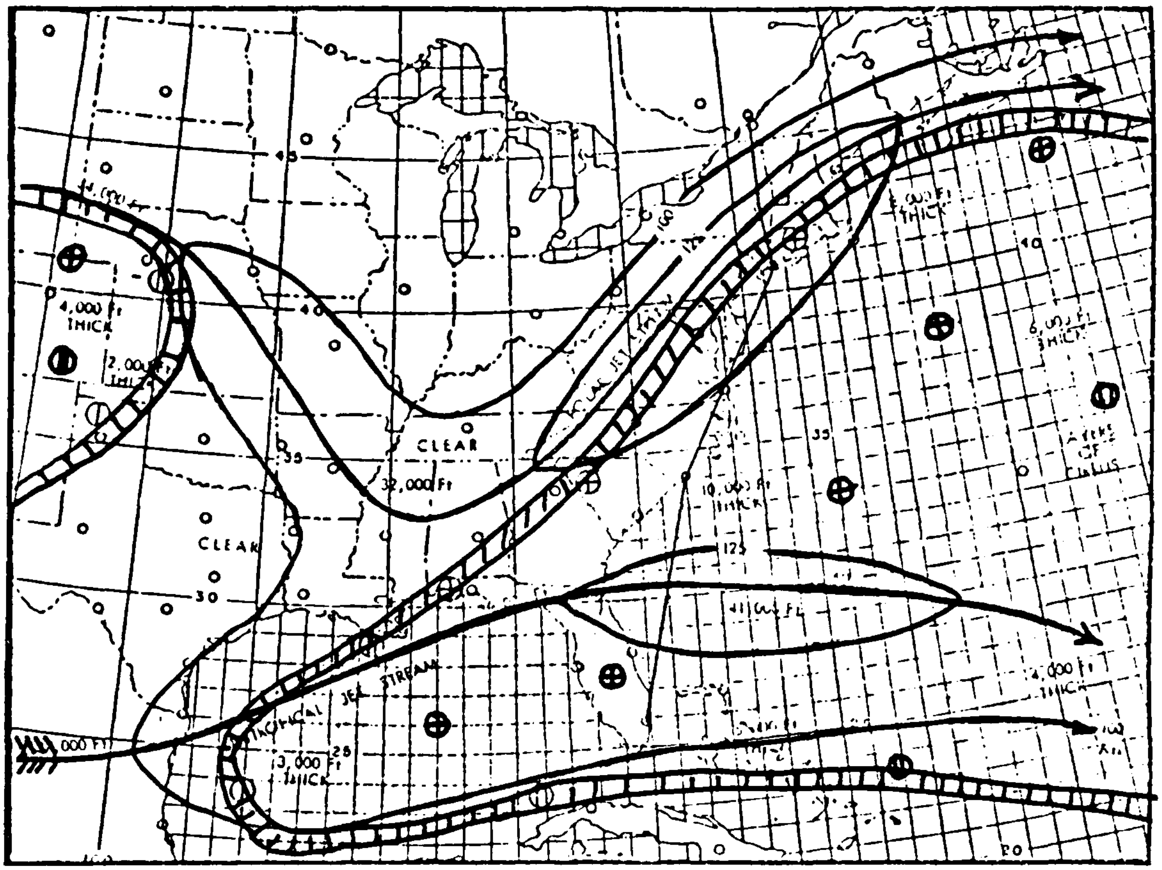

Figure 3. Plan View of Polar and Subtropical Jet Streams with Cirrus Pattern Model Type B. (from Kadlec, 1964)

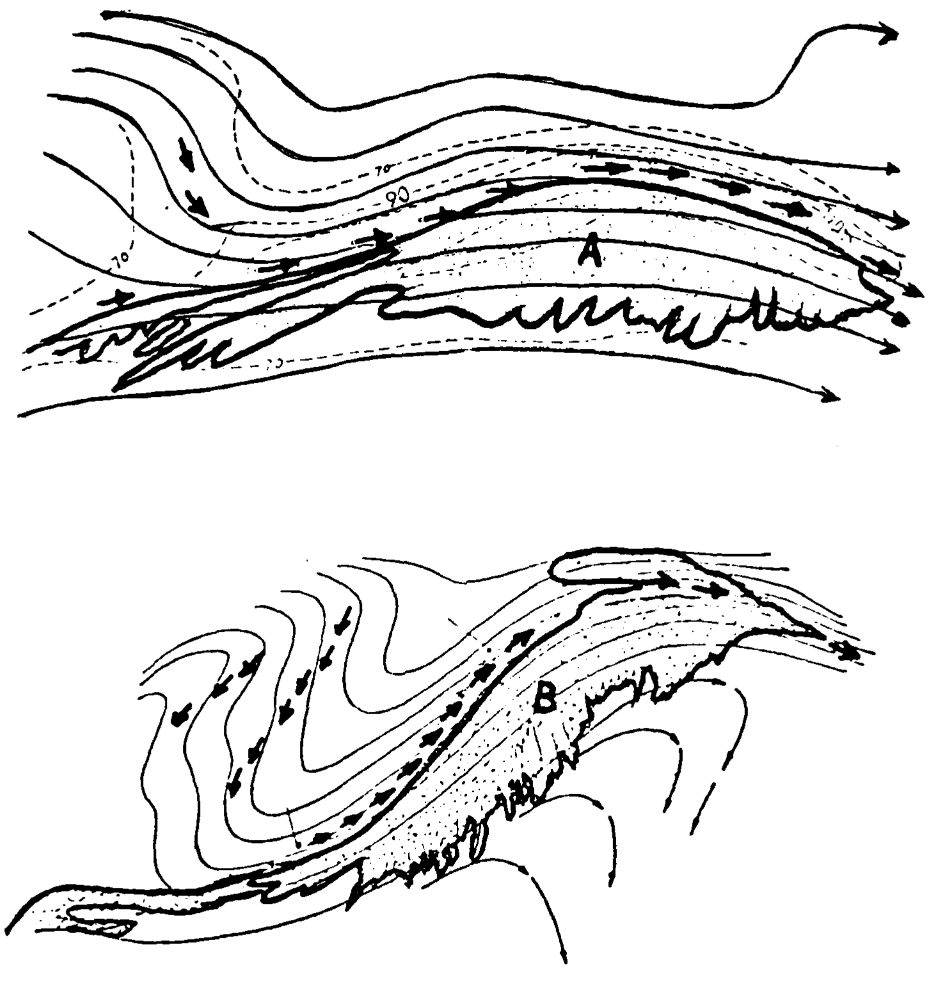

Figure 4. Baroclinic Leaf as Depicted in Low Amplitude Trough (A above) and High Amplitude Trough (B above). (from Weldon, 1979)

associated with the lower middle tropospheric baroclinic zone (jet stream front). This northern border will most likely have a gentle "S" shape curvature. The low amplitude "S" consists of a downstream transition from an area with a concave poleward edge through an inflection point to an area with a convex poleward edge. The poleward edge can also be (in order of frequency of occurrence) all convex, nearly straight or all concave.

The normal variations in a leaf configuration are depicted in Fig. 5. Here the pattern takes on a "wing" or "leaf" shape, depending upon the predominant poleward branch configuration. The "wing" shape (pattern d) is associated with the surface frontal zone and frontal wave development. It is considered by Weldon to be of a channeled nature when related to the upper-wind flow. This type of development usually involves the head cloud (to be described later) in its later phases. The "leaf" shape (pattern c) indicates upper or middle-level development which is advanced, in respect to time, relative to low-level development. Weldon relates the leaf shape to positive vorticity advection. This pattern can evolve directly into a comma cloud (Fig. 6) or include a head cloud to comma cloud development. This advection-type development may be associated with "Polar Lows" and the process of "instant occlusions."

Weldon's treatment of the baroclinic leaf has not been completely described in the preceding discussion. There are numerous variations and implications which deserve further study. One important difference is in the distinction between the baroclinic zone cirrus mentioned earlier and the baroclinic

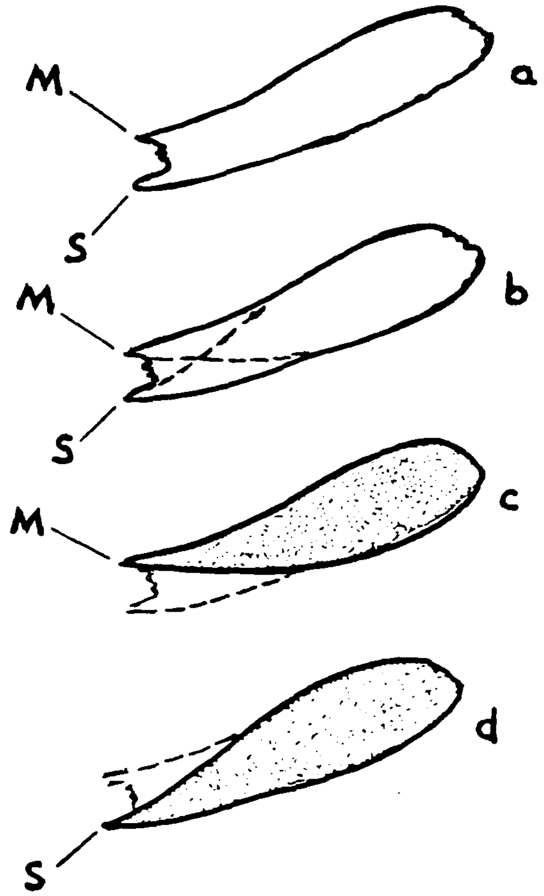

Figure 5. Variations of Baroclinic Leaf Configuration where M and S Represent Middle and Surface Level Developments. (from Weldon, 1979)

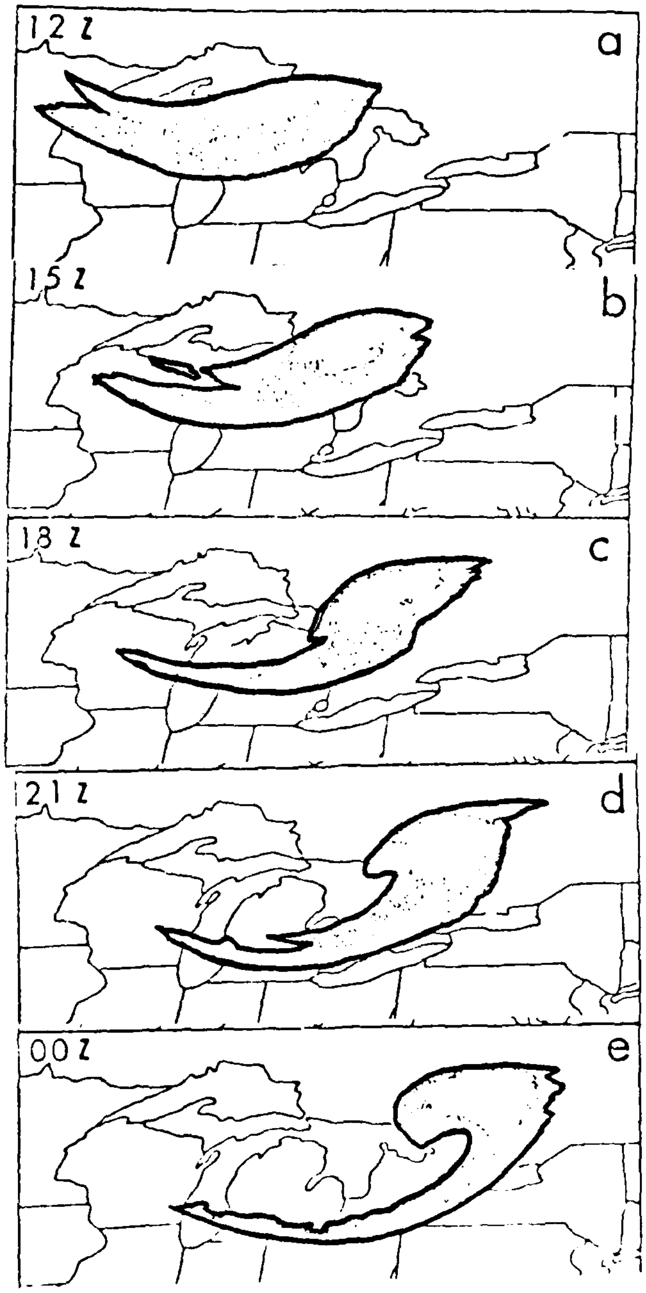

Figure 6. Development of a Pattern d "Wing Shaped" Baroclinic Leaf. The "S" or Surface Dominated Development is Portrayed over a 12 h Period. (from Weldon, 1979)

leaf. According to Weldon, the baroclinic leaf has relatively distinct borders on both sides of the leaf pattern, the normal difference being found in the definition of the equatorward (southern) border. Weldon indicates that the equatorward side of the baroclinic zone cirrus is normally not well defined. He discusses four categories where the equatorward border will display the definition required for baroclinic leaf designation. Three of these categories would appear to be of interest: (1) association with a surface frontal zone, (2) a double jet stream or double jet maximum structure and (3) an elongated vorticity maximum. A cloud pattern with a well-defined equatorward border may fit into one or more of these categories (Fig. 7). Thus, the subsequent evolution of Weldon's baroclinic leaf is influenced by the strength of the surface frontal zone and may include complex upper-level patterns which have multiple jet stream structures.

Weldon continues to describe the baroclinic leaf as well defined with a relatively uniform cold top area. He limits the majority of its evolution to a period of 24 hours. Its early growth consists of an increase in distinctiveness and continued maintenance of the general leaf shape. This increase in sharpness of appearance is often accompanied by a clearing or decrease in cloudiness adjacent to the main cloud area. Subsequent evolution provides for the disappearance of the poleward edge band and develompoment of a comma-like shape. At this point Weldon suggests a surface low pressure center forms.

Just prior to the comma cloud phase, Weldon suggests a division in the future development. At this point, development

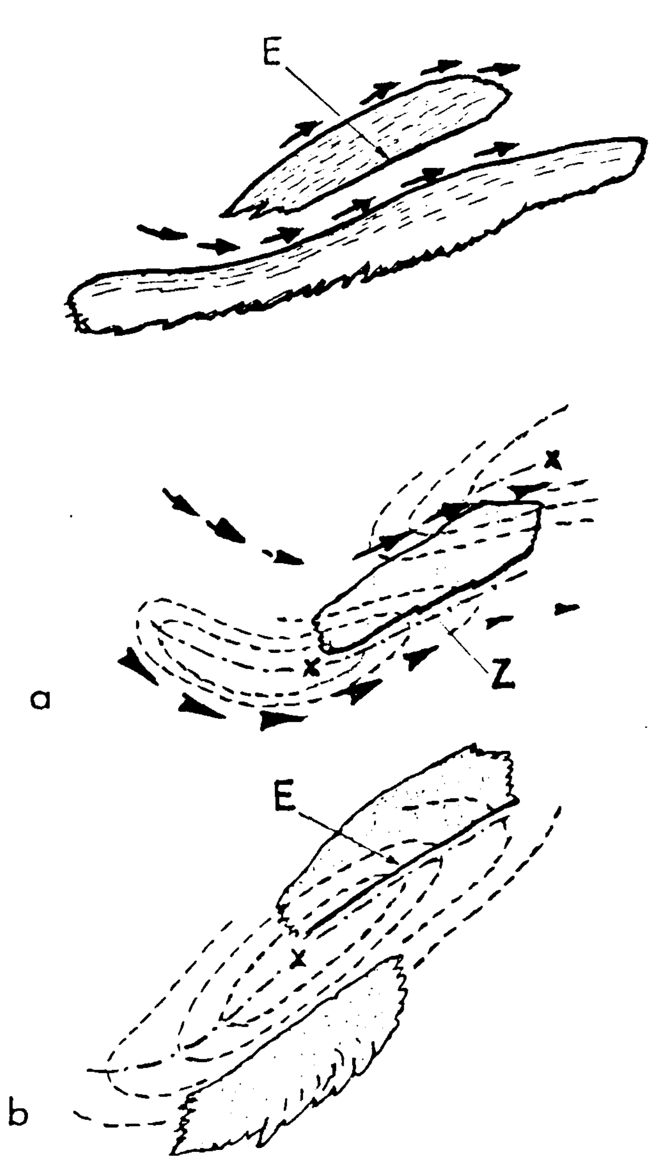

Figure 7. Depiction of Sharp Southern Edge on Baroclinic Leaf. Sharp Delineation of Pattern is Seen at Edges E and Z Above. (from Weldon, 1979)

of the main cloud area is influenced by the strength of the accompanying surface frontal zone. The pre-existence of a surface frontal zone in close proximity to the baroclinic leaf brings about the extended development of the convex portion of the leaf.

The change of curvature of the poleward edge is also related to the synoptic environment in which the system is located. If the system is forming within the flow around a high amplitude trough, the convex portion of the leaf is decreased and the concave portion is enhanced. The opposite is true in zonal flow or a longwave ridge, especially when an old pre-existing frontal zone is involved. Here, the convex portion is dominant and the ridge builds rapidly even before evolving into the comma stage. This convex dominant growth rapidly amplifies the middle tropospheric ridge and is referred to by Weldon as a baroclinic "arch."

B. CYCLONE RELATED CLOUD PATTERNS

1. The "Comma" Cloud Pattern

Weldon (1979) defines the primary characteristic of cloud "comma" patterns to be the "S"-shaped relatively well-defined back border. A typical comma cloud pattern, as seen in satellite imagery, is composed of a combination of clouds and associated boundaries at primarily different levels. Weldon (1979) provides the following cloud comma pattern characteristics, which determine comma appearance:

1. the relative age or stage of evolution of the system.
2. direction of the relative 500 mb vorticity center.

3. location of the 500 mb vorticity center.

4. location of the jet speed maximum and general orientation.

