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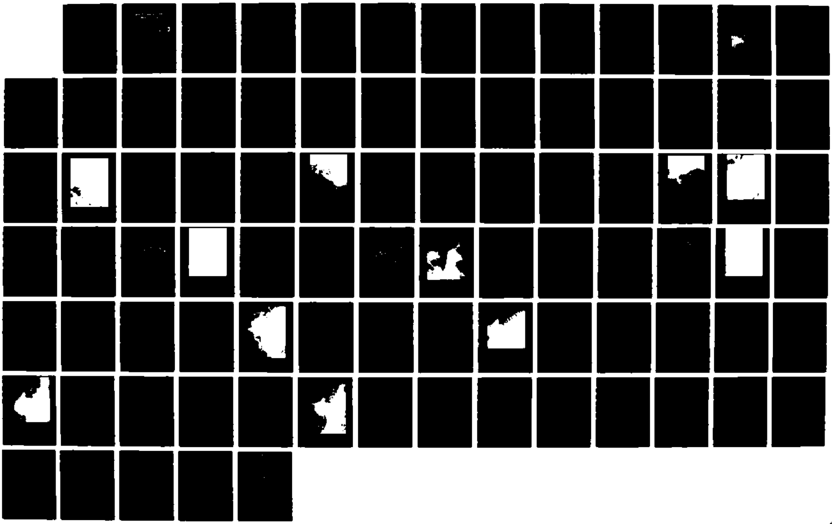

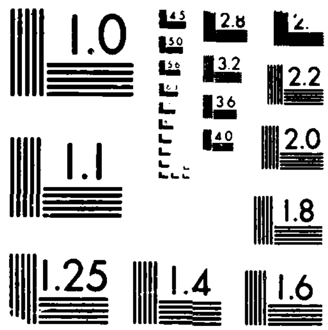


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# NAVAL POSTGRADUATE SCHOOL
## Monterey, California



# THESIS

METEOROLOGICAL FEATURES DURING
THE MARGINAL ICE ZONE EXPERIMENT
FROM 20 MARCH TO 10 APRIL 1987

by

Ryan R. Schultz

December 1987

Thesis Advisor K. L. Davidson

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MIZEX 1987 is separated into five periods with distinct meteorological conditions. In the first period, from 20 to 23 March, the MIZ region was dominated by a large scale surface high pressure system. During the second period, from 24 to 27 March, a mesoscale boundary-layer front dominated the MIZ. This front was the object of a more detailed case study. During the third period, from 28 to 31 March,

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a weak surface synoptic-scale low pressure system dominated the MIZ. During the fourth period, from 1 to 3 April, a low developed 100 km east of Greenland and subsequently moved to the east, filling when it reached central Norway. During the fifth and final period, from 4 to 10 April, two lows developed 100 km north of Iceland which traveled northeastward along the classic secondary climatological storm track to a postion 100 km southwest of the Svalbard Islands. When the first low of this fifth period stalled and was overtaken by the second low of this fifth period a combined and considerably enhanced system developed which extended along the west coast of the Svalbard Islands to the Norwegian Sea. All described features appeared clearly on NOAA 9 and 10 imagery and surface sensed properties are related to the satellite sensed properties.

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# Meteorological Features during the Marginal Ice Zone Experiment (20 March - 10 April) 1987

by

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Lieutenant, United States Navy
B.S., United States Naval Academy, 1981

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND OCEANOGRAPHY

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## ABSTRACT

Described are synoptic and mesoscale meteorological conditions which occurred during the Marginal Ice Zone Experiment (MIZEX-87) conducted from 20 March to 10 April 1987 in the marginal ice zone (MIZ) of the Greenland Sea (Fram Strait). Meteorological measurements were made from three ships and weather analysis and ice edge location analysis were provided by shore meteorological support at Tromso, Norway

MIZEX 1987 is separated into five periods with distinct meteorological conditions. In the first period, from 20 to 23 March, the MIZ region was dominated by a large scale surface high pressure system. During the second period, from 24 to 27 March, a mesoscale boundary-layer front dominated the MIZ. This front was the object of a more detailed case study. During the third period, from 28 to 31 March, a weak surface synoptic-scale low pressure system dominated the MIZ. During the fourth period, from 1 to 3 April, a low developed 100 km east of Greenland and subsequently moved to the east, filling when it reached central Norway. During the fifth and final period, from 4 to 10 April, two lows developed 100 km north of Iceland which traveled northeastward along the classic secondary climatological storm track to a postion 100 km southwest of the Svalbard Islands. When the first low of this fifth period stalled and was overtaken by the second low of this fifth period a combined and considerably enhanced system developed which extended along the west coast of the Svalbard Islands to the Norwegian Sea. All described features appeared clearly on NOAA 9 and 10 imagery and surface sensed properties are related to the satellite sensed properties.

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# I. INTRODUCTION

The expansion of the United States Navy to 600 ships has opened up new areas of operation of which the Arctic has become a region figuring prominently in use of this new maritime power (LeSchack, 1987). Existing Arctic environmental knowledge is lacking to allow this postulated power projection to be used optimally. This is because past scientific priority given to the Arctic environment by the United States has been low when compared to its other Arctic neighbors such as the Soviet Union (Westermeyer, 1984). Recognizing this, the United States Navy has placed increasing emphasis on enhancing its operating capability in this region along with expanding its scientific knowledge of this vital area of the world. The President's United States Arctic Policy (14 April 1983) and Congress' Arctic Research Policy Act of 1984 emphasizes both the critical role of the Arctic and the need for priority research attention because of three major elements; natural resources, strategy concerns and basic scientific research (Arctic Marine Services Research, 1985; National Science Foundation, 1987).

An important specific operational requirement for the Arctic is the United States Navy's Arctic/Cold Weather Surface Ship Plan specified by Vice Chief of Naval Operations for Surface Warfare (OP-03). OP-03 currently evaluates the Navy's surface ship severe weather operating capability as being adequate south of a line extending from Maine, across the Atlantic, to central Norway (Fig. 1.1). Significantly, this line excludes much of the ocean waters adjacent to the Arctic. As shown in Fig. 1.1, OP-03 future objectives move this limiting line successively northward until it reaches the edge of the marginal ice zone (MIZ) by 2010.