2. The "Cloud Head" Formation

Weldon's baroclinic arch seems similar to the "cloud head" of Bottger et al. (1975). An example of this pattern is provided in Figs. 3A-5A (Fett et al. 1981). Bottger et al. relate the cloud head formation to a normal cyclogenetic process involving a condition of extreme baroclinity along a front between subpolar and subtropical air masses. The head cloud formation is described by Fett et al. (1981) as consisting of a compact anticyclonically-curved cirrus canopy which is centered over the surface disturbance. They describe a large field of open cellular cumulus which surrounds the system on the cold-air side.

Additional characteristics are an anticyclonically-curved cirrostratus shield covering the entire system and the associated degree of curvature depending upon the stage of development, and a sharp northern limit of the shield coinciding with the jet stream axis. This characteristic shape can appear in the early stage of deepening when nothing except a very weak wave is discernible on the surface pressure analysis.

Bottger et al. (1975) cite a statistical investigation of the period 1968-73 which indicates that all extratropical hurricane developments viewed in the eastern North Atlantic Ocean were preceded by the appearance of cloud heads. They further conclude that no cloud heads occurred without being followed by major deepening at the surface. It must be considered that this study was based on ESSA imagery and only one stage of development could be seen within the 24-hour image intervals. Thus, a continual evolution of the head cloud pattern was not provided.

As pointed out be Weldon, the lack of a pre-existing surface frontal zone brings about a baroclinic leaf to comma cloud development. Weldon also describes cases where the cloud pattern evolves directly into a "comma shape". He provides illustrations of three categories of comma cloud patterns (Fig. 8). The first of these is associated with low and lower middle tropospheric boundaries. The second type has high-level baroclinic zone cirrus associated with it. In this case the major high-level baroclinic zone is not as well developed as the middle and lower levels. The third type directly involves a perturbation of the upper troposphere. When the system evolves directly into this pattern, the upper level development is often advanced (in time) beyond the low-level development or the system may develop at upper levels only.

3. <u>Fett's Enhanced Cumulus Wedge</u>

Another indication which might be significant in explosive-deepening is enhanced convection in the trailing tip of the comma cloud or leaf. Fett (1981) suggests the importance of an enhanced wedge of convection in satellite imagery of explosively-deepened storms. Weldon refers to this wedge as the tail of the developing comma cloud and considers it to be an indication of middle-level frontogenesis. Anderson *et al.* (1974) points to enhanced convection associated with the northward intrusion of the subtropical jet over the trailing edge of a

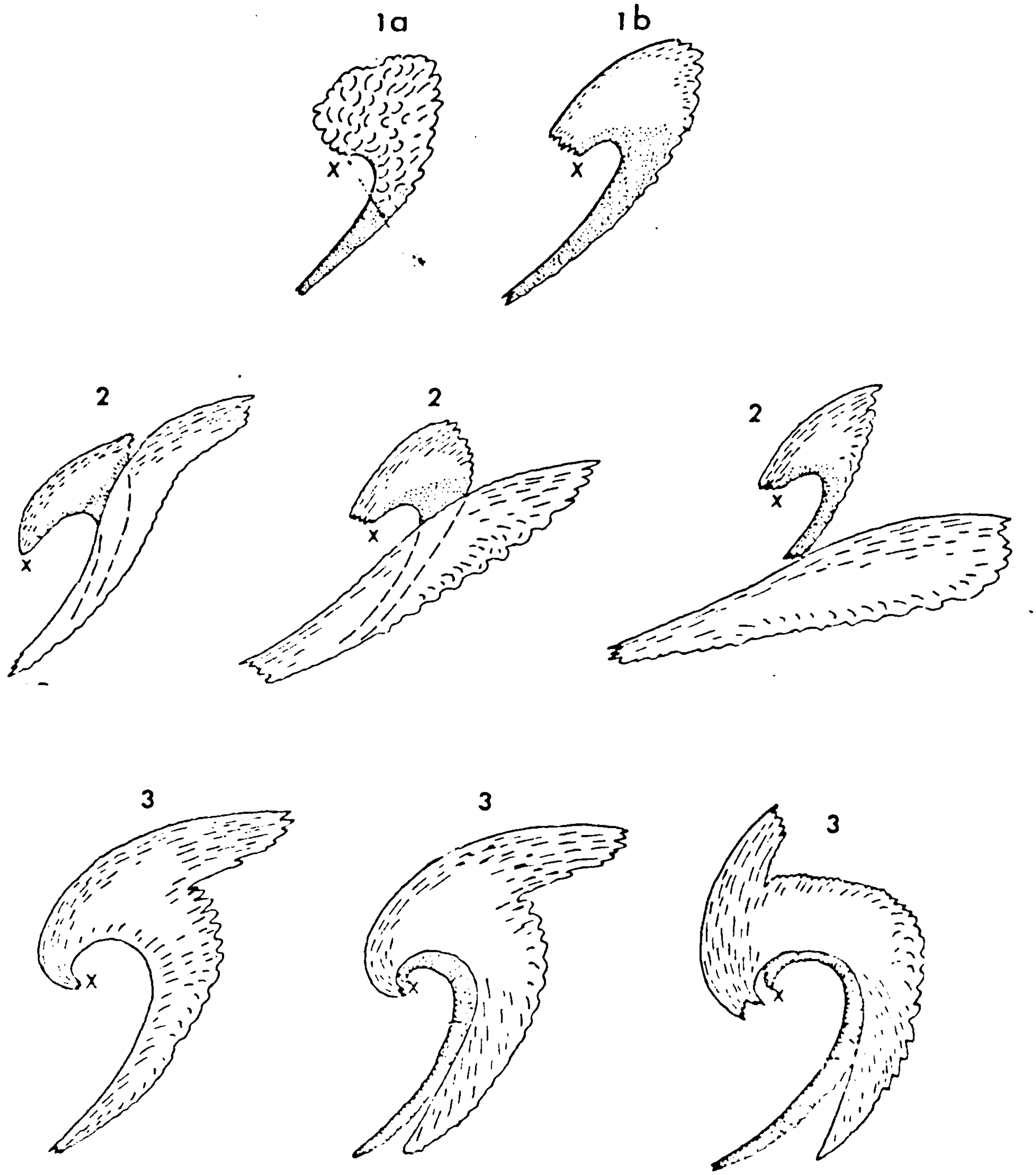

Figure 8. Weldon's Three Categories of Comma Cloud Patterns.
(from Weldon, 1979)

frontal zone during summer. This intrusion is a key factor in severe weather predictions for the summer months.

4. Weldon's Cloud Tip and Slot

The existence of a gap or slot, which is often observed in the upper cloudiness of developing systems, can be provided through the emergence of a lower-level comma cloud on the cold-air side of a baroclinic cirrus deck. Also, it may be a sign of early development of a comma cloud. Oliver et al. (1964) discuss a dark streak in cirrus clouds which is caused by a change in height of cloud tops across an area of converging jet streams. At least one area in the presented case could not be explained by sun angles and was concluded to have been a cloud break or slot. Weldon (1979) discusses the emergence of a lower-level comma cloud. This break provides one additional case of a well-defined southern border as seen along edge E in Fig. 9 This is a dual jet case and Weldon indicates that the channeled wind maximum between the two jet streams will often advance across the comma tail at point B and cause a break in the frontal weather. This advance leaves two separate cirrus patterns; Weldon considers the lower-level comma emergence and dual cirrus modification to be an indication of extensive deepening beyond that observed in normal cyclones.

5. Polar Lows

Reed (1979) and Mullen (1979) discuss the theory of polar low formations. Mullen defines these cyclones as cold air-mass cyclones which are found to be associated with deep baroclinity throughout the troposphere. They are located on the low pressure

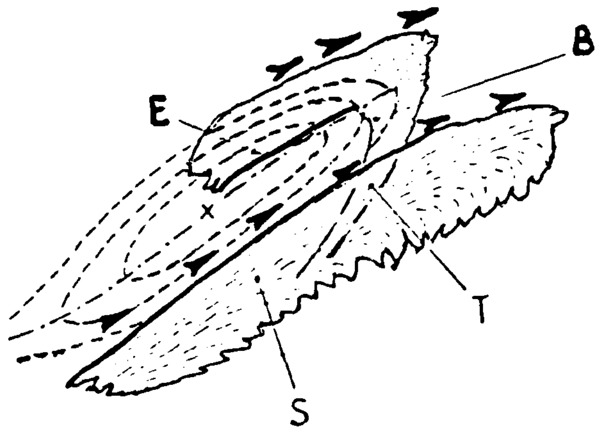

Figure 9. Advance of a Channeled Wind Maximum Between Jet Streams. (This Often Causes a Break at B and Dual Cloud Signature.) (from Weldon, 1979)

side of well-developed jet streams in regions of strong cyclonic wind shear. Mullen concludes the lower troposphere to be conditionally unstable and strongly heated by the warmer ocean water below during the early stages of development. Reed (1979) reports that satellite photographs reveal the small cyclones to be characterized, in the mature stages, by a comma-shaped pattern. Bottger et al. (1975) also point to a relatively small cyclone with a diameter of less than 1000 km.

III. DATA

The dates and locations of "bomb" occurrences were selected from a listing provided by an extended study of the subject by Sanders and Gyakum (1980) for the 1979-80 season. This listing and supplementary occurrences for the period after the 1980 paper were kindly provided by Robert W. Fett, Naval Environmental Predictions Research Facility (NEPRF), Monterey, California.

Because of a need to set geographical limits for the study and restrictions of available satellite imagery and meteorological data, the boundaries of the study extend from the east coast of the United States eastward to 40°W. The northern boundary was selected at 50°N, as suggested by decreasing frequency of occurrence in the Sanders and Gyakum (1980) study. The southern boundary was considered to be the equator, but for all practical purposes was 20°N. Within these boundaries 37 occurrences of explosive cyclogenesis were found during the period from September 1978 until May 1980. Of the original 37 storms, 23 had sufficient data and satellite imagery for analysis. See Table I for a listing of storm events on which this study was based.

Initial procedures included the timeplots of individual storm tracks and the graphical display of pressure patterns versus time for each storm (Table II). This information was taken from National Meteorological Center final surface analyses which were available in the archives of the Department of Meteorology, Naval Postgraduate School, Monterey, California. To conclude the

TABLE I

Listing of Studied Storms and Location of Attainment of Lowest Pressure (from Sanders and Gyakum (1980) and Fett (1981))

NUMBER	DATE	POSITION
1	19 JAN 1979	41N 59W
2	28 JAN 1979	32N 80W
3	01 FEB 1979	35N 70W
4	10 FEB 1979	35N 70W
5	14 FEB 1979	40N 54W
6	19 FEB 1979	31N 78W
7	12 MAR 1979	46N 46W
8	01 NOV 1979	46N 46W
9	05 JAN 1980	33N 78W
10	20 JAN 1980	43N 60W
11	24 JAN 1980	45N 60W
12	30 JAN 1980	35N 63W
13	01 FEB 1980	35N 65W
14	05 FEB 1980	33N 62W
15	07 FEB 1980	36N 74W
16	11 FEB 1980	41N 61W
17	13 FEB 1980	42N 59W
18	22 FEB 1980	50N 49W
19	26 FEB 1980	37N 70W
20	01 MAR 1980	48N 55W
21	03 MAR 1980	34N 74W
22	12 MAR 1980	47N 65W
23	15 MAR 1980	45N 68W

TABLE II

Explosive Pressure-Fall Statistics

STORM NUMBER	INITIAL PRESSURE (mb)	LOWEST PRESSURE (mb)	PRESSURE AT FALL START (mb)	PRESSURE AT FALL FINISH (mb)	HOURS OF FALL (h)	RATE OF FALL (mb/h)
1	1008	972	1008	986	12	1.83
2	1006	960	1002	962	36	1.11
3	1012	949	1008	966	30	1.40
			964	949	12	1.25
4	1017	940	1004	940	30	2.13
5	1012	982	1004	984	12	1.66
6	1019	978	1012	996	12	1.33
			996	980	12	1.33
7	1008	950	1008	950	36	1.61
8	1006	990	1002	990	12	1.00
9	1009	980	1009	996	12	1.08
10	1014	963	1012	992	18	1.11
11	995	938	989	958	24	1.29
			956	938	12	1.50
12	1019	965	1010	994	12	1.33
			995	965	24	1.25
13	1015	972	1016	1000	12	1.33
			992	972	18	1.11
14	1013	964	999	981	18	1.00
			980	964	12	1.33
15	1016	970	1012	982	24	1.25
16	1008	956	1008	956	48	1.08
17	1006	968	994	968	24	1.08
18	1007	956	997	984	12	1.08
			980	956	24	1.00
19	1013	966	1003	984	18	1.05
20	1002	956	1001	956	30	1.50
21	1009	972	997	972	12	2.08
22	1009	964	1009	964	36	1.25
23	1001	972	993	972	18	1.16

analysis packages for each storm, satellite imagery (both infrared and visual imagery of GOES East and GOES West) and upper-air NMC facsimile analyses (200, 300 and 500 mb) were also compiled.

IV. ANALYSIS

During the analysis phase the available satellite imagery and meteorological charts were studied for a period of seven days for each individual storm. The seven days were divided into two periods of five days up to and including attainment of lowest pressure, and two days after attainment of lowest pressure. Originally, the period up to attainment of lowest pressure was studied for three days. The period was extended to five days to attempt evaluation of a long range pattern correlation. For the purpose of this study infrared imagery were found to best depict the upper-level cloud patterns. Infrared imagery were routinely available in three-hour increments and the intermediate coverage provided by GOES West and visual imagery was utilized as an interim supplement.

The procedure for analysis consisted of viewing the sequential imagery and denoting observed cloud patterns (on the pressure pattern graphs) by time of occurrence. Subsequent analyses of each data set were compiled without reference to previous analyses in order to evaluate the consistency of detectability of the chosen cloud patterns.

The overall analysis scheme provided: (1) a plotted pressure curve for each storm, (2) the velocity of associated jet maximums at 200 and 300 mb, (3) plots of individual storm tracks and (4) sequential listings of cloud pattern occurrences. Utilizing the outputs from each analysis, statistics were then developed for pressure patterns, signature occurrences, jet maximums and the areal coverage of individual patterns.

V. FINDINGS

The original procedures designed for this study required repetitive analysis of numerous satellite photographs. During the analyses each individual storm seemed to develop in an evolution of its own. It soon became evident that the formulation of a classical developmental model, utilizing the designated cloud signatures, was an unrealistic goal. Also strongly apparent was the practice required to recognize the basic patterns in a large-scale satellite photograph. All of the chosen signatures and some additional ones were found at some point during the development of the majority of cases. As in the development of individual storms, the development sequence of designated patterns varied as did the individual characteristics of these patterns.

Uccellini et al. (1981) provided insight to the complexity of one individual storm. In their analysis of the President's Day Cyclone, they concluded: "The interactions of tropical-extratropical regimes associated with the subtropical and polar jets, the upper-lower tropospheric coupling associated with the development of the low-level jet, the terrain modification due to the damming effect, and the complex baroclinic process associated with the initiation of the cyclone by the second wave and polar jet streak all combined to produce the rapid cyclogenesis that marked the President's Day Cyclone."

The sequential development of individual storms is provided in Table III. A careful study provides a pattern which closely

TABLE III

Chronological Order of Storm Signature Development

STORM	BAROCLINIC LEAF	ENHANCED CUMULUS	CLEAR JET AREA	HEAD CLOUD	COMMA CLOUD	TIP AND CLOUD SLOT
1		1	2	3	5	4
2	3	1	2	4	6	5
3	1		2		4	3
4	2	3	1	4	6	5
5		3	1	4	2	
6	1	3	4	2	6	5
7	2		1	3	5	4
8		2	3	1	5	4
9	1	2	3	4	6	5
10		1	2	3	4	
11	4	1	2	3	[illegible]	
12	6	1	3	2	4	5
13	2	1	3			
14			1	2	4	3
15		2	3	1	5	4
16	1	2	3	4	6	5
17			1	2	4	3
13		4	5	1	3	2
19	3	2	1	4	6	5
20	2	4	1	3	6	5
21	2	1	3	4	6	5
22	2	3	1		5	4
23	1	3	4	2	6	5

follows Weldon's baroclinic leaf development. If the head cloud is considered to be the end result of the convex-dominated leaf development, the process becomes a variation of the baroclinic leaf concept. The cirrus models which were formulated by Kadlec would seem to be related to the baroclinic zone cirrus discussed by Weldon (1979). The description of the baroclinic zone cirrus is adequately covered in Weldon's narrative. The gross physical dimensions follow closely those provided by Kadlec (1964). The positive aspects of retaining Kadlec's models are based more upon their descriptions as applied to the curvature of associated jet stream(s). The curvature of the cirrus cloud edges can be related to jet stream maxima and the long wave pattern. In the case of anticyclonic curvature they would appear to indicate the presence of the subtropical jet stream. The formation of these long bright areas of cirrus also indicate the presence of strong jet streams. Thus, even though Kadlec's patterns cannot be directly related to explosive cyclogenesis, these patterns are related to long-wave patterns which would indicate some form of cyclogenesis potential. The cases of anticyclonically-curved patterns could very well be the earliest detectable characteristic of explosive-type developments. Furthermore, the baroclinic leaf is most often seen to develop from the baroclinic zone cirrus.

The key descriptive factors of Weldon's baroclinic leaf pattern (Weldon, 1977 and 1979) is the concave to convex "S" shape and the sharp outline of the cloud area. Jager (1984) provides a case study of a baroclinic development. He finds a sharp northern edge which displays anticyclonic curvature, even though the jet stream is cyclonically curved; the formation to be comprised of highly reflective cold clouds; the leading and trailing edges somewhat less well-defined and a final change from "leaf" to "comma" configuration. As seen from the analysis of this study the southern end will usually terminate in a pointed or conical shape. During a few of the developments the concave end displays two end segments or a branch configuration. This branch moves progressively up the poleward edge and appears to be the indication of a short wave trough and its associated jet maximum.

The convex end is normally curved in an anticyclonic manner which resembles an arch. The case described by Jager (1984) would appear to be a case where this segment was dominant. In the cases studied there was a high percentage correlation of baroclinic leafs to head cloud formations. The common element of convex dominant baroclinic leafs, head clouds and Kadlec's Type B pattern is the anticyclonic curvature of the northern edge. Kadlec (1964), Weldon (1979), Fett (1981), Reiter and Whitney (1969) and others associate dual jets, anticyclonic curved jet streams, upper-level baroclinity and upper-level divergence with this anticyclonic curvature.

The "comma cloud" formation is undoubtedly associated with cyclogenesis. The association with explosive cyclogenesis is slightly more difficult to define. The comma cloud appears to evolve and deepen much in the manner of other less intense storms. Its major distinguishing feature is the relative compactness of the observed development. As an additional investigation during this study, the plotted pressure curve for each storm was utilized to study the imagery versus pressure correlations which were developed by Junker and Haller (1980). The basic patterns would appear to apply to explosive cyclogenesis. They can be utilized to detect explosive cyclogenesis in its mature stages after the surface low has developed.

The "cloud head" formation follows the description of Bottger et al. (1975), and Fett and Bohan (1981). Additional descriptions derived from this study are the cloud heads' resemblance to a semicircle and its high percentage of evolutions which involve alterations of an existing baroclinic leaf. The point at which a convex dominant baroclinic leaf is designated as a head cloud is debatable. The correlation with plotted pressures and points of change in deepening rates seems to indicate a relationship with the ratio of pattern length to pattern width. Repeated analyses have formulated a width to length factor of greater or equal to one half. The physical dimensions of studied head clouds varied over a wide range. These patterns can be of lengths from 1,500 n mi to as small as 300 n mi. The average size for head clouds was 720 n mi long and 360 n mi in width.

The "cloud tip and slot" are related to the first visible indications of vortex development and do not appear to be definite indicators of only explosive storms. The tip and slot are a combined indicator since the slot is the open area between the cloud mass and the emerging comma tip. This indicator was discernible in 19 of the 23 studied storms. The relative smallness of the tip often causes it to be difficult to detect but its parallel appearance with the cloud slot provides a fairly strong indicator of the early stages of vortex formation.

The "enhanced cumulus wedge" was also found in 19 of the 23 studied storms. This pattern provided the first identifiable indicator in six of these storms. The pattern appears to be tied to extremely deep convection and may be one of the strongest indicators of explosive cyclogenesis.

The sequential development of individual storms was provided in Table III. A careful study provides a pattern which closely follows Weldon's baroclinic leaf development. If the head cloud is considered to be the end result of the convex-dominated leaf development, the process becomes a variation of the baroclinic leaf concept.

Two cases are presented to illustrate these patterns. Storm number seven, 12 March 1979, shows a straightforward development from baroclinic cirrus deck to baroclinic leaf to head cloud formation. The early appearance of a baroclinic cirrus deck (Fig. 10) lacks the characteristic shape of the leaf "S" although the northern edge is extremely well defined. This image displays many of the features of Kadlec's Type "B" and appears to represent a superposition of two jet streams. The southern jet can be easily discerned as it crosses the Baja area and over the western tip of Texas. Most likely there is a polar front jet associated with the major trough which is bringing clear skies

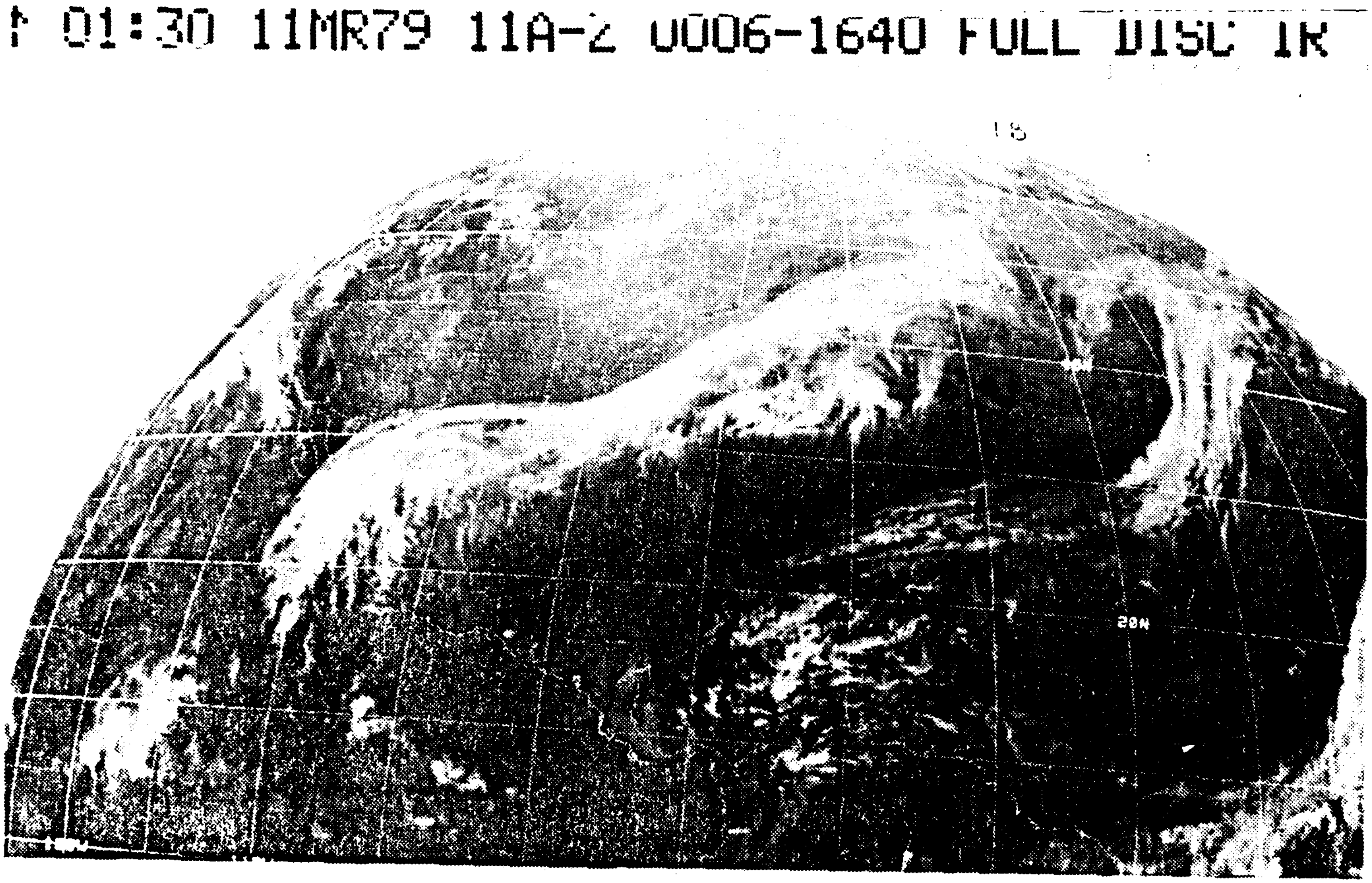

Figure 10. - GOES Imagery 0130 GMT 11 March 1979

to the majority of the continental United States. The characteristic "S" shape of the baroclinic leaf is evident along the sharp northern cloud border in Fig. 11. Three hours later (Fig. 12) the amplitude of the convex end increases significantly and a clear jet area extends toward the northeast as the jet exits the North Carolina coastline. Whether the area is a cloud shadow or an indication of dry air due to subsidence between two closely-spaced jet streams is strictly a matter of judgement. The cirrus pattern shown in Fig. 13 has reached an amplitude sufficient for head cloud designation. The pressure at this time is 993 mbs. According to Junker and Haller (1980) this pressure is associated with a pronounced cyclonic bowing of the frontal cloud band. The further evolution continues along the head cloud development through times represented by Figs. 14 and 15. In the period from 0730 until 2230, 11 March, the surface pressure falls from 1006 mb to 984 mb, with a steady drop of 1.61 mb/h. This fall rate continues for a period of 36 hours as the pressure fell to a low recording of 950 mb. The storm was the only one studied which maintained a steady explosive pressure fall for the entire deepening cycle. The steady explosive pressure fall and extended head cloud development make this storm the most intriguing of those studied. The correlation to Kadlec's Type B Model and the extension of the early development process may be integral parts of the observed pressure fall anomaly.

As evidence of the variability in individual storm development, the storm of 10 February 1979 is described, utilizing Figs. 16 through 21. This storm includes the clear