The MIZ is that part of the Arctic region where an interface occurs between the atmosphere and both the ocean and ice surfaces and as such it plays a critical role in both local and large-scale weather development (Denner, 1985). Major comprehensive studies of the MIZ occurred in the Greenland Sea during the summers of 1983 and 1984. A large amount of meteorological data for both the MIZ and the Greenland Sea was obtained and results presented by studies of Phegley (1985), and Lindsay, *et al.*, (1986). Unfortunately, current meteorological knowledge and forecast ability in this area does not meet minimal operational requirements. To realize the U.S. Navy's goals, as stated by OP-03, a much more detailed and comprehensive understanding of the unique Arctic meteorological environment will be required.

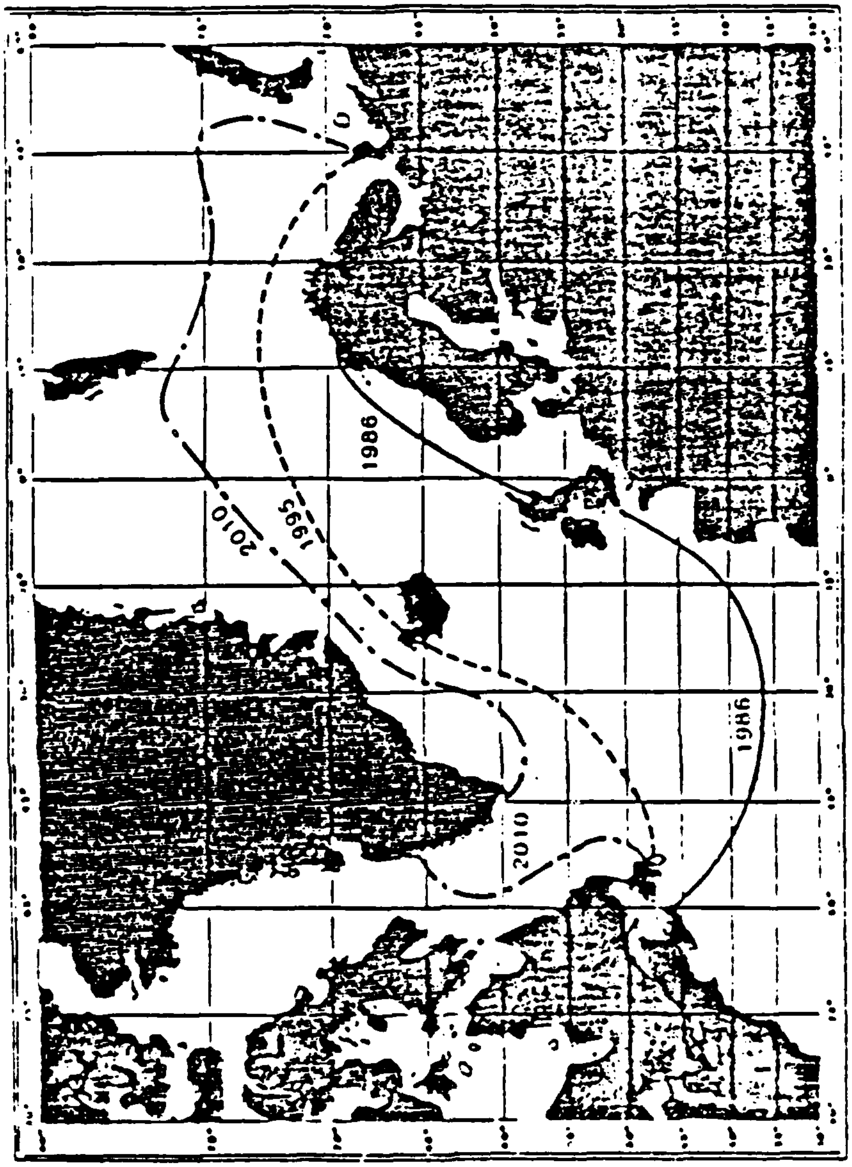



Fig. 1.1 OP-03 Severe Weather Operating Goals.

The Greenland Sea, Fig. 1.2, is a region of roughly 4 million square km. Of special military significance to the U.S. Navy is the Greenland Sea MIZ region which represents the only deep underwater access to the polar basin. Important geographic

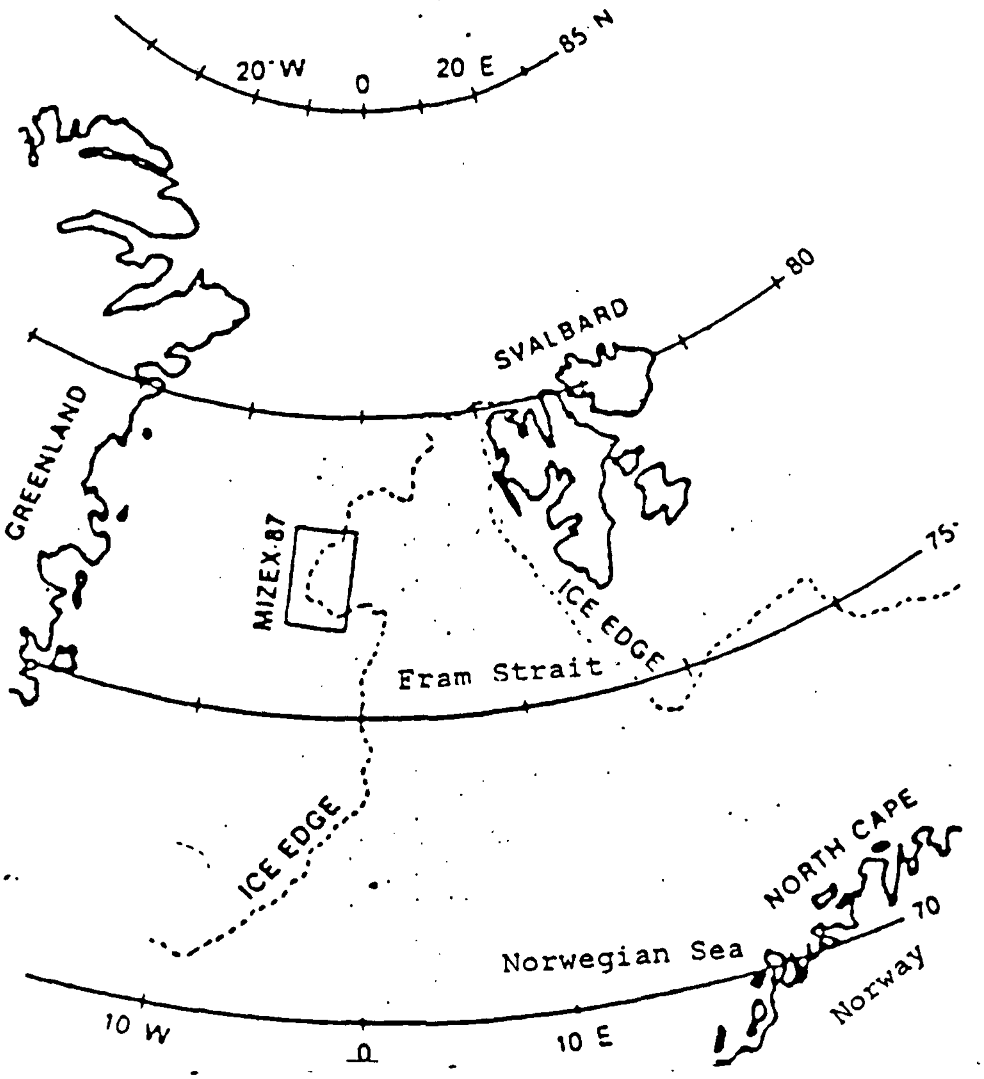



Fig. 1.2 MIZEX 1987 Area of Operations (Johnson and Hawkins, 1987).

features are Greenland to the west, Iceland to the southwest, Norway to the southeast and the islands of Svalbard to the northeast. The major strait of the region is the Fram Strait which is that passage of water between Greenland and Svalbard entering into the Arctic basin. The Norwegian Sea is the body of water just off the coast of Norway which borders the Fram Strait to the north.

The Marginal Ice Zone Experiment (MIZEX) 1987 occurred during March and April (20 March to 10 April) of 1987 and was the first comprehensive late winter and early spring study in the Greenland Sea MIZ. The meteorological goal for the MIZEX 1987 program was to obtain detailed atmospheric microscale, mesoscale and synoptic-scale descriptions of the the MIZ region (Marginal Ice Zone Experiment (Project Office, 1987). This experiment was in the same geographic area as summer MIZEX's in 1983 and 1984.

Three ships were involved in the meteorological measurement program. The Valdivia, a German research ship, took three-hour surface weather observations and launched six-hour rawinsondes. The Hakon Mosby and Polar Circle, Norwegian ships, took three-hour surface weather observations and launched rawinsondes every six hours and also were instrumented with systems which made continuous measurements of mean wind, humidity, temperature, surface pressure and turbulent wind. Naval Postgraduate School personnel performed all meteorological activities on the three ships. The author of this thesis, LT R.R. Schultz, was on the Valdivia as primary meteorological investigator (P.I.). The thesis advisor, K.L. Davidson, was meteorology coordinator for MIZEX 1987 and the meteorology P.I. on the Hakon Mosby. A Naval Postgraduate School meteorologist, P.S. Guest, was the meteorology P.I. on the Polar Circle.

The experiment area is shown in Fig. 1.2. The Valdivia was at various locations in the Fram Strait from 20 March to 3 April operating between 74 and 80° N and 17° E to 3° W. The Hakon Mosby was mostly at locations off the West Fram Strait ice edge from 23 March to 11 April and operated between 74.6 and 79° N and 19° E to 3.7° W. The Polar Circle was mostly at locations within the West Fram Strait ice edge from 23 March to 11 April and operated between 74.5 and 79° N and 19° E to 6.5° W. The box in Fig. 1.2, labeled MIZEX-87, indicates where the the Hakon Mosby and Polar Circle were for the majority of the experiment.

In addition to the data collection on the three ships, a MIZEX shore forecasting center, directed by Mr. R. Fett of the Naval Environmental Prediction Research Facility (NEPERF), was established at Tromso, Norway and its activities were coordinated with those at the Norwegian Meteorological Institute. At the Tromso forecasting center, MIZEX ship reported data were combined with the routine shore and ship station data provided by the WMO reporting organization. Advanced Very High Resolution Radiameter (AVHRR) imagery from the NOAA 9 and 10 polar-orbiting satellites were also collected and analyzed at the Tromso center.

This thesis presents meteorological features observed in MIZEX 1987. In Chapter II, a detailed climatological review is presented for the region for both synoptic and subsynoptic-scale features. In Chapter III discussions of synoptic and mesoscale observed conditions are presented according to five periods of distinct meteorological activity. The first period was influenced by a high over the Greenland Sea MIZ from 20 to 23 March. In the second period, 24 to 27 March, a mesoscale phenomena, called the boundary-layer front, impacts on the Greenland Sea MIZ weather. The third period, 28 to 31 March, was influenced by a small scale surface low persisting over the Fram Strait region. The last two periods (fourth and fifth), 1 to 3 April and from 4 to 10 April, were controlled by a series of three synoptic-scale lows approaching the Greenland Sea MIZ. In Chapter IV, a more detailed examination is made of the westward propagating boundary-layer front during the second period (24 - 27 March). Chapter V presents concluding remarks and discussion.

# II. SPRING CLIMATOLOGY

## A. DOMINANT FACTORS

### 1. Distinctive Daylight and Darkness Regimes

Due to the tilt of earth's axis distinctive regimes of daylight and darkness occur in the higher Arctic latitudes such as in the Greenland Sea. In winter darkness a severe radiational loss at the earth's surface occurs. Summer, with constant daylight, also has a net radiational loss at the surface but it is not as great as in the winter. MIZEX 1987, occurring during the months of March and April, is a transition period between extremes. The shift from darkness to daylight is quite rapid, with every passing day bringing an extra 25 minutes of daylight in the Greenland Sea. At the beginning of the experiment, in mid-March, daytime is 9 hours. By mid-April daytime is lengthened to 21 hours.