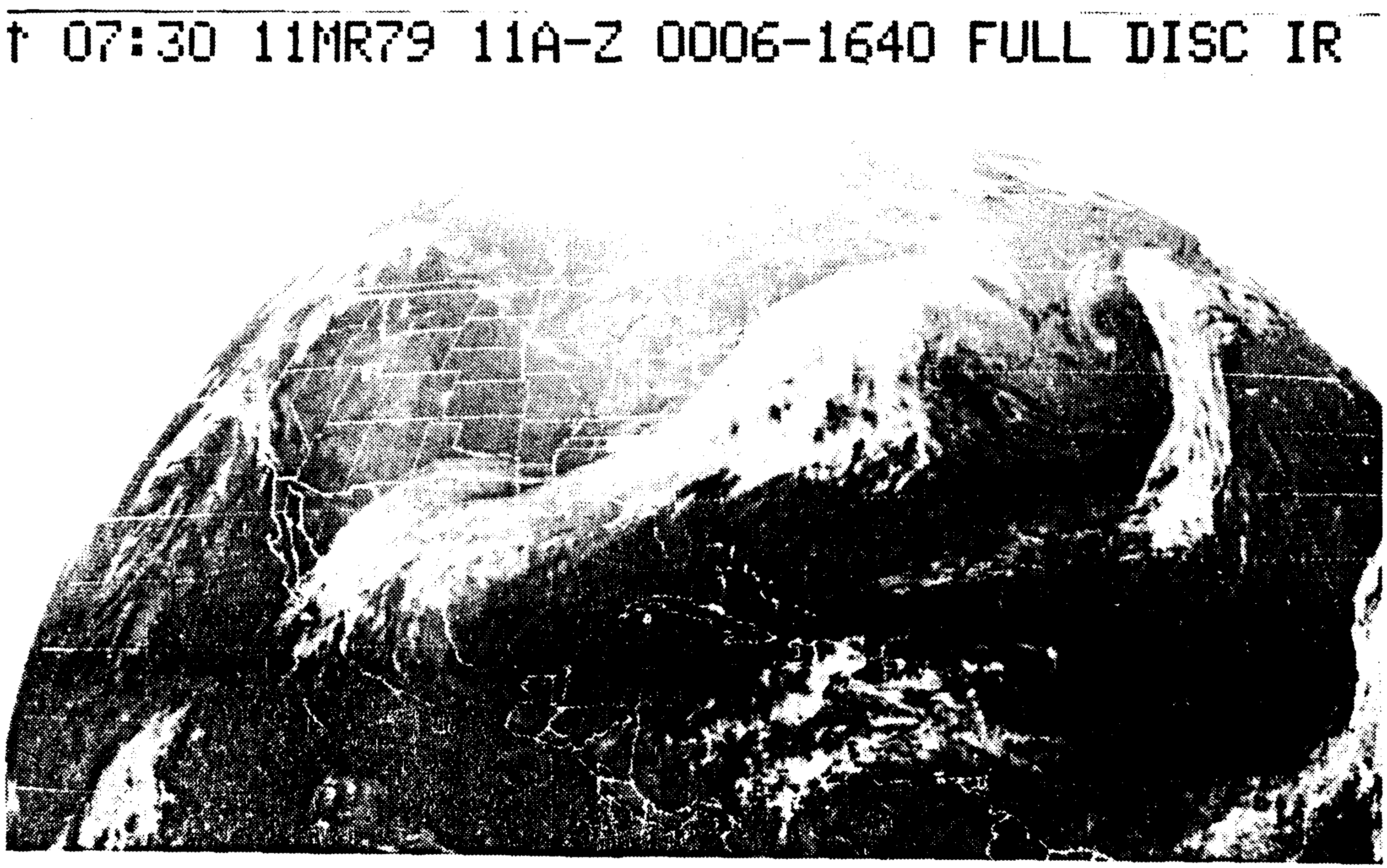

Figure 11. GOES Imagery 0730 GMT 11 March 1979

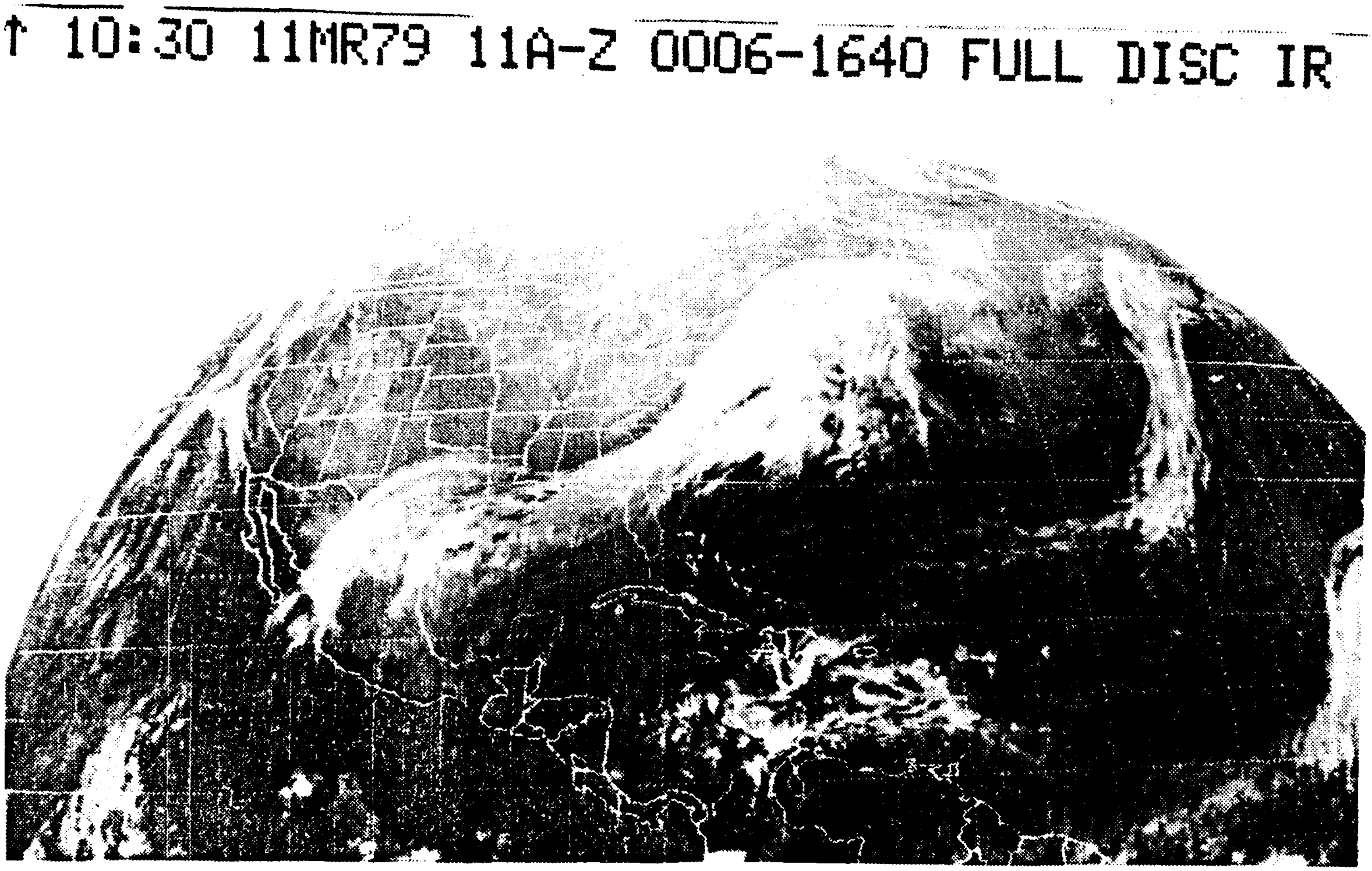

Figure 12. GOES Imagery 1030 GMT 11 March 1979

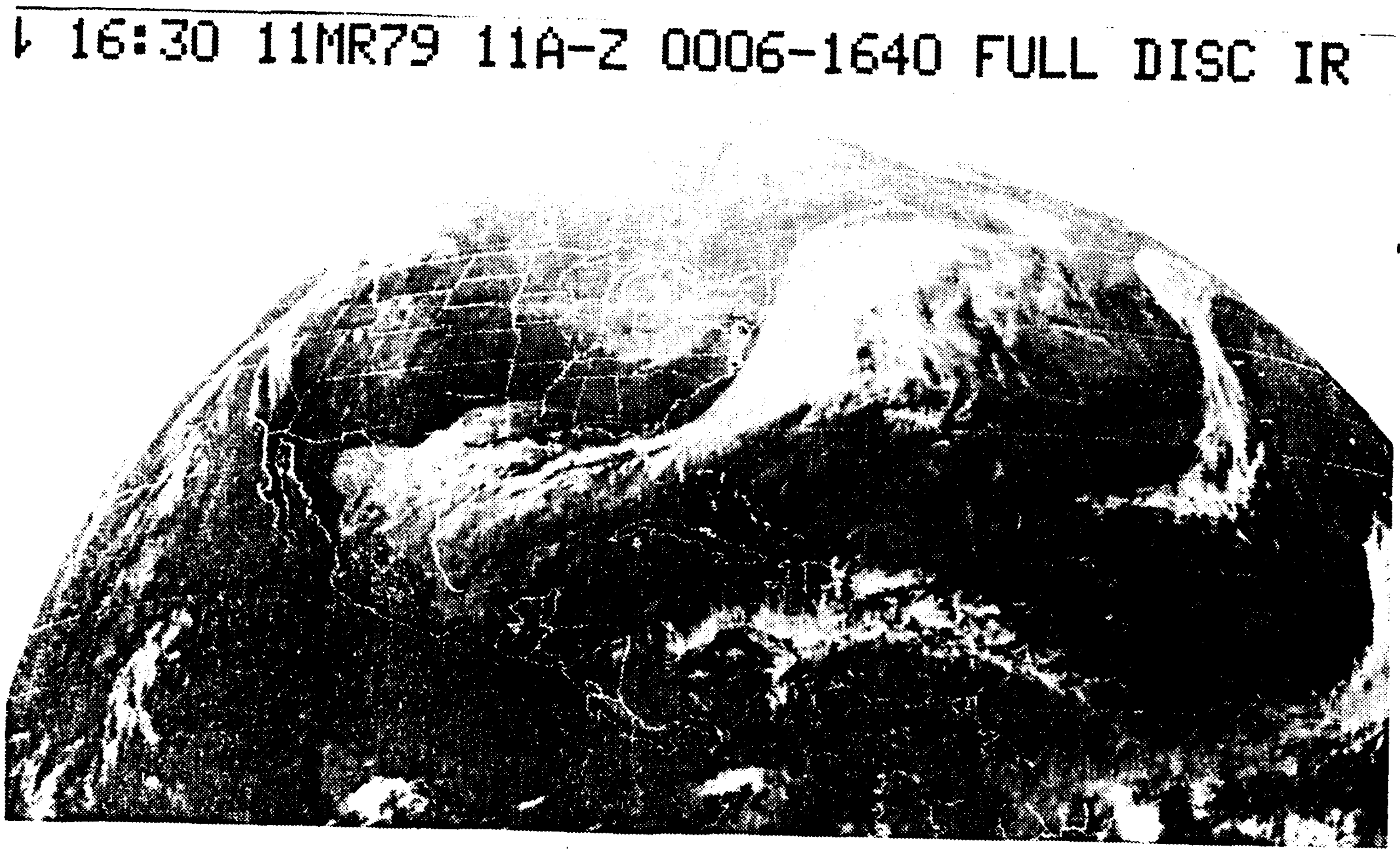

Figure 13. GOES Imagery 1630 GMT 11 March 1979

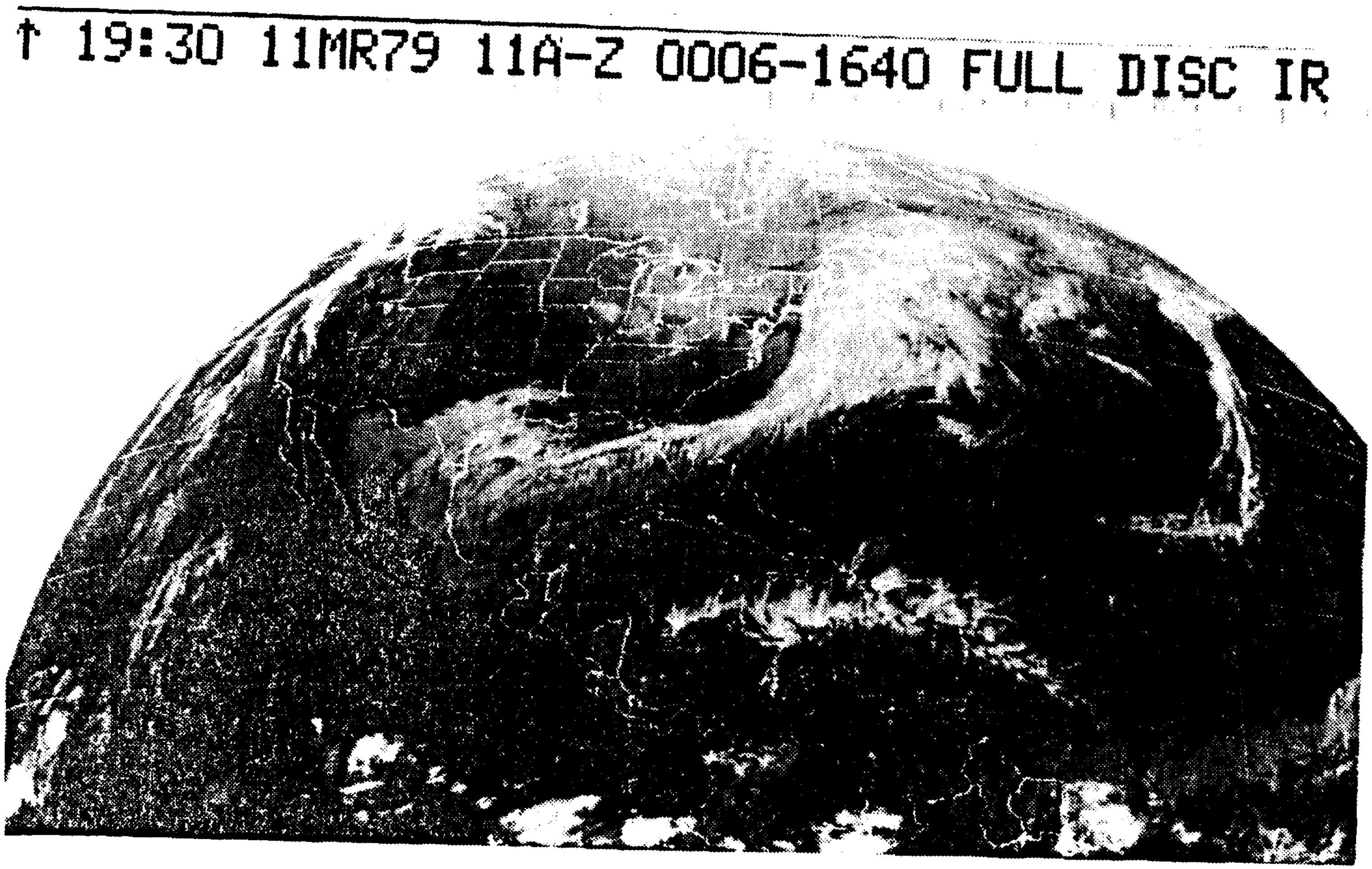

Figure 14. GOES Imagery 1930 GMT 11 March 1979

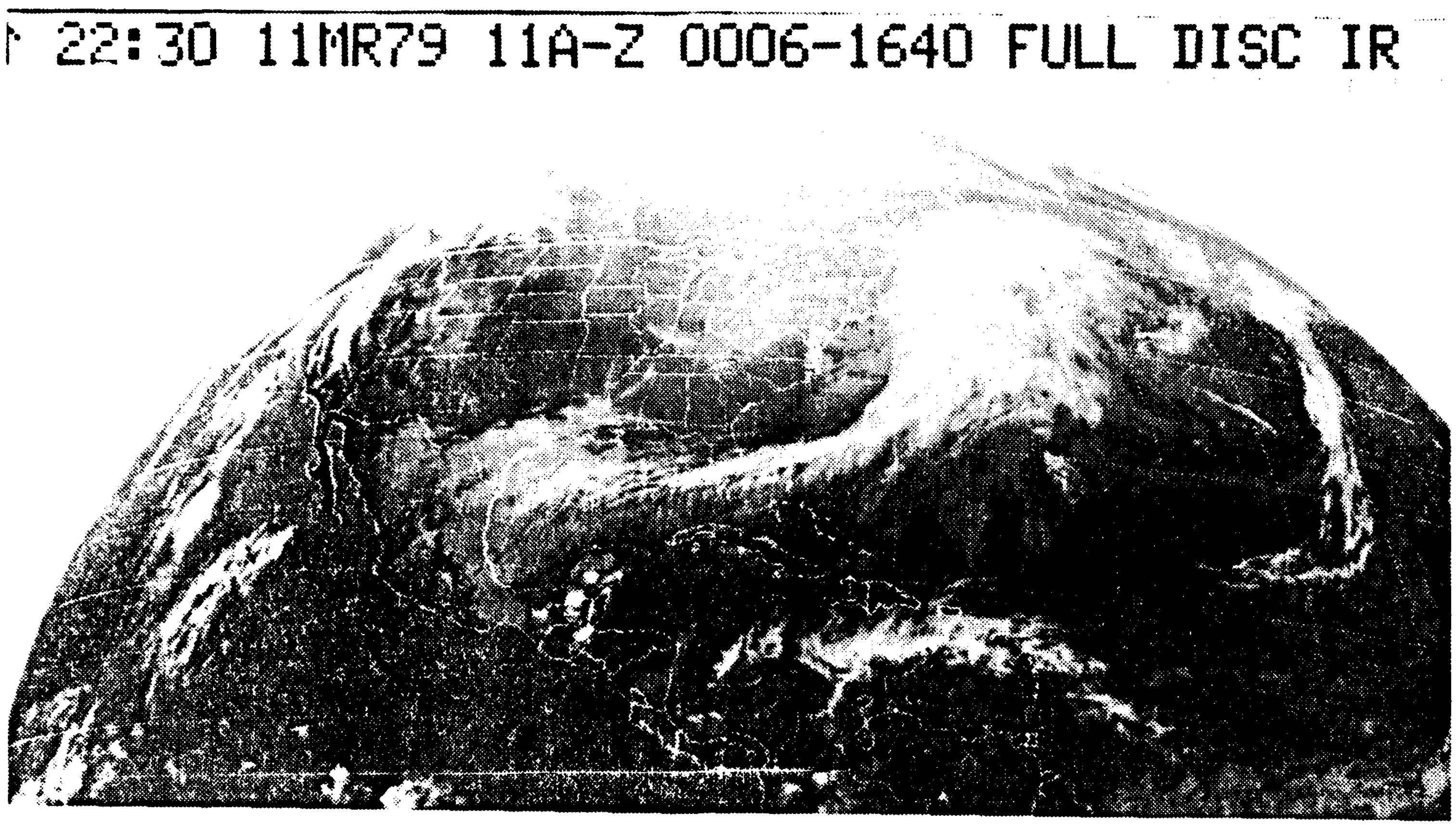

Figure 15. GOES Imagery 2230 GMT 11 March 1979

jet area and displays intense squall line development. In Fig. 16, yet another configuration of the baroclinic leaf is depicted in the cloud mass to the south of the clear jet area. This leaf has an inverse "S" shape on its southern boundary. The rear edge of the "S" shape is found by a bright rope-like cloud feature. The northern cloud mass has a convex dominant shape. A sharper definition of the southern leaf pattern and the development of a convective wedge at its southernmost end is displayed in Fig. 17. The northern cloud mass shows increased definition as it approaches a semicircular shape (995 mb). The semicircular head cloud pattern is shown in Fig. 18. The southern cloud mass now becomes elongated and loses the "S" configuration of its southern edge.

In Fig. 19 the two cirrus patterns begin to merge across the clear jet area (992 mb). By 1330 GMT 10 Feb (Fig. 20) the northern area displays an emerging comma tip in the vicinity of 40°N and 55°W. The associated pressure pattern begins to show an explosive fall rate at 1200 GMT on the 10th and the pressure is presently 984 mb. The southern cloud mass has now most of its definition, but the lower gray-shaded clouds of a frontal band are now visible underneath the cirrus remains. The merger across the clear jet area is now nearly complete as the system reaches comma cloud status.

In the last image (Fig. 21) the comma pattern is well defined. This storm develops with two pressure fall periods which exceeded 2 mb/h. The overall pressure fall starts at 1004 mb and maintains a rate of 2.13 mb/h for over 30 hours. The