### 2. Circumpolar Vortex

An important feature of the Arctic region is an upper-level large scale cold-core low, centered roughly on the North Pole, containing a belt of westerly winds aloft at its outer edge and a corresponding area of strong meridianal temperature gradients (Petterssen, *et al.*, 1956). This region is called the circumpolar vortex and can be seen by looking at the spacing of the 700 mb gradient lines, Fig. 2.1, which is based on a 12-year monthly mean for the month of April (Sater, *et al.*, 1971). The packing of the 960 and 990 dm lines, especially over the North Atlantic and North Pacific Oceans, indicates the strength of this feature. Most weather systems are closely associated with its strength and location. Spring finds the vortex in transition from its winter (southern most) position to its summer (northern most) position and also from strong to weak gradients. In all four seasons the belt of maximum westerlies is south of the MIZEX area. The stronger vortex creates a stronger flow of westerlies and hence a trend towards stronger and more frequent cyclogenesis.

### 3. Ice Coverage

The polar ice cap covers a large portion of the Greenland Sea and plays a controling influence on Arctic climatology. A representative March-April ice edge in Fig. 2.2 is representative of the large extent and coverage of the ice pack during MIZEX 1987. In March the ice has its maximum coverage before increasing late-

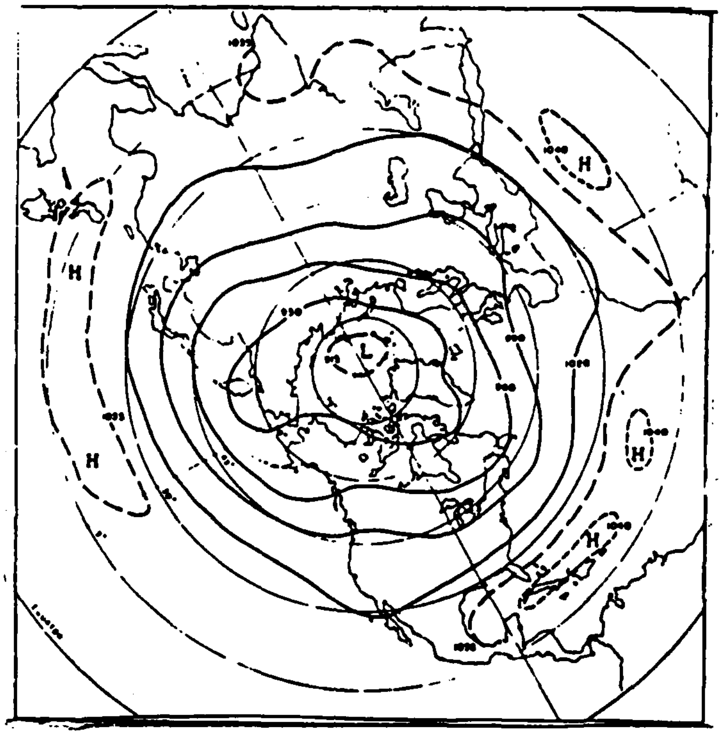


Fig. 2.1 Climatological 700mb Heights, April (Sater, *et al.*, 1971).

spring temperatures start melting and causing the retreat of the ice edge (Sater, *et al.*, 1971). The cold ice and snow surface cools the overlying air mass. This causes large areas of cold air in this region which then interacts with the warm oceanic waters at the MIZ.

#### 4. Surface Temperature Inversion

Strong temperature inversions exist over the ice and snow covered areas due to radiative cooling at the surface. Other mechanisms contributing to this inversion include cloud-top radiative cooling, advection, subsidence and mixing. The inversion layer is usually quite strong, relatively cold and stable. The inversion can typically extend to above 850 mb with a temperature increase of more than 5° C across the inversion. The stable layer inhibits heat transfer from the upper and middle-level air masses while at the same time preventing any surface moisture from penetrating through this layer. This creates a cold, moist surface layer and a relatively warm, dry upper air layer above (Sater, *et al.*, 1971). In ice free areas of the Greenland Sea, strong elevated inversions exist due to buoyant heating and mixing from below.