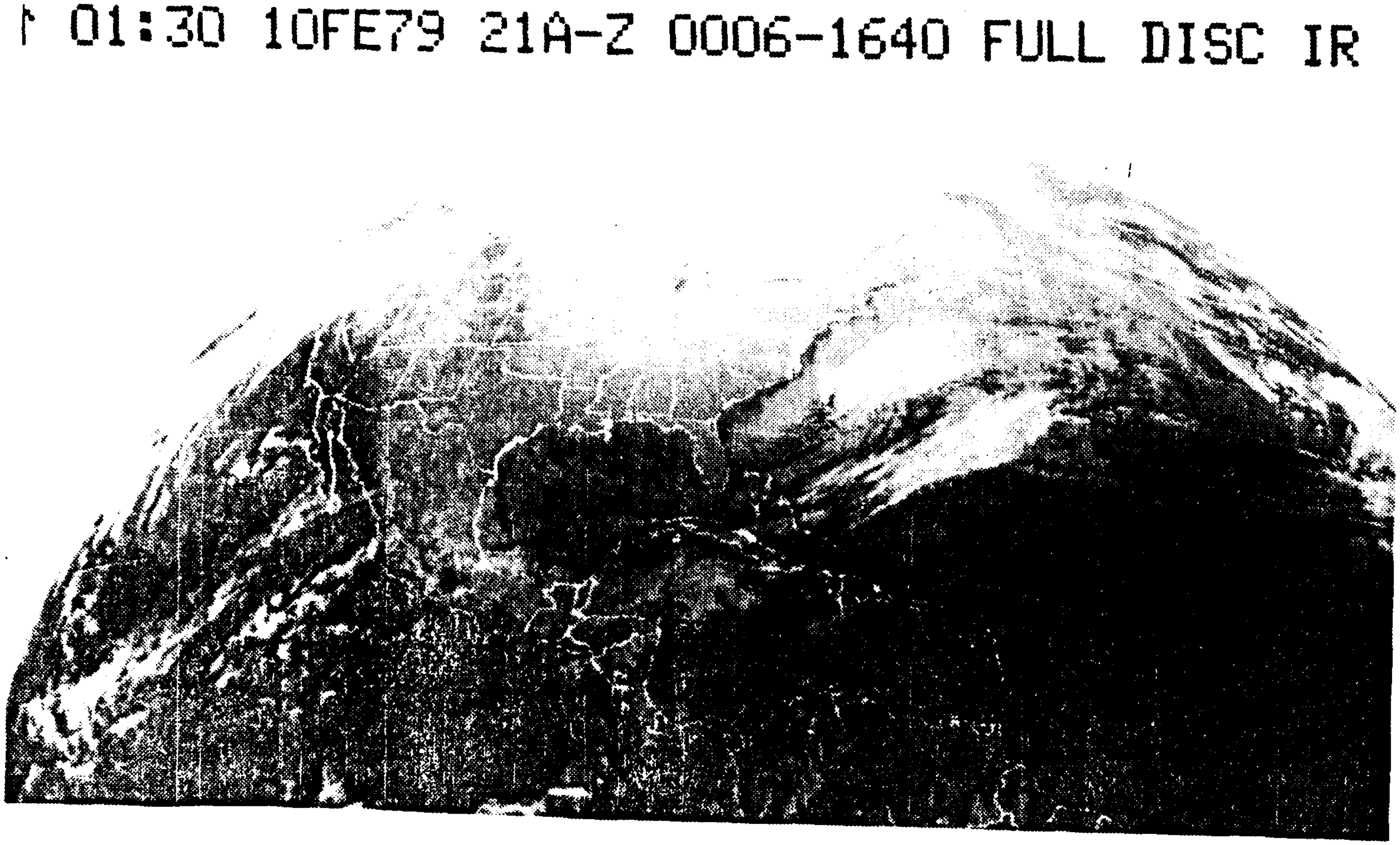

Figure 16. GOES Imagery 0130 GMT 10 February 1979

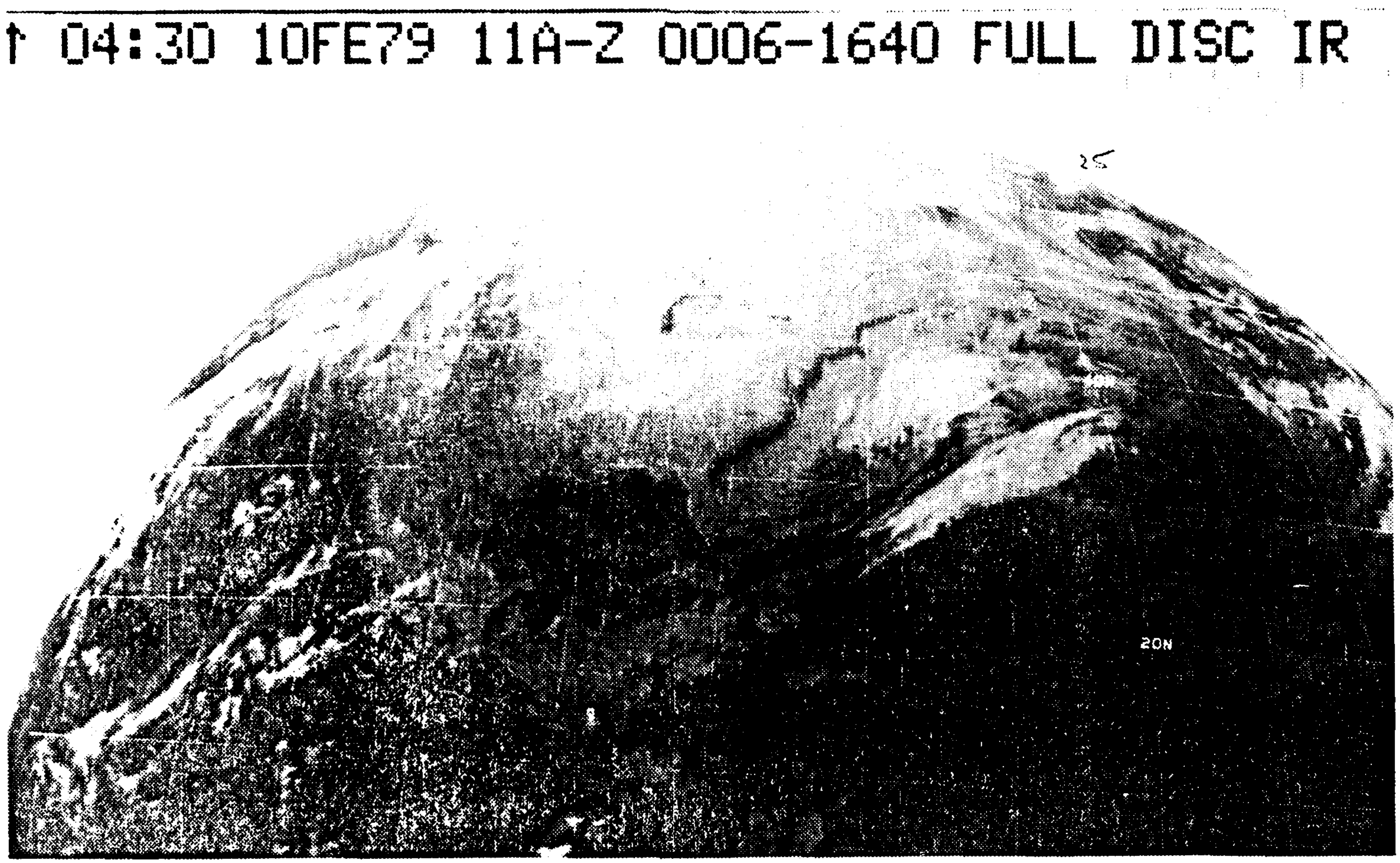

Figure 17. GOES Imagery 0430 GMT 10 February 1979

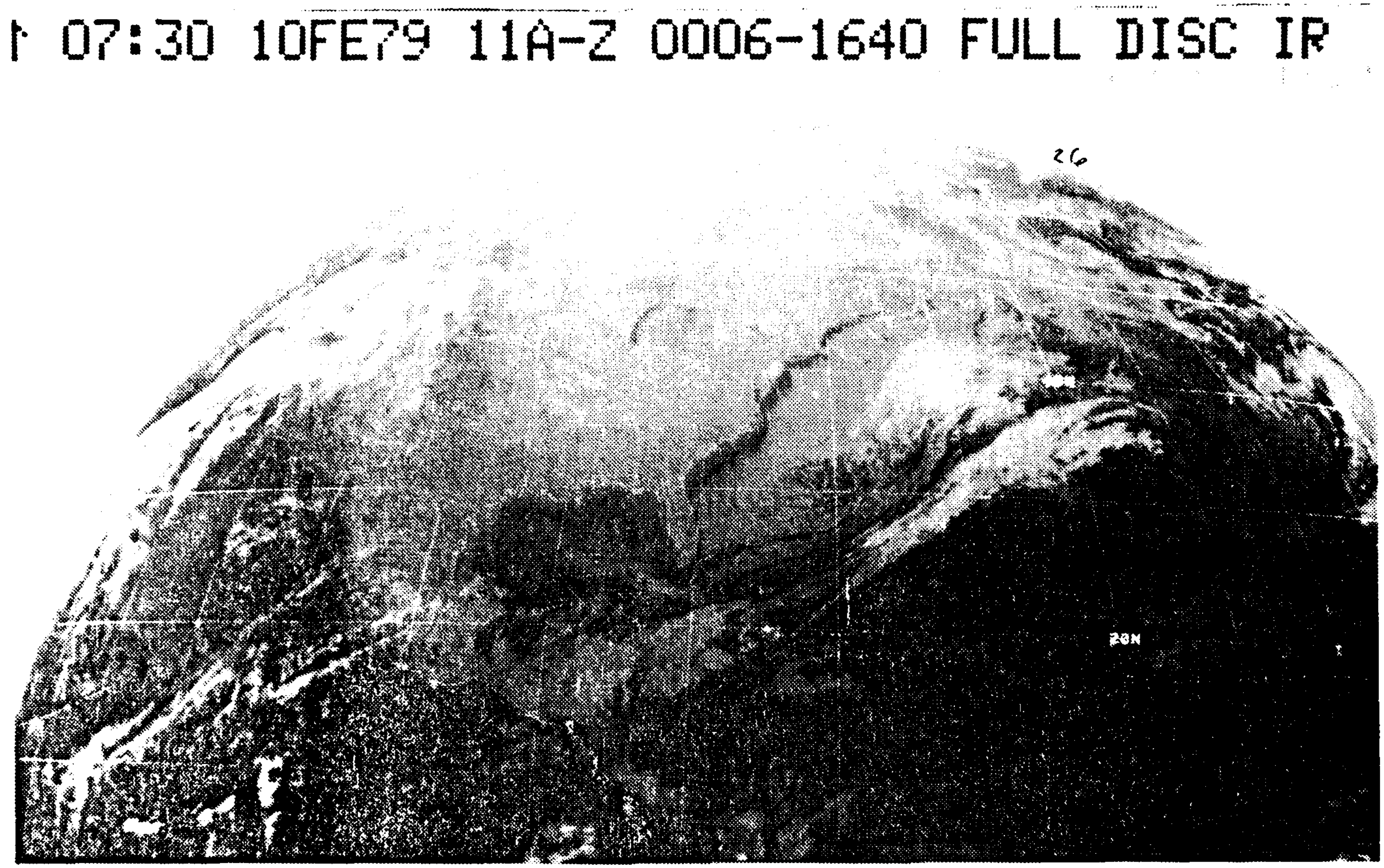

Figure 18. GOES Imagery 0730 GMT 10 February 1979

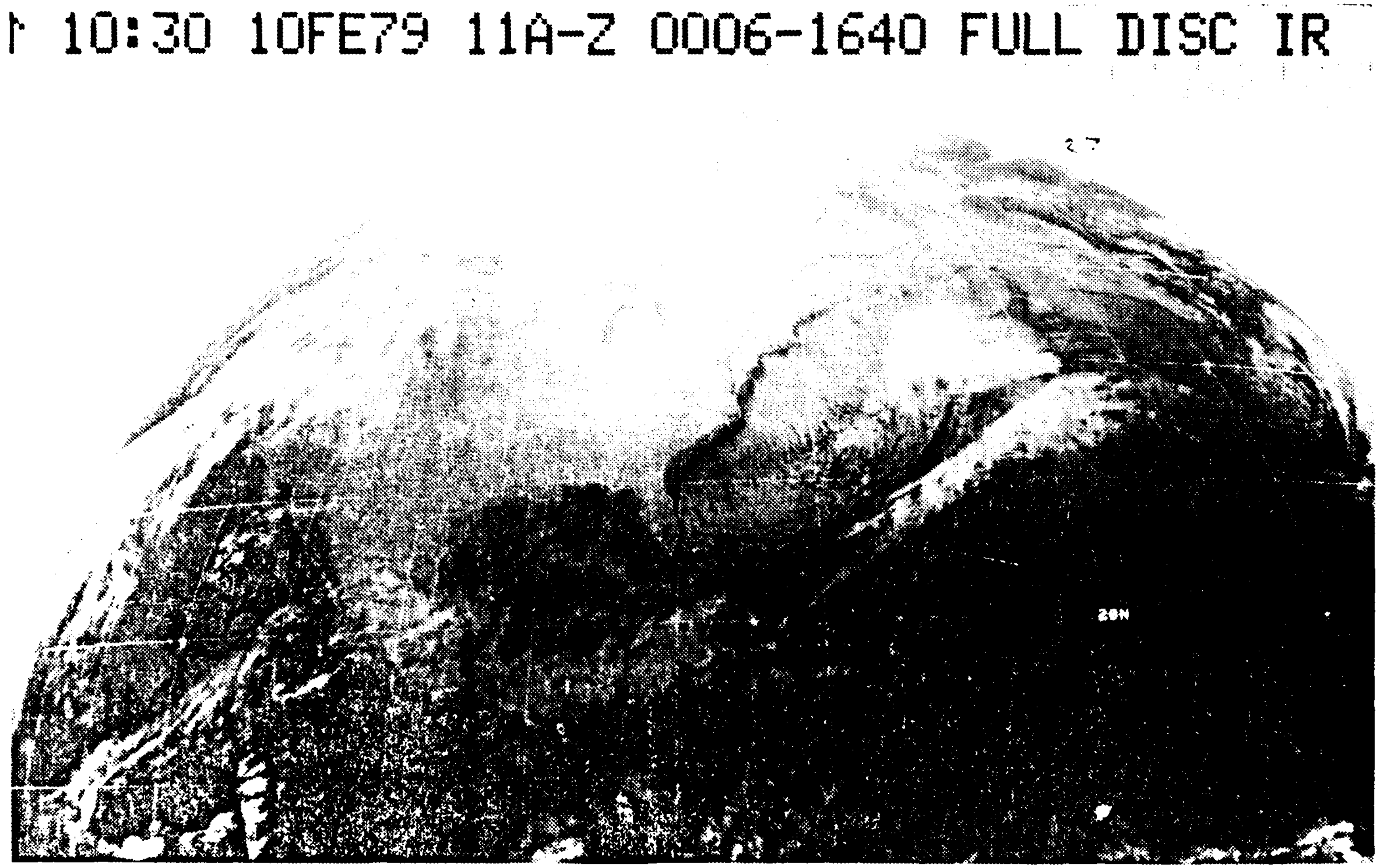

Figure 19. GOES Imagery 1030 GMT 10 February 1979

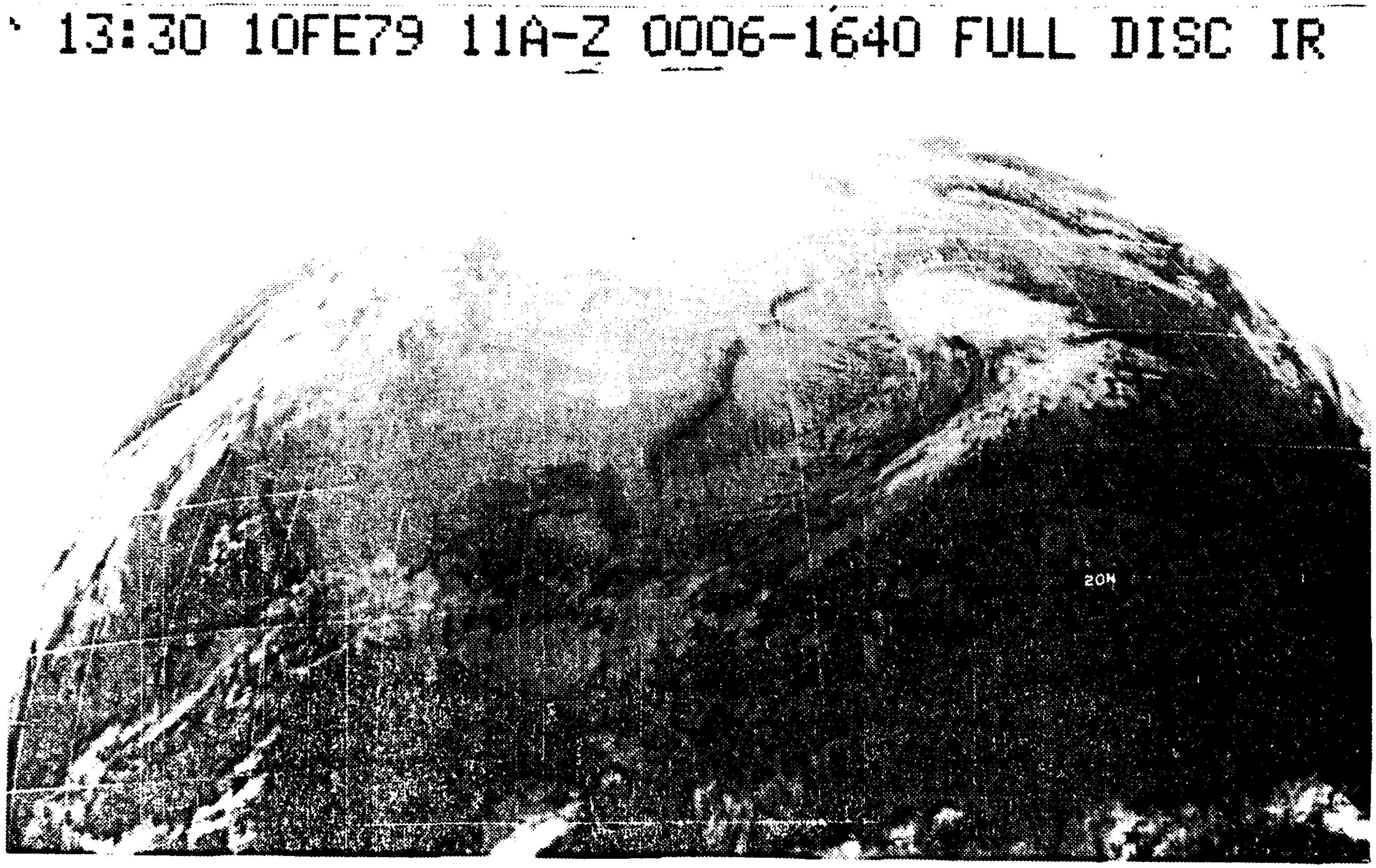

Figure 20. GOES Imagery 1330 GMT 10 February 1979

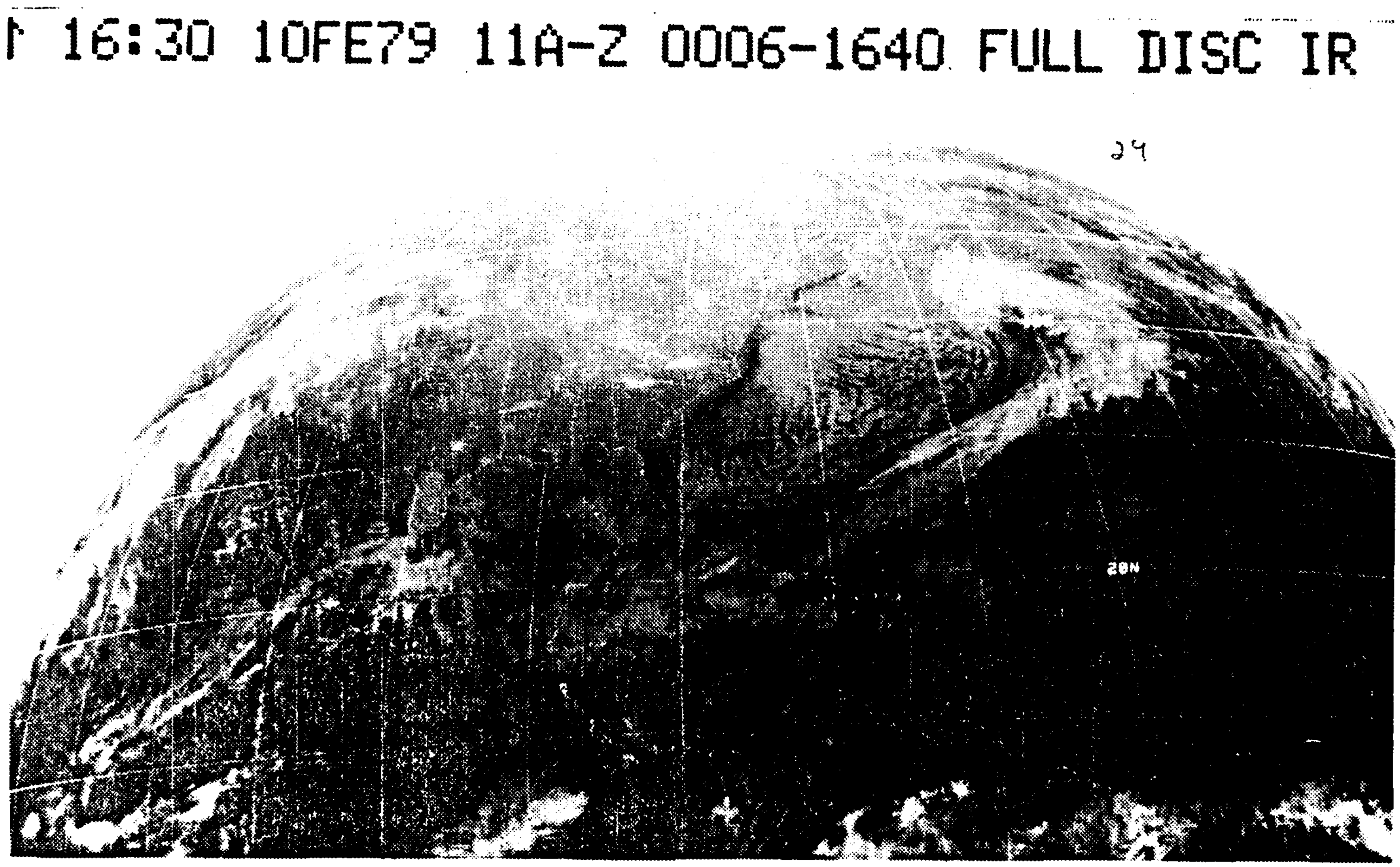

Figure 21. GOES Imagery 1630 GMT 10 February 1979

rate from cloud system merger (990 mb) to complete vortex closure (940 mb) provided a deepening rate of 2.77 mb/h.

Storm number 10 demonstrates the concept which will be called a dual cloud element storm here. Two patterns have been correlated with extended breaks in large cloud elements. These are Kadlec's "Dual Jet Split" and Weldon's special subset of the well-defined southern edge for the baroclinic leaf. In storm number 10 the main cloud areas are divided into two distinct cloud elements. The clear area which separates these cloud elements appears to be a manifestation of jet stream(s) presence. The inability to determine the exact cause(s) of these clear areas precludes designation as one of the aforementioned categories. For this reason the phenomenom is simply referred to as a clear jet area. The additional problem of dual element storms can cause cloud patterns to become highly variable during the storm's history.