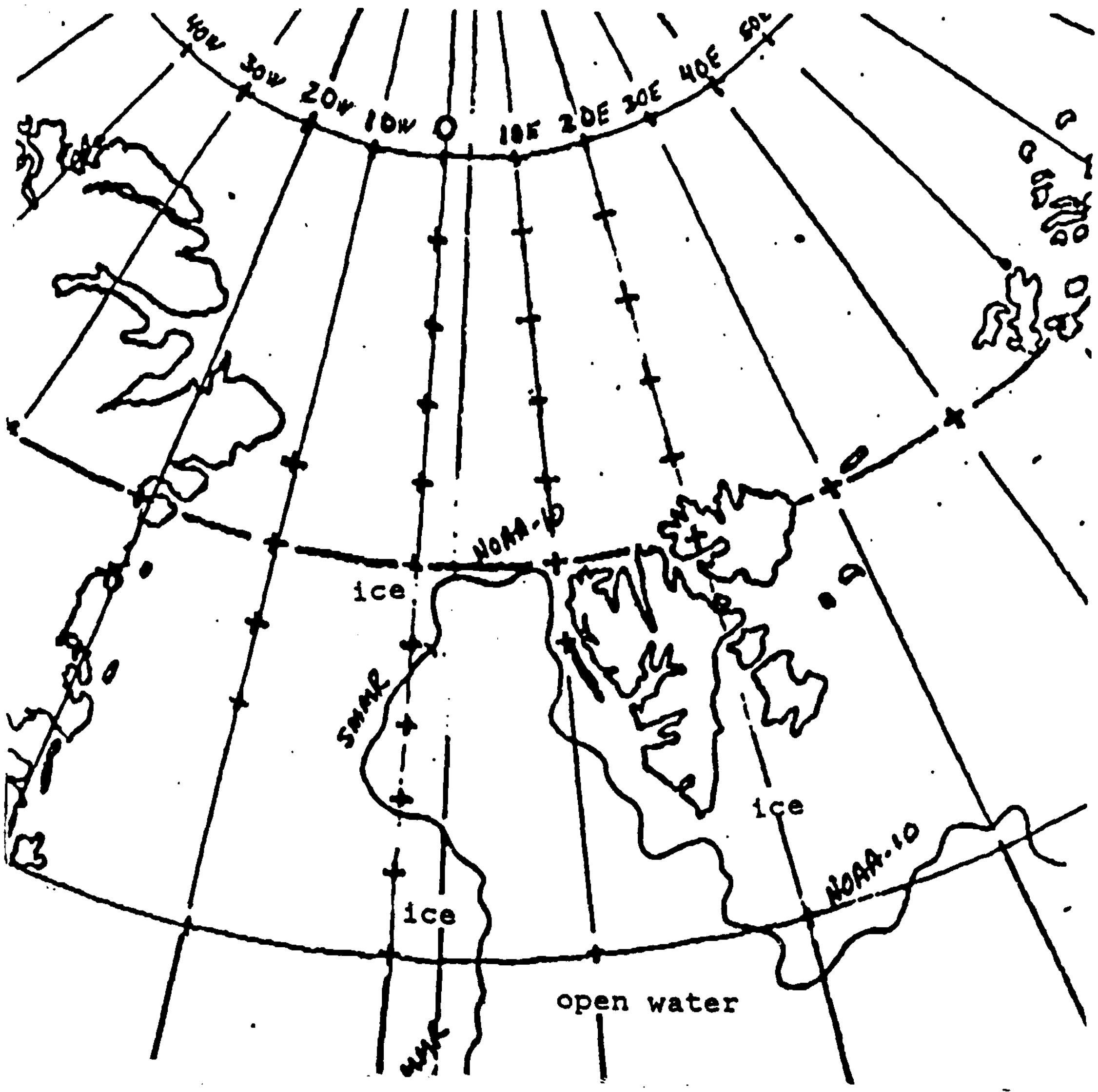



Fig. 2.2 Representative Ice Edge during MIZEX 1987.

## B. GENERAL SPRING SYNOPTIC-SCALE FEATURES

Important Arctic large scale synoptic feature (ridges or troughs) persist in time for up to periods of a month. Broad ridging patterns stall and maintain themselves over relatively long time periods. Regionally, this results in extended periods of abnormally cold or warm conditions (Sater, *et al.*, 1971). An objective of this thesis is to relate the March-April 1987 synoptic-scale features to the occurrence of such patterns. The purpose of this section is to present climatological information for later reference.

### 1. March-April Climatology

#### *a. Surface Pattern*

Based on 12-year climatological means, the spring Arctic surface pattern, Fig. 2.3, is characterized by a weak and variable surface high over central Greenland called the Greenland High. A high is also evident centered roughly on the North Pole. The springtime Icelandic Low is weaker than that in winter and shifts its position to the northeast of its winter position west of Iceland. The polar front is the belt of continuous lows, Fig. 2.3, starting with the Icelandic Low and extending across northeast to the North Cape of Norway. This belt is strongly influenced by the circumpolar vortex. In March and April the polar front is weaker than the winter maximum and progresses slightly northward from the winter,more southern, position. Even so, it is still south of the MIZ. For the MIZEX area, the predominate spring feature is easterly flow due to the transitory lows to the south.

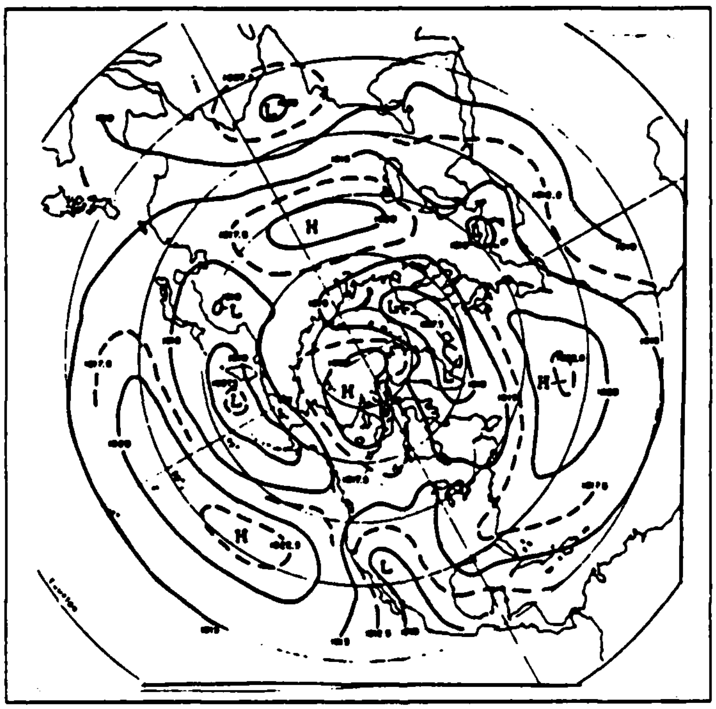


Fig. 2.3 Mean Sea-Level Pressures, April (Sater, *et al.*, 1971).

*b. 700mb Pattern*

The climatological April 700mb pattern, Fig. 2.1, has an upper-level low centered roughly on the North Pole. Over the East Greenland Sea, a slight poleward bulge in the height contours occurs resulting in southwest to northeast orientations of contours over the Fram Strait and southwesterly 700 mb flow.