The numerous variations which are possible in a dual element storm are depicted in Figs. 22 through 29 of storm number 12. The earliest detectable indication of development is the "enhanced cumulus" cloud which appears as a bright circular area in the extreme southern part of the cloud mass (Fig. 22). This area, located between 10 and 15 degrees longitude east of the southern tip of Florida, is an example of a variation to the enhanced wedge development discussed by Fett and Bohan (1981). This very bright cloud element was found during the development of all but four of the studied storms. It provided the first identifiable indicator in six of these storms. In Fig. 23 this

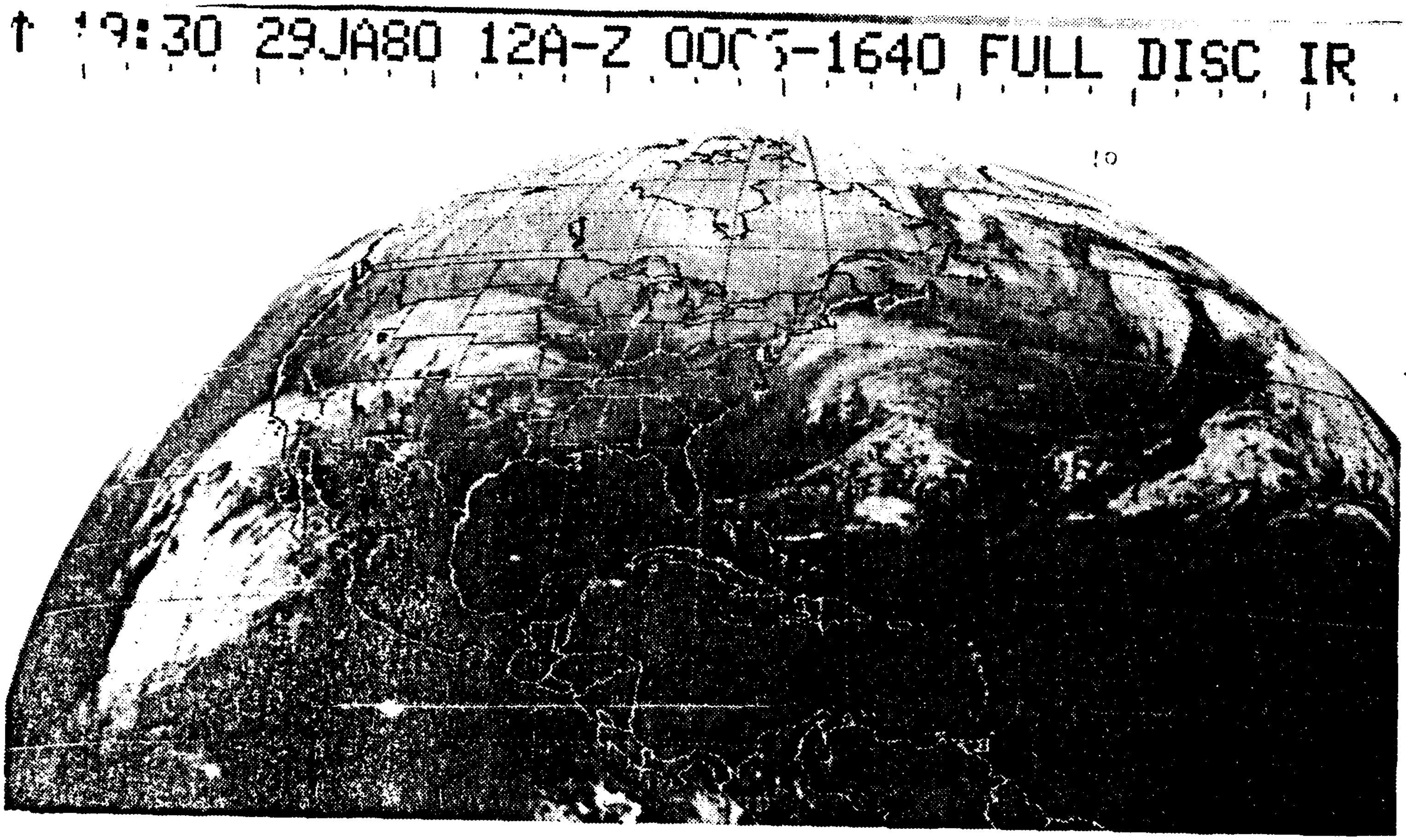

Figure 22. GOES Imagery 1930 GMT 29 January 1980

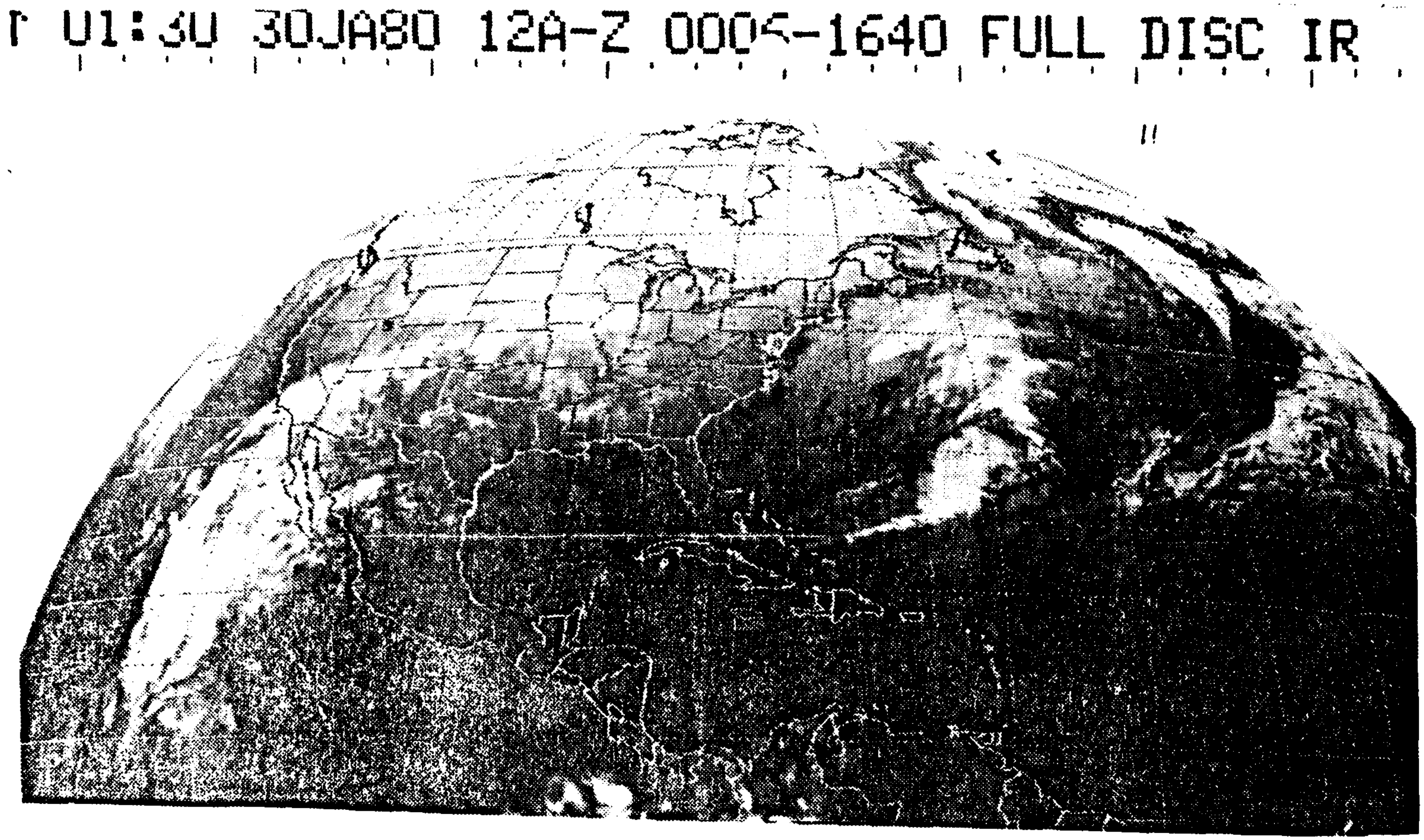

Figure 23. - GOES Imagery 0130 GMT 30 January 1980

enhanced area has developed into a distinct head cloud formation. The cloud-free area around the head of the cloud pattern separates it from the cloud areas to the north. This clear jet area was found in a majority of the studied cases and was the most consistent indicator. The clear area was usually well defined and of an equal width along its entire length. It provided a distinct separation between the northern or western boundary of the cloud element and other cloud masses. This area was usually from 300 to 500 n mi wide and was defined by very distinct cloud edges on both the storm signature and the adjacent cloud mass.

By 0730 GMT 30 Jan (Fig. 24) the southern cloud mass has begun to break down and the northern area is forming a head cloud with a western edge which is comma shaped. The southern end of this comma cloud is the traditional wedge shape of Fett's enhanced cumulus wedge. In the majority of cases where the head cloud subsequently developed into a comma shape, the comma developed in the western or northwestern edge of the head cloud. The head cloud shaped mass (Fig. 25) has expanded and the cloud slot and tip of a developing vortex now can be detected in its northwestern perimeter. The southern cloud mass begins to reform as a baroclinic leaf and the forked southern edge can be seen in the two points on its southernmost end. The characteristic clear jet area still remains as the separation between the two cloud masses.

The evolution continues (Fig. 26) as the southern cloud mass shows a wing-shaped configuration. The northern mass shows a clear vortex rotation and a cloud slot. The pressure pattern