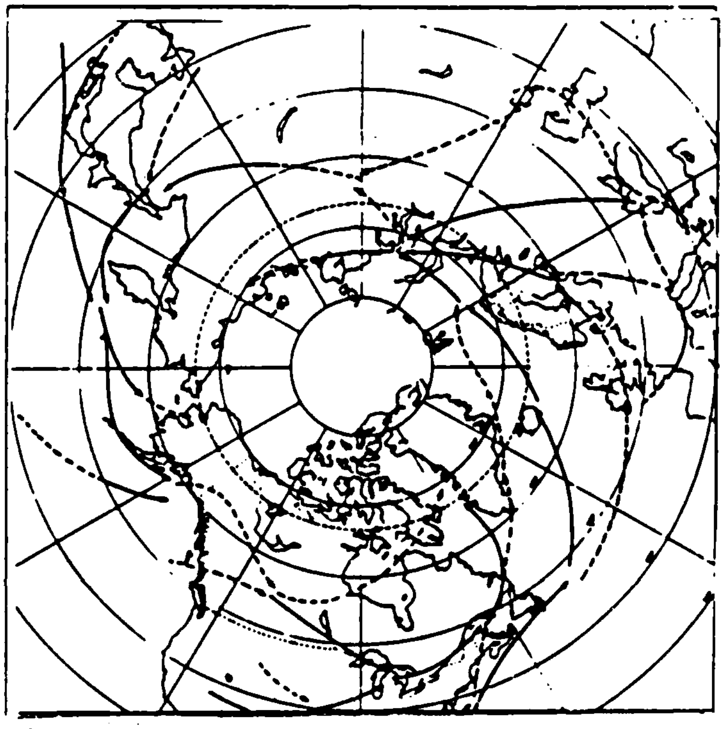


Fig. 2.4 Principal Cyclone Tracks, April (Sater, *et al.*, 1971).

**2. Arctic Cyclones**

Normally, Greenland Sea Arctic cyclones move eastward, with a small northward component, and are steered by the westerly flow associated with the circumpolar vortex (Petterssen, *et al.*, 1956). They usually occlude very quickly and, if formed outside the Arctic, they occlude quickly upon entering the influence of the circumpolar vortex. Relatively higher temperatures, strong frontal zones, high winds and cloud cover are all associated with Arctic cyclones. Cyclones are much weaker in the summer season than in the winter. Therefore, Greenland Sea springtime has storms of a slightly weaker strength than those encountered in the winter (Sater, *et al.*, 1971). Also spring storms move and persist farther north than in the winter but the primary and secondary storm tracks are still south of the MIZEX area (Fig. 2.4).

The Greenland Sea region of the Arctic is a very active area for cyclogenesis due to surges of cold dry air flowing off the ice over the warm oceanic waters (Petterssen, *et al.*, 1956). Arctic region interfaces between ice and oceanic water or even land and oceanic water can be considered a region of potential maximum cyclonic activity. Fronts associated with cyclones tend to have relatively weak temperature contrasts, especially when compared to mid-latitude fronts. In addition, extensive cloud features, as is common in mid-latitude systems such as high/middle/low cloud sequences, are usually lacking with Arctic fronts. (Sater, *et al.*, 1971)

The April cyclone tracks in the Greenland Sea, Fig. 2.4, reveal a primary storm track which originates in a region near the Icelandic Low and is directed northeastward to just off the coast of northern Norway. A secondary storm track, originating between Iceland and Greenland, is also directed northeastward ending up in the same position off of northern Norway as the primary storm track. In both cases the strong influence of the upper level westerly flow is evident in steering these cyclones. (Sater *et al.*, 1971)

3. **Polar Lows**

Polar Lows, also called Arctic Lows, are important features peculiar to high latitude cyclogenesis. Polar Lows in the Norwegian, Greenland and Barents Seas were the subject of a multi-year study (1983-1986) by the Norwegian government and other individual groups. This study was called the Polar Low Project and resulted in 25 technical reports and several published papers. Polar Lows, as opposed to the normal Arctic cyclones, are intense systems of less than 100 km width which form in cold air masses poleward of major fronts and jet streams. The Polar Low is normally generated with outbreaks of cold Arctic air over the seas adjacent to the ice edge. Energy for cyclogenesis is provided by both heat and moisture fluxes from the surface and energy transformation within the atmospheric synoptic-scale patterns (Reed and Duncan, 1987). Polar Lows rapidly attain wind speeds of over 30 m $s^{-1}$ in the first hours of development although they lack the pronounced frontal structures throughout much of their lifetime (Rasmussen, 1985). They usually appear on satellite imagery as comma shaped cloud masses (Rasmussen, 1985). Interestingly, studies have shown a slight peak in frequency of cyclogenesis in the month of March in the Norwegian Sea although the reasons for this are not clearly understood (Wilhelmsen, 1985).

4. **Arctic Anticyclones**

Arctic anticyclones are usually large and irregular areas of high pressure characterized by strong subsidence and stability creating a relatively dry air mass. These systems are usually shallow and slow moving, perhaps oscillating around a single point or even changing shape rather than having a detectable movement. These types of systems bring clear, cold and calm conditions and favor strong inversions at the boundary layer. (Sater, *et al.*, 1971)

Arctic anticyclones are commonly found in the northern regions of the Arctic. In the Greenland Sea, anticyclones are usually located over central Greenland or north of the Svalbard Islands. Anticyclones tend to form away from any interfaces which hinder the formation of cold dry Arctic air and its associated subsidence. Since these anticyclones are cold-core in nature the middle and upper-level influence is usually slight.

5. **Ice Edge Boundary-Layer Front**

The ice edge boundary-layer front was studied on the basis of aircraft data obtained by crossing the front and dropping rawinsondes (Shapiro, *et al.*, 1987). The data was collected during the Polar Low Project. The front formed along the ice edge west of Svalbard under conditions of northerly flow. The frontal study by Shapiro, *et al.*, (1987) and its associated low level (850 mb) jet revealed several of the details of this feature. A band of convective cumulus along the front was associated with its development. Shapiro, *et al.*, (1987) describes the front as forming between two distinct boundary layer flows. Initially, the cold ice pack air is moved south in northerly flow conditions. After exiting the ice pack west of Svalbard, the western part of this flow passes over the warm waters and warms due to upward sensible heat flux plus, with any cloud formation, latent heat flux. The adjacent flow to the east is not heated as it travels over the ice and snow of the Svalbard Islands. A distinct cloud band is formed by adiabatically forced vertical circulation in the vicinity of the boundary layer front. Additional forcing may be obtained by the narrow sea-surface temperature structure along the ice edge and West Spitzbergen Current. (Shapiro, *et al.*, 1987)

Shapiro, *et al.*, (1987) found that the ice edge boundary-layer front had a cross frontal low-level wind shear of 14 $m\ s^{-1}$. The vertical structure sloped upwards from the sea surface to 860 mb. In the horizontal, a 5° C gradient existed at the surface across a distance of 80 km. The east side of the front had near-adiabatic thermal stratification and a superadiabatic zone existed over the area of high sea surface temperature. At 870 mb, a low level jet existed with speeds up to 30 m $s^{-1}$. This northeasterly flow existed just above the baroclinicity of the boundary-layer front. Convective overturning in the boundary-layer front seemed to create the band of cumulus clouds noted in satellite imagery.