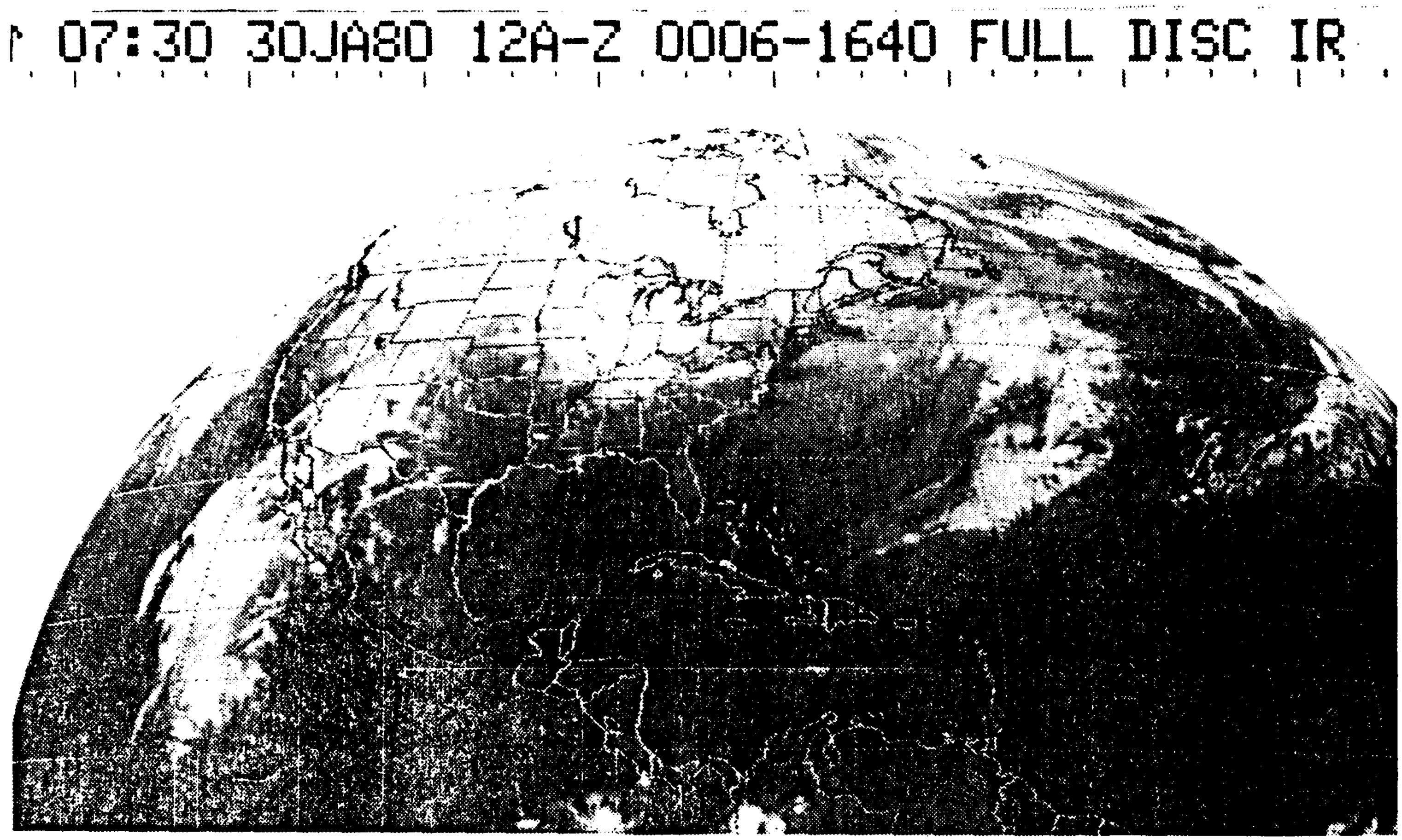

Figure 24. GOES Imagery 0730 GMT 30 January 1980

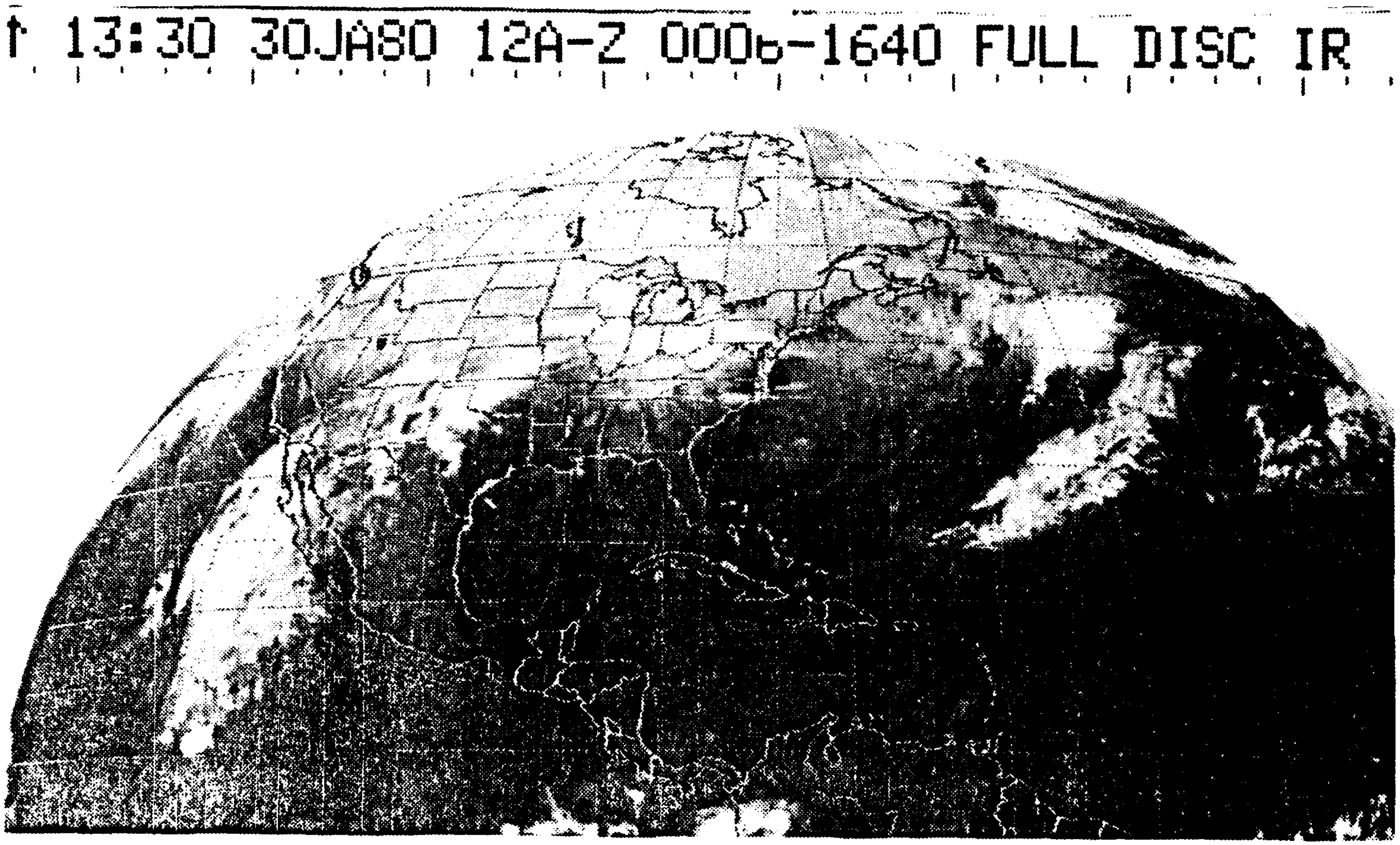

Figure 25. GOES Imagery 1330 GMT 30 January 1980

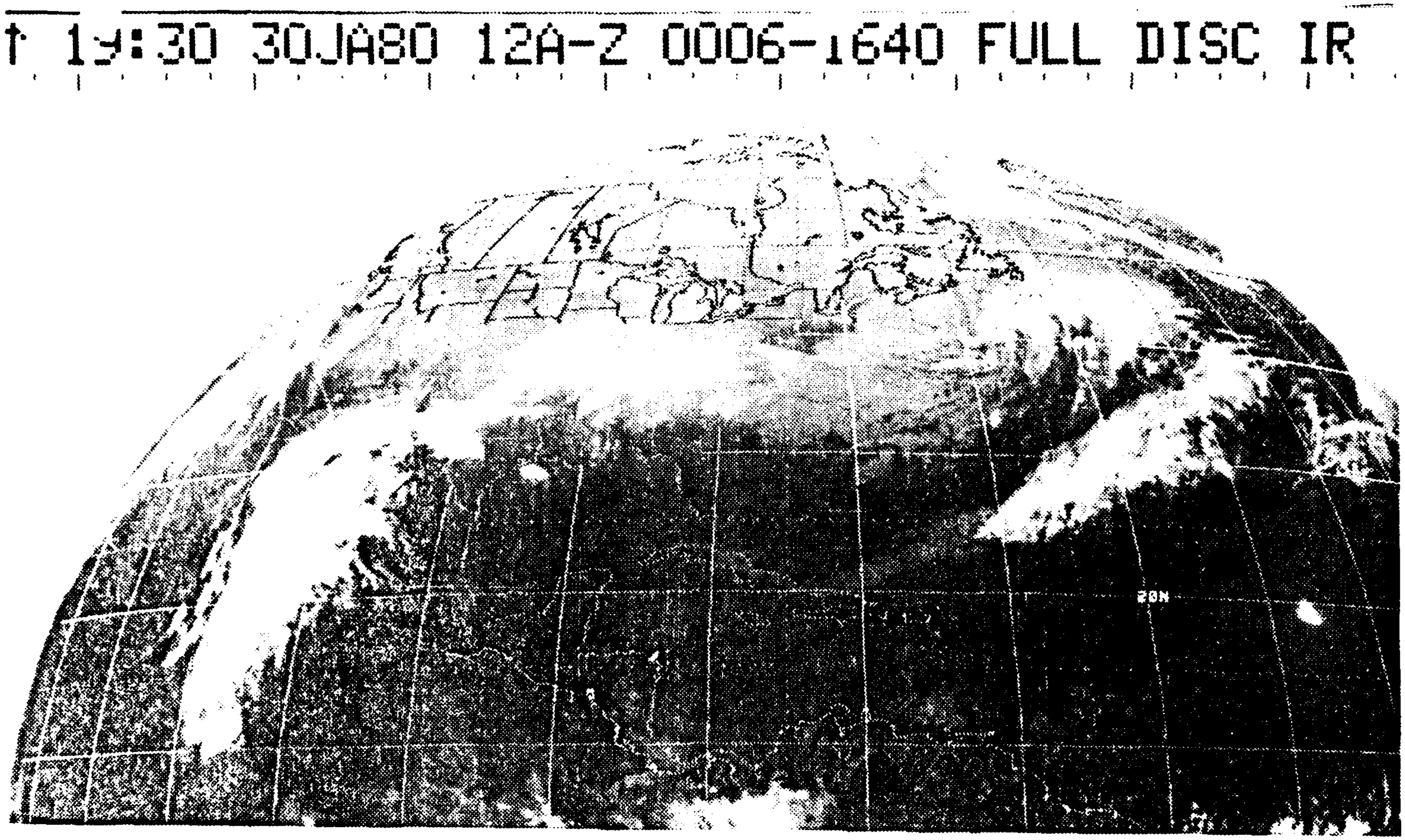

Figure 26. GOES Imagery 1930 GMT 30 January 1980

for this storm indicates the start of a second explosive pressure fall at 1800 GMT on the 30th at a pressure of 995 mb. This pressure fall continues for 24 hours and reaches a low pressure of 965 mb. The northern vortex (Fig. 27) has become better organized and would indicate a closure of approximately one-half turn. The pressure at this point is analyzed at 981 mb. This pressure is within the 980-989 mb range set by Junker and Haller (1980). The southern area is now showing an increased amplitude. A strong line of convective elements is crossing the clear jet area which separates the two cloud masses. This line of convection is possibly organized into a strong squall line and may be an indication of the "instant occlusion" process which is discussed by Reed (1979). Fett et al. (1983) discuss the rapid intensification of a depression following the movement of a jet streak around the base of an upper-level trough. They further indicate the development of a squall line in response to the dynamics associated with a polar and subtropical jet merger. They continue by pointing out that even though the baroclinic zone associated with the subtropical jet is confined to the upper troposphere beneath the jet core, a polar jet stream and its characteristic deep baroclinic zone, in close proximity to the northern border of a subtropical jet, provides the mechanism for convection to develop through a deep vertical layer.

Further development in Fig. 28 (968 mb) and Fig. 29 (965 mb) shows the continual closing of the northern vortex and the indications of still another head cloud formation in the southern cloud mass. In reviewing the imagery from Figs. 25 through 29

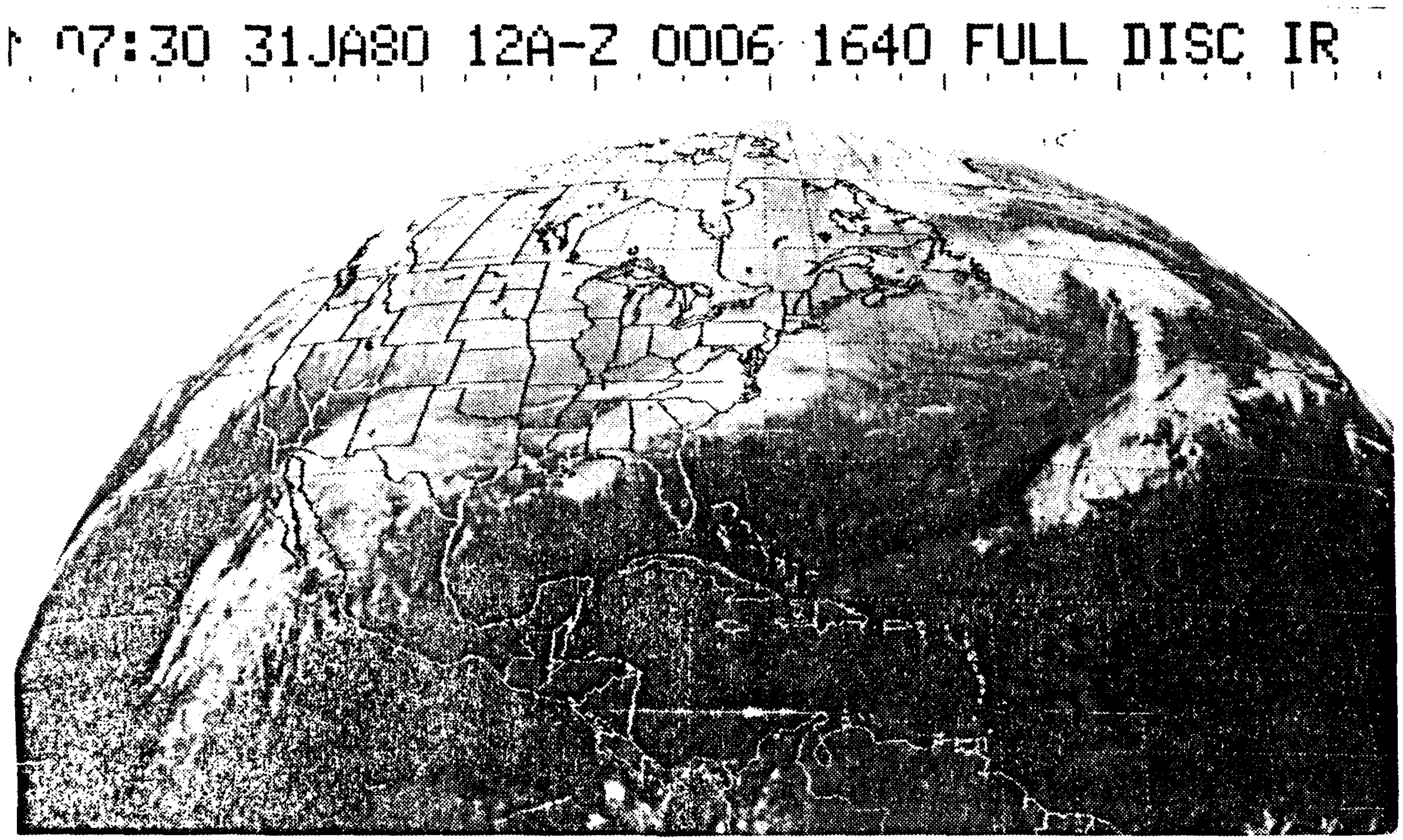

Figure 27. - GOES Imagery 0730 GMT 31 January 1980

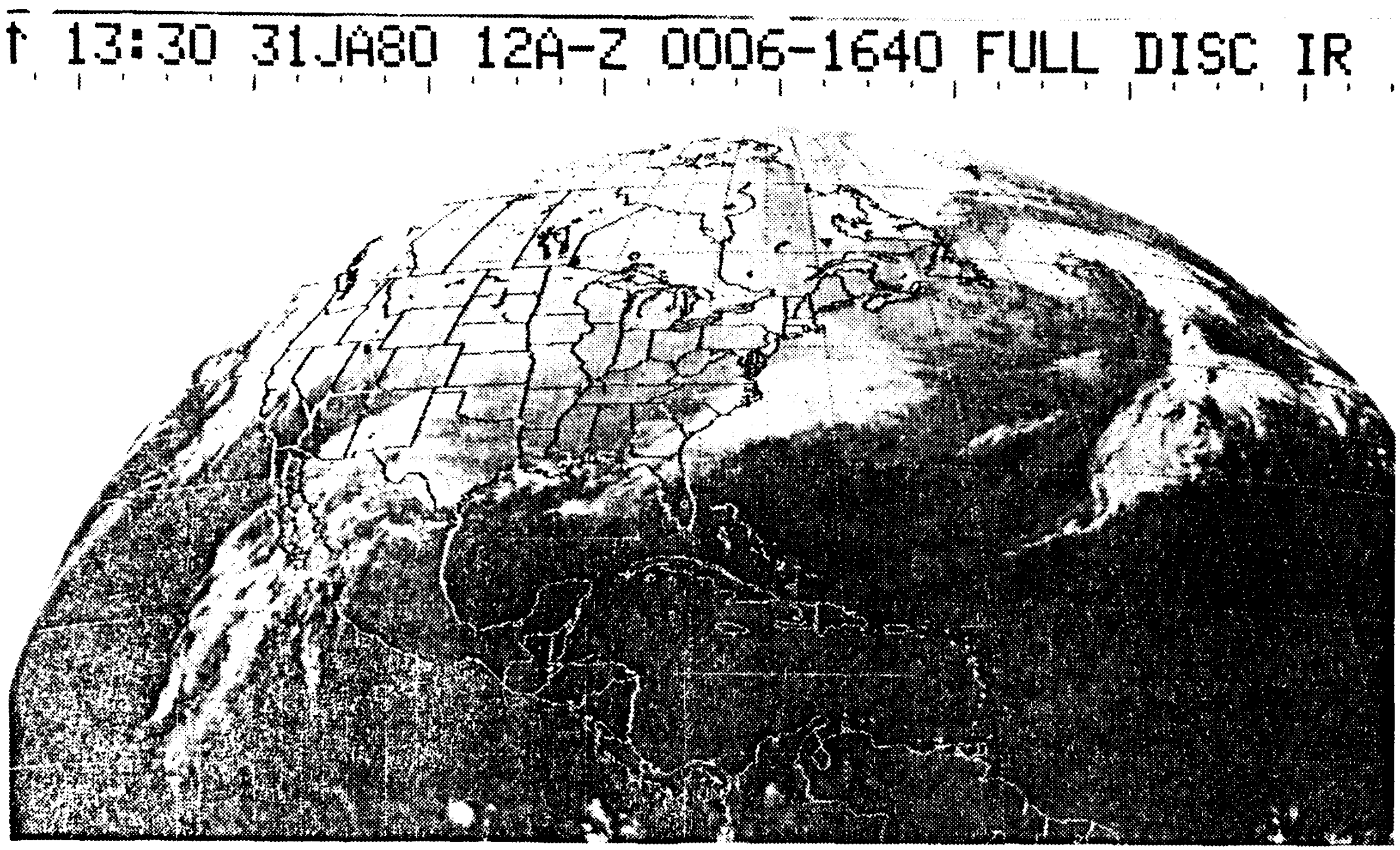

Figure 28. GOES Imagery 1330 GMT 31 January 1980

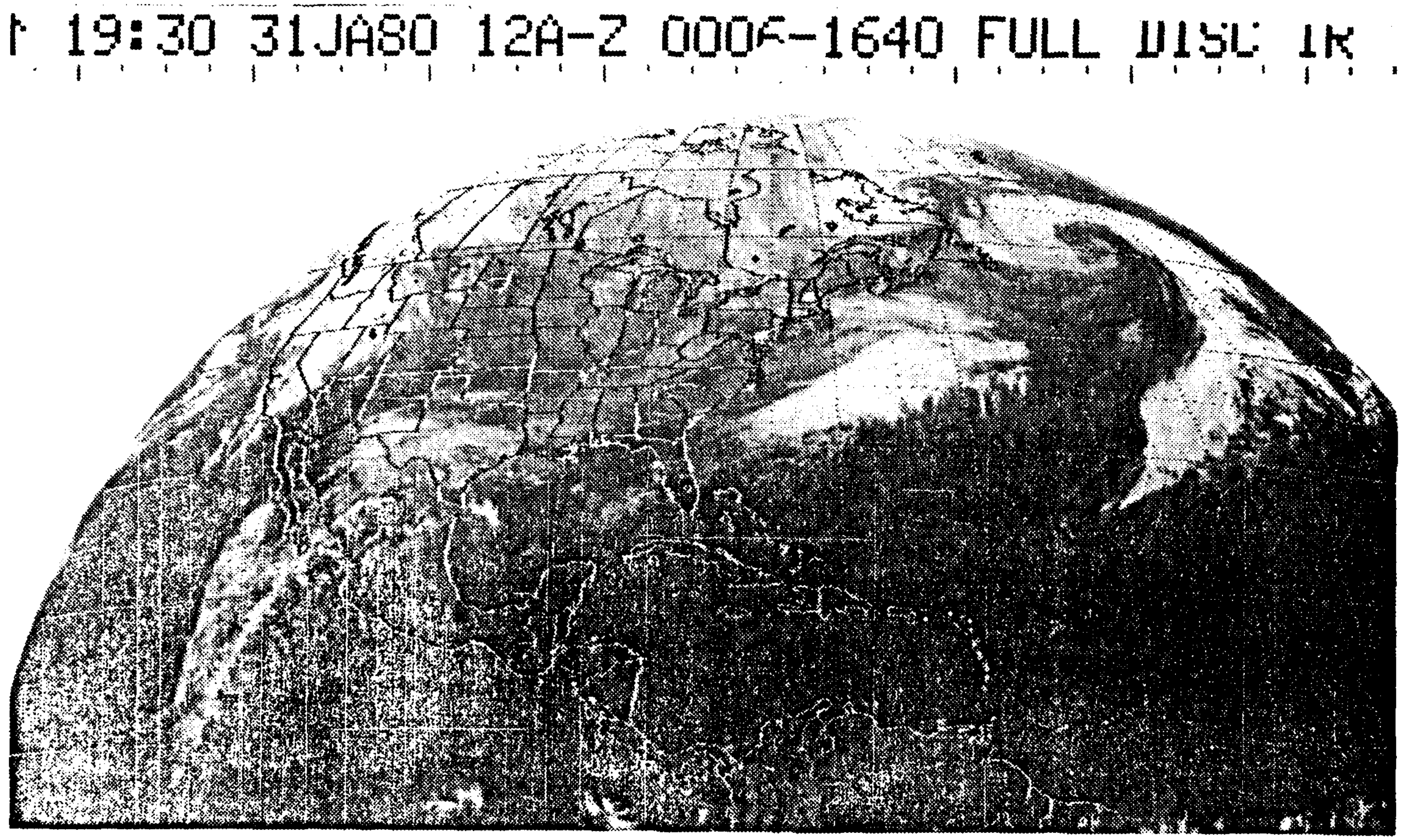

Figure 29. GOES Imagery 1930 GMT 31 January 1980

one can see the development of a new clear jet area to the north of the northern vortex. The narrowing of this northern jet break coincides with the onset of vortex closure. Also over the east coast of the United States the development of a slightly different configuration of a baroclinic leaf is seen. This development is unquestionably in a cloud element which has its origin in the tropical eastern North Pacific Ocean. Enhanced convection as well as Fett's enhanced cumulus wedge are seen in the Gulf of Mexico (Fig. 27). The characteristic distinctiveness of the baroclinic leaf continues to sharpen to a well-defined outline (Fig. 29). Yet, this system did not develop into an explosive storm. The absence of a jet stream clear area and a secondary cloud mass seems to be the only major differences.

In these three storms the presence of all six patterns is discernible. Additionally, the correlation with Kadlec's patterns and numerous small-scale features, which were not major interests of this study, are also present. The variation of patterns between and within individual storms has been demonstrated along with the variation of the patterns themselves.

One significant finding indicates that explosive episodes were not consistently maintained during the entire life cycle of the majority of studied storms. Of the studied cases, seven have two distinct pressure falls which could be separated into two of three observed categories: (1) early in storm growth while the surface pressure was higher than 980 mb, (2) the normal frontal wave development range between 1000 and 960 mb and (3) falls in the range below 970 mb. Of these seven storms all but two have pressure falls which were separated by 12 hours or more. The remaining two were separated by six hours. Analysis of Table II indicates that six of these falls are most likely valid dual-fall storms. Storm number 14 may have been affected by analysis error even though the rate of observed pressure fall did change over the six-hour period.

The early falls can be associated with baroclinic leafs or head clouds and often included Fett's enhanced cumulus stage. The problem with verification of the early falls stems from the fact that the storms were often associated with accelerated falls when first designated on sea-level pressure charts, and these falls did not continue for the requisite twelve-hour period. Ten of the storms sampled had original pressures in excess of 1010 mb and all of these exhibited dual pressure falls, a major single fall to below 980 mb or a fall which terminated above 980 mb. Three additional storms had initial pressures between 1009 and 1006 mb.

These early pressure falls are thought to be associated with upper-level frontogenesis, cyclogenesis or both. Early designation of sea-level low pressure areas at pressures greater than 1010 mb might have extended the number of storms which underwent these early explosive events.

The second subset of observed pressure falls is usually within the range which is commonly associated with surface-level cyclogenesis. These falls terminated in a range near 960 mb and are associated with head clouds and/or comma cloud patterns. It is during these falls that the development of polar-like lows is experienced. Although the upper-air analyses are not considered to be sufficient for documentation, the process seems to be initiated by the advection of positive vorticity or wind speed maximum along the polar front jet stream. Of the twelve storms which underwent deepening below 970 mb, eleven include head cloud development and the twelfth is of a comma cloud form. Three additional storms deepened to pressures between 980 and 970 mb and all of these are head cloud formations.

The third category of deepening is found by the storms which reached pressures below 960 mb. These storms show upper-level vortex closure in which cyclonic turning exceeds one full turn. The extended cyclonic turn is most often found in conjunction with a narrowing of the clear jet area on the storm's northern or western border or the development of a head cloud formation in the area of the triple point to the south of the main storm center. The findings concerning pattern usage correlate quite well with the conclusions of Weldon. In fifteen cases where the pressure fell below 980 mb, a head cloud is present in all but one. Thus, from Weldon's findings the majority of cases point to the presence of an advanced low level frontal zone development. This fact, coupled with Weldon's suggested cause for a well-defined southern edge on the baroclinic leaf, lead to the consideration of the characteristic clear jet area. The dynamic reasoning which would explain the clear jet area has not been well documented. McLean (1957) describes a discontinuity in the cirrus coverage near the jet stream core which produces cloudless skies to the immediate north. When the cirrus extended to the north of the jet stream core his study reports often show a narrow break in the cirrus at the core itself. McLean concludes, "High clouds and middle clouds show definite preference for certain sectors of vertical cross-sections perpendicular to the jet stream. The absence of clouds above the level of maximum wind is an outstanding feature." He further states that the maxima of cloud occurrence are found in the upper troposphere four to five degrees north of the core and immediately above the jet stream front four to six degrees south of the core.

The repeated correlation between periods of explosive pressure falls and the reduction of width of the clear jet area to less than five degrees is amazingly consistent. All storms are associated with the clear jet area. Further analysis also correlated the widening of the clear jet area to greater than five degrees in width as marking the conclusion of explosive pressure falls. The subject clear jet area has been linked to wind maxima of jet streams by McLean. Kadlec has linked the extension or recession of cirrus clouds, in the area north of a jet stream, to changes in jet stream velocity. Weldon and Kadlec have connected dual jet stream interaction with the baroclinic leaf and anticyclonic cirrus curvature.

Reiter and Whitney (1969) discuss the subsidence of dry air within the shear line between two jet branches. They conclude that the dry air is indicative of subsidence from stratospheric levels through a "tropopause gap." They also conclude that, at least in the case being studied, the subsidence of stratospheric air within the baroclinic frontal zone beneath a jet stream is most effective in regions where two well-developed jet branches are merging. Reiter (1975) also attributes a cloud-free upper troposphere to the subsidence of air in the polar front branch to the rear of the combined jet maximum.

An additional problem was experienced in an attempt to correlate jet maximums with the occurrence of head or comma clouds. Reiter (1975), among others, indicates that the subtropical and polar front jet streams are usually found near 200 and 300 mb, respectively. Aside from the obvious problems of poor oceanic coverage, termination of soundings by strong wind fields and poor subtropical jet definition, due to the tropical blend zone of utilized models, the resolution and 12-hour increments of the available upper-air analyses made them a poor tool for this study. This problem is amplified by the inclusion of the jet stream interactions. Whitney et al. (1966) discuss the ambiguities associated with upper-air analyses in the area of two parallel or converging jet streams which are within 300 n mi of each other. They feel that a revised analysis is needed to permit the axis of strongest winds to cross contours at small angles in accordance with the acceleration characteristics of the associated jet stream. They point out that jet stream characteristics in satellite imagery may sometimes lead to the analysis of a single primary jet stream where multiple jets adhering to contour channels might otherwise have been analyzed. Reiter and Nania (1964) provide evidence that trajectories on isentropic surfaces do not support the classical model of confluence and difluence of the polar front and subtropical jet streams. As seen from their analyses, the northwesterly jet branch seemed to submerge beneath the warmer southwesterly jet. This causes one jet axis to appear in the horizontal where there may be two, one superimposed upon the other.

Though sufficient upper-air data are not available for complete analysis of all storm events, jet maximums of 130 kt or greater at 200 or 300 mb, or both, occurred during some part of the development cycle of the majority of storm cases. Most of these maximums were in the range of 150 to 170 kt. With the mentioned limitations in mind, there appears to be a correlation between jet maximums in the southern jet branch and head cloud formations which did not further evolve into comma clouds. In conjunction with southerly jet maximums, the head cloud signature would most often occur on the southern or right side of a clear jet area. The comma cloud or head cloud to comma cloud evolution most often appears north or west of the clear jet area when the maximum is found at 300 mb in the northerly jet branch.

One additional observation came about through the usage of coverage from both GOES East and West imagery. During imagery analysis GOES West was routinely utilized to supplement GOES East imagery. After viewing numerous GOES West images, a particular cloud pattern seemed to be present during the period from three to five days prior to the onset of explosive cyclogenesis episodes over eastern offshore waters. This cloud pattern consists of a long cirrus shield which crossed the west coast of North America in the vicinity south of central California to the southern tip of the Baja Peninsula. Further investigation of this pattern shows a remarkable resemblance to the "Low Latitude Block" model of cloud cover which is discussed by Elliott and Thompson (1969). Clark (1976) discusses an east coast winter storm during early February, 1976. One of his major points concerns the tracking of an upper-level cold core low from over southern Baja, California. He associates early development of this storm to" the bright clouds over lower Baja, the Gulf of California and Mexico." In subsequent analyses of the storm set the presence of this extended bright cloud could be found during the period from three to five days prior to the onset of east coast explosive storms. This long cirrus plume is a characteristic which is depicted in the "Low Latitude Block." A further correlation of "Low Latitude Blocks" to southern United States developments and "High Latitude Blocks" to northern United States storms also shows potential. Figs. 30 and 31 display the cloud pattern diagrams for a "low" and "high" latitude block.

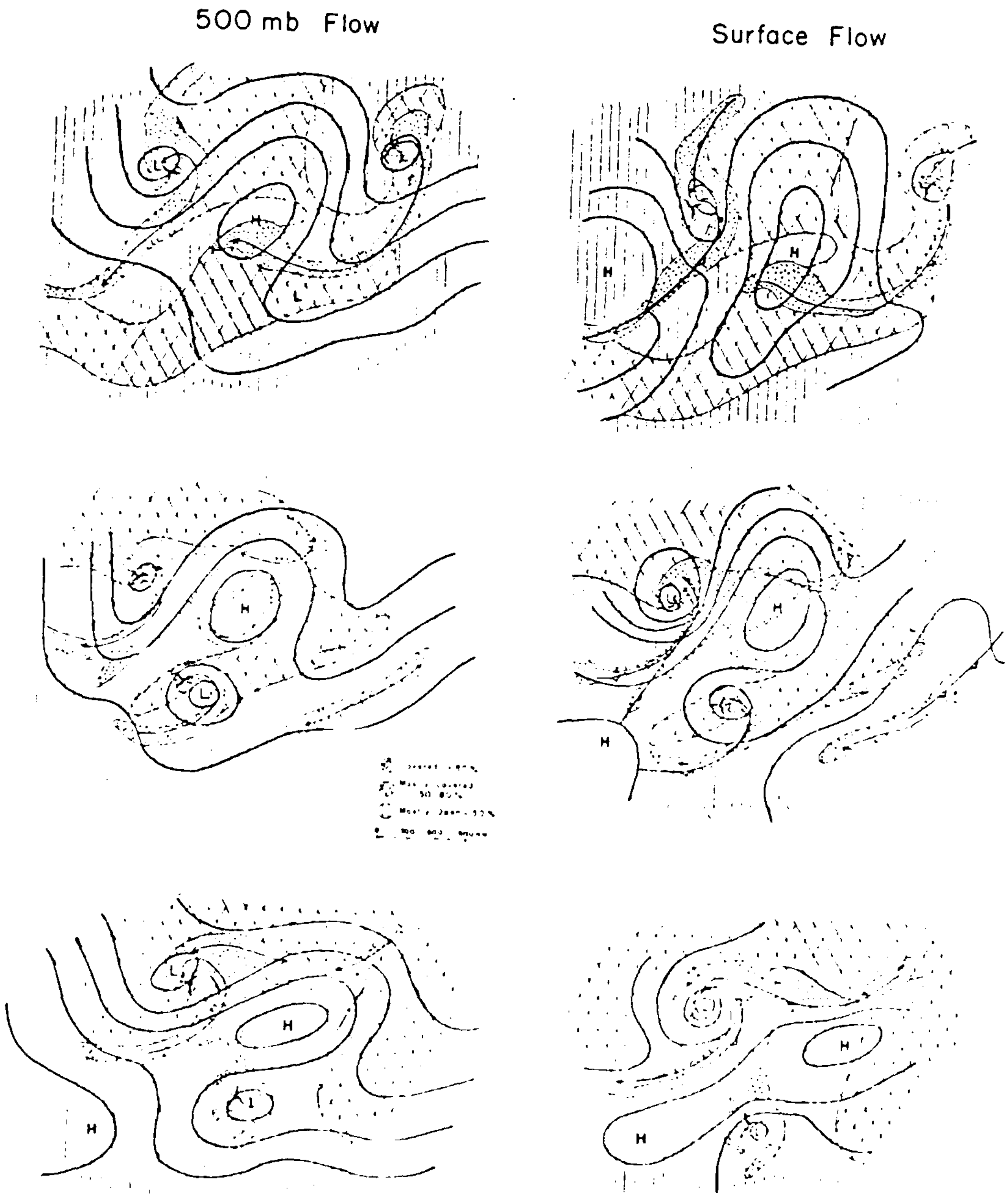

Figure 30. Low Latitude Block Cloud Cover Diagram (from Elliott and Thompson, 1969)

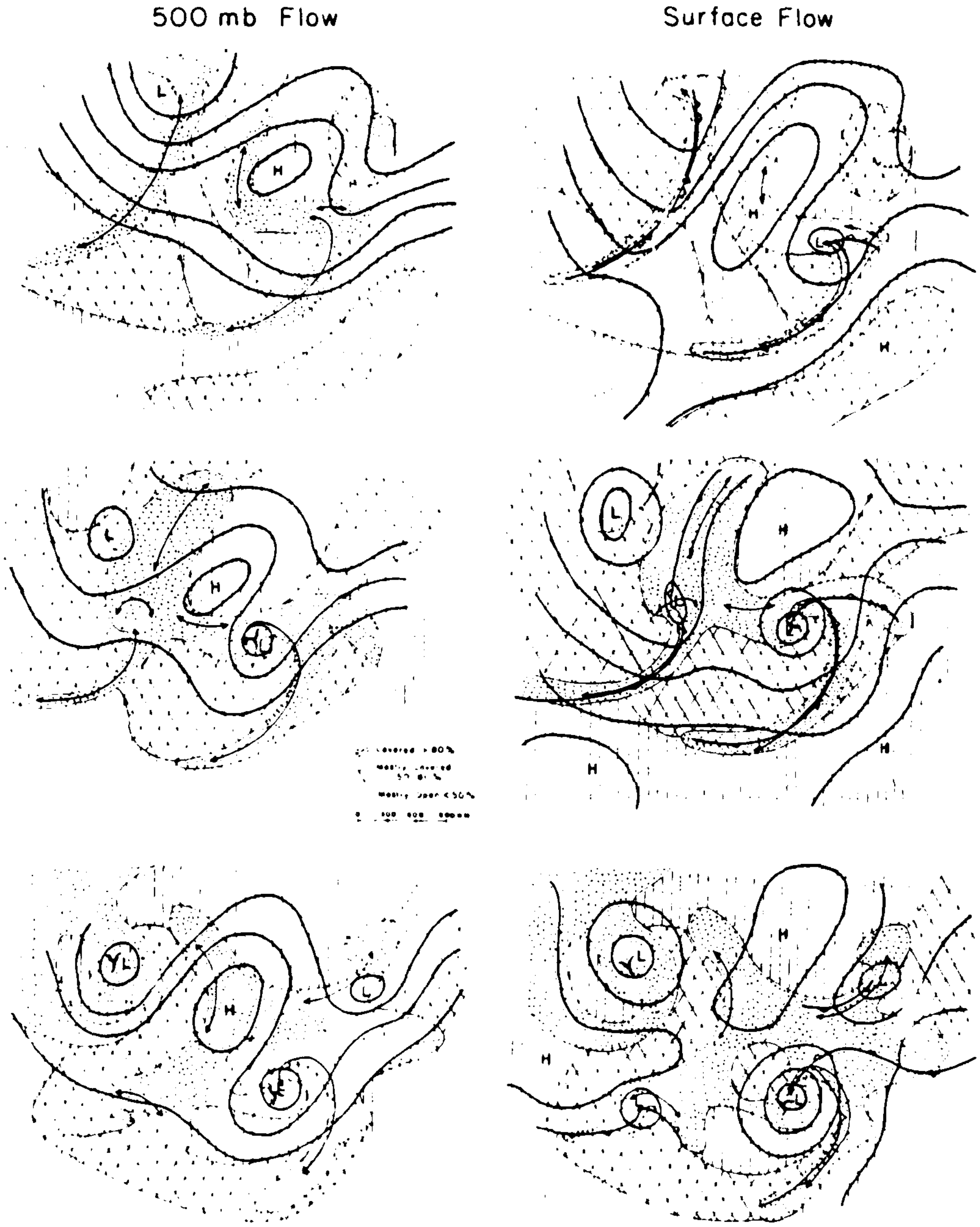

Figure 31. High Latitude Block Cloud Cover Diagram. (from Elliott and Thompson, 1969)

VI. SUMMARY AND CONCLUSIONS

A. SUMMARY

This study was originated as an observational study, in synoptic framework, of documented cases of explosive cyclogenesis. The conclusions which may be drawn are linked to high-level cloud evolutions which were found in existing literature or during research analysis. Although all patterns were found to occur during explosive cyclogenesis events, all cannot be considered as strict indicators of its presence.

It would appear, as a general requirement, that explosive cyclogenesis should be considered as a multi-cycle event. The pressure intervals which appear to apply as divisions are: (1) above 980 mb and usually above 1000 mb, (2) from 1000 mb to 960 mb and (3) below 970 mb. These divisions equate fairly well with the intervals set by Junker and Haller (1980) and follow closely the vortex closure and pressure relations which they formulated. The early cloud patterns (980 mb or above) can be related to a channeled or dual jet interaction and normally form on the southern or right side of the jet stream axis. The cirrus can extend to the northern side of the jet axis and may have a clear area at the core of the jet stream. Weldon associates this leaf shape to PVA advection.

Whether the results of dual jet interaction, height center merger or a single strong jet channeled area, the first stages of storm development are usually found to consist of baroclinic leaf-type developments. The particular configuration of the leaf pattern is influenced by the strength and position of the surface front and the major long wave pattern. The majority of studied baroclinic leafs were convex dominant and occurred on the southern side of the associated clear jet areas. These early pressure falls would appear to be surface manifestations of upper-or middle-level developments. Bottger et al. (1975) also indicate that the head cloud formation precedes extreme surface deepening. They found the head cloud to precede storms of hurricane intensity by approximately 24 hours. The indications of this study are that the head cloud does precede significant surface development by a period of 24 to 36 hours.

The second cycle of explosive development is related to the cyclogenetic process. It is consistently associated with the northern cloud mass when the clear jet area is present. This segment of pressure falls may be an extension of a head cloud or baroclinic leaf. In the majority of cases it is depicted as a comma cloud formation and subsequent vortex closure. One exception is in the March 1979 storm which was discussed earlier.

The third set of pressure falls is found in the attainment of pressures below 970 mbs. These falls tend to be marked by continued cyclonic vortex closure beyond one full turn. Junker and Haller (1980) found that when the pressure drops below this level the cloud band has wrapped completely around the center. The more central the circulation within the cloud spiral, the lower the pressure. The continued spiraling of the vortex is usually brought about by the approach of another PVA maximum.

The identifier for this occurrence can be in a new head cloud formation at the storm's triple point or in the approach of a small-scale comma cloud from the upstream direction of flow.

B. CONCLUSIONS

The conclusions from this study are:

* An early accelerated pressure fall is associated with both the "baroclinic leaf" and the "head cloud".

  These early pressure falls usually have weak surface-related circulations and are indicative of middle-to-upper-level tropospheric development.

* The majority of these storms are vertically deep systems. The characteristic bright and distinctive patterns which would indicate development at all levels are normally found in each storm development sequence.

* Junker and Haller's (1980) basic cloud pattern models were found to correlate with pressure and imagery relations developed in this study.

* Anticyclonic curvature in high-level cirrus cloud bands is strongly associated with the explosive cyclogenesis phenomenon.

* Major distinguishing features of studied vortices is the relatively compact and distinctive appearance of the vortex.

* The majority of studied cases seem to indicate the presence of advanced low-level frontal zone development.

* An increase or decrease of the clear jet area to greater than or less than 300 n mi indicates the respective beginning and cessation of explosive pressure falls. This change is believed to be the result of an increase in local jet stream velocity brought about by the passage of a vorticity maximum.

* Kadlec's (1964) "Jet Stream Cirrus Patterns" and Elliott and Thompson's (1969) "High and Low Latitude Block Models" provide early indicators of potential for explosive cyclogenesis events.

C. SUGGESTED FURTHER STUDY

The recommendations for further study are:

* The consistency of cloud patterns which have been tentatively correlated to dual jet interactions would tend to support a study on the affect of jet stream mergers on extratropical cyclogenesis.

* The anomalous cloud sequence and sustained explosive pressure falls of the 10 March 1979 storm appear to indicate an extension of the dynamic processes which have been equated to the early pressure fall segments. A study of the dynamic processes present in this storm may provide a better understanding of explosive cyclogenesis events.

* The development of the head cloud signature on the southern or right side of the clear jet area can be theoretically linked to propagation of a PVA maximum through the subtropical jet stream or the southern branch of a split in the polar front jet stream. The possibility of propagating maximums in the subtropical jet stream and their effect on explosive cyclogeneis warrants careful study.

* The correlation of the change in width of the clear jet area and a parallel change in pressure fall rates of studied storms is an extremely consistent factor. This is the most consistent indicator of explosive cyclogenesis characteristics. An improved understanding of the atmospheric forcing which affects the width of the clear jet area would provide significant improvement in forecasting procedures.

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