Shapiro, *et al.*, (1987) suggested differential heating and cooling for the frontal formation. Radiative heat losses from the Arctic sea-ice pack and adjacent snow/glacier covered land produce a strong surface based inversion. This heat loss will be strongest in the winter. Thermally stable air with high potential vorticity flows off the ice cap and over relatively warm oceanic waters. The air is warmed through sensible heat flux at the surface which destroys the low-level thermal stratification. The boundary-layer associated jet stream and associated potential vorticity field are formed by thermal wind effects in this frontal zone separating the heated ocean boundary-layer and the relatively cool land/ice boundary layer. Shapiro, *et al.*, (1987) also noted that these fronts were observed to propagate to as far away as Norway and the United Kingdom.

# III. SYNOPTIC/MESOSCALE OVERVIEW OF MIZEX 1987

## A. DATA SOURCE

Interpretation of surface weather patterns for MIZEX 1987 was based on sea-level pressure analysis performed at three-hour intervals at the Norwegian Meteorological Institute's Tromso station. The analyses were based on routine WMO reported data, satellite imagery and the reports available from the MIZEX 1987 ships. Due to the sparsness of the reporting network, the three MIZEX ships provided a significant increase in the resolution for the MIZ area and enhanced the analysis. In most cases the MIZEX 1987 ship data were timely. Where possible this late information was incorporated in this study for more accurate and complete analyses. Interpretation of upper-air features was based on the Navy Operational Global Analysis and Prediction System (NOGAPS) analysis. NOGAPS 500 mb contour analyses usually were not based on the MIZEX ship reports due to delay of the reports. Even with the additional surface data for current and post-analysis, this study benefited considerably from satellite imagery interpretation.

## B. GENERAL METEOROLOGY FEATURES

### 1. Time Series

Time series of the surface layer vector wind, pressure, temperature and relative humidity measured on the Hakon Mosby during the the period 23 March to 11 April (Fig. 3.1) gives a good summary of the meteorological variability during MIZEX 1987. Throughout most of this period, mesoscale phenomena dominated local weather conditions. The strong temperature inversion present in the Arctic inhibits downward momentum transfer from the upper and mid-level westerlies. Therefore, unless a strong cyclone or front destroys the inversion through intense convective mixing, the surface winds are usually quite weak, with 3 to 5 m $s^{-1}$ being quite common, coming from a highly variable direction (Sater, *et al.*, 1971). During MIZEX 1987 wind speeds ranged from calm to 24 m $s^{-1}$. Both extremes were short in duration, however. The lower wind speeds were associated with the influence of Arctic highs while the higher wind speeds were associated with transiting fronts and Arctic cyclones.

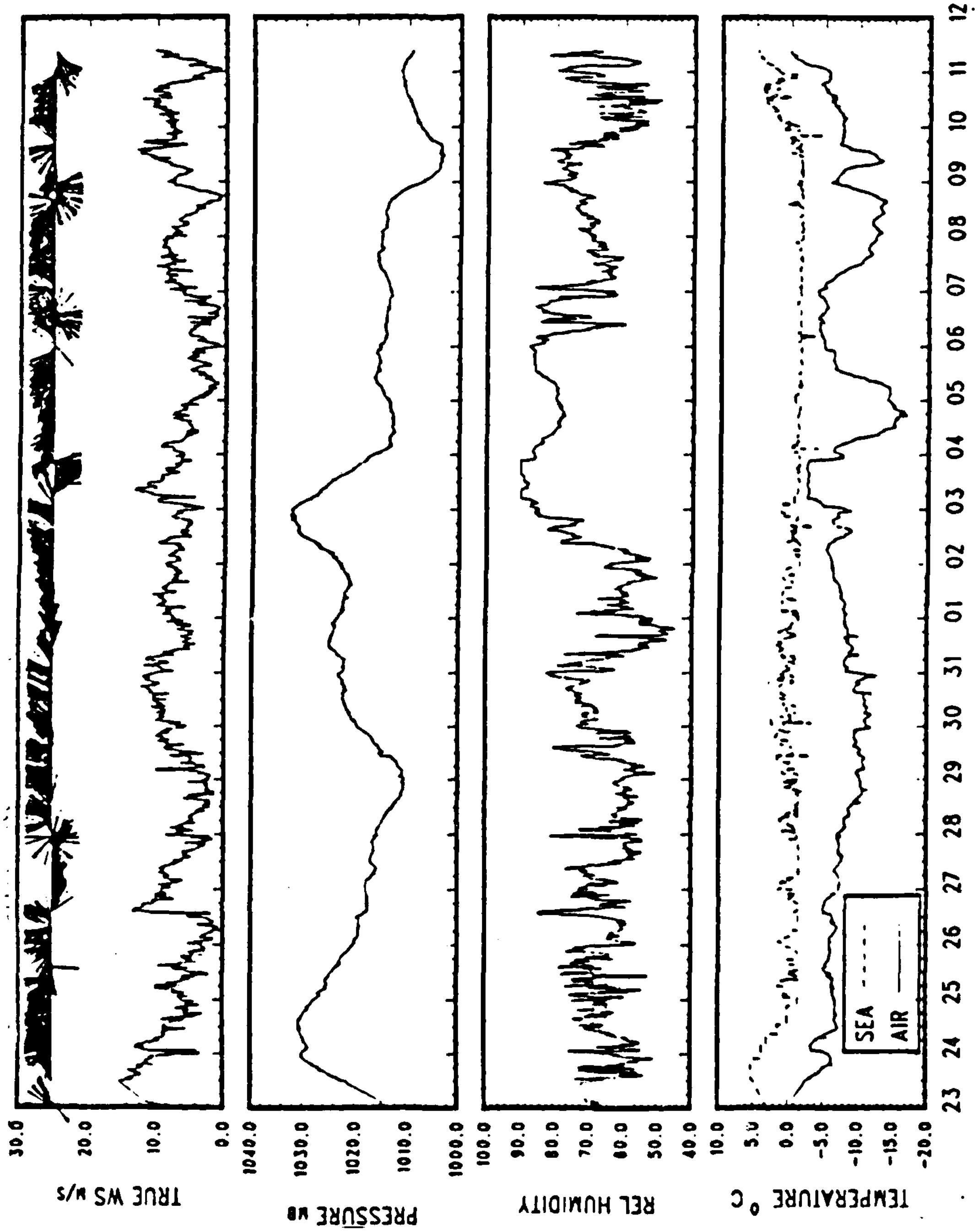



Fig. 3.1 Hakon Mosby Time Series, MIZEX 1987
23 March to 12 April 1987.

During MIZEX 1987, surface temperature ranged from -20.0° to 2.0° C. Sea-surface temperatures ranged from -1.7° C at the MIZ to 4.5° C in the waters just off the west coast of the Svalbard Islands. Climatological temperatures for the month of April, based on 12-year mean, show typical values in the Fram Strait MIZ of -8° C to -12° C (Sater, *et al.*, 1971). Over ocean waters a different situation exists. A warm tongue of the Gulf Stream penetrates northward, just west of Svalbard Islands, and is called the West Spitzbergen Current. These waters, with temperatures as high as 3° C to 5° C, provides a significant source of sensible heat and moisture for any overlying air mass. In the ice edge itself the water is maintained at a constant -1.7° C due to the presence of sea ice which forms and melts near these temperatures.

The MIZEX 1987 time series, Fig. 3.1, can be separated into five periods of distinct meteorological activity, described in the introduction. The first period, from 20 to 23 March, was influenced by a surface high pressure situated over the Fram Strait and is evidenced by the rise in surface pressure recorded on the Hakon Mosby until a maximum was reached early on 24 March. Associated with the high were northerly winds near 10 m $s^{-1}$. In addition, near-surface air temperatures were higher than the climatological value since they were above -5.0° C throughout this period. Measured relative humidity values were mostly in the 55 to 75 percent range.

During the second period, from 24 to 27 March, a mesoscale phenomena, referred to as a boundary-layer front, affected the Fram Strait weather. During this period a surface high over the Fram Strait had weakened and a boundary-layer front formed just west of the Svalbard Islands. The Hakon Mosby recorded surface pressure falling through the last day of this period (27 March). Northerly winds were evident, Fig. 3.1, until the boundary-layer front had passed and then wind speeds increased and wind direction shifted to the southeast.

The third period, from 28 March to 31 March, was influenced by a small scale low which persisted until the last two days when a steady rise in surface pressure was recorded. Surface temperature remained near constant throughout much of this period and wind direction was northerly.

The fourth period, from 1 to 3 April, was controlled by a small high pressure system over the Fram Strait. A synoptic-scale low which passed south of the Greenland Sea MIZ had little direct impact on the Hakon Mosby's time series observations. Hakon Mosby's measured wind values were 5 m $s^{-1}$ early on 1 and 2 April increasing to 10 m $s^{-1}$ late on 3 April with an associated wind direction shift to southerly and an increase in the relative humidity to 90 percent.

The fifth and last period, from 4 to 10 April, was influenced by the approach and passage of two synoptic-scale lows. During this period, the Hakon Mosby recorded variable wind directions and speeds. Relative humidity decreased from 90 percent and became highly variable. Sea-level pressures dropped until a frontal passage occurred mid-day on 9 April. As the synoptic-scale lows approached, the wind speed increased and, with the frontal passage, a wind direction shift occurred. An associated drop in surface pressure and temperature with this frontal passage lead to the lowest recorded values by the Hakon Mosby during MIZEX 1987.

### 2. Ice Edge during MIZEX 1987

The ice edge positions in MIZEX 1987 were analyzed by staff from the Naval Polar Oceanography Center, Suitland, Maryland stationed at the Tromso station for the experiment period. The analysts incorporated information from imagery of NOAA 9 and 10 polar-orbiting satellites and from the NIMBUS 7 SMMR. The representative ice edge during MIZEX 1987 (Fig. 2.2) reveals a 200 km wide inlet formed into the ice pack just west of the Svalbard Islands in the West Spitzbergen Current. During MIZEX 1987 the ice edge did not vary significantly from the postion shown in Fig. 2.2.

## C. DESCRIPTION OF SYNOPTIC/MESOSCALE CONDITIONS

### 1. Surface High over the Fram Strait (20 - 23 March 1987)

20 March was the first full day of field operations for the Valdivia in the Fram Strait. The sea-level pressure analysis for 12 UT 21 March, Fig. 3.2, reveals a typical March situation in the Greenland Sea. A large high is situated over northeast Greenland and a low is situated east of Iceland. This synoptic pattern persisted throughout the 20 - 23 March period. Svalbard Islands reported light and variable winds with little or no clouds during this period. On 21 March the Valdivia reported (Fig 3.4) winds of 10 to 15 m $s^{-1}$ from the east which was indicative of the moderate strength of the high. At 12 UT 21 March Valdivia's surface pressure reported was 1033.6 mb. In addition, no middle or low clouds were reported during the first half of this period. A composite DMSP IR image (Fig. 3.3) reveals a clear area over the Fram Strait region (A) further supporting the analysis of the extensive high over the region. Cyclonic activity (B) is also evident in Fig. 3.3 to the south near Iceland.

The time series data for the three ships is shown in Fig. 3.4. The Valdivia arrived in the MIZ area at 06 UT 20 March at 75.5° N and 017.0° E. At 06 UT 20 March the Valdivia reported easterly winds of 10 m $s^{-1}$ which increased in speed to 24 m $s^{-1}$ at 21 UT 20 March. Valdivia's sea-level pressure gradually rose during this period from 1022.0 mb at 00 UT 20 March to 1037.6 mb at 09 UT 23 March. No relative humidity measurements are available from the Valdivia due to the lack of a instrument which could measure relative humidity below freezing. The Polar Circle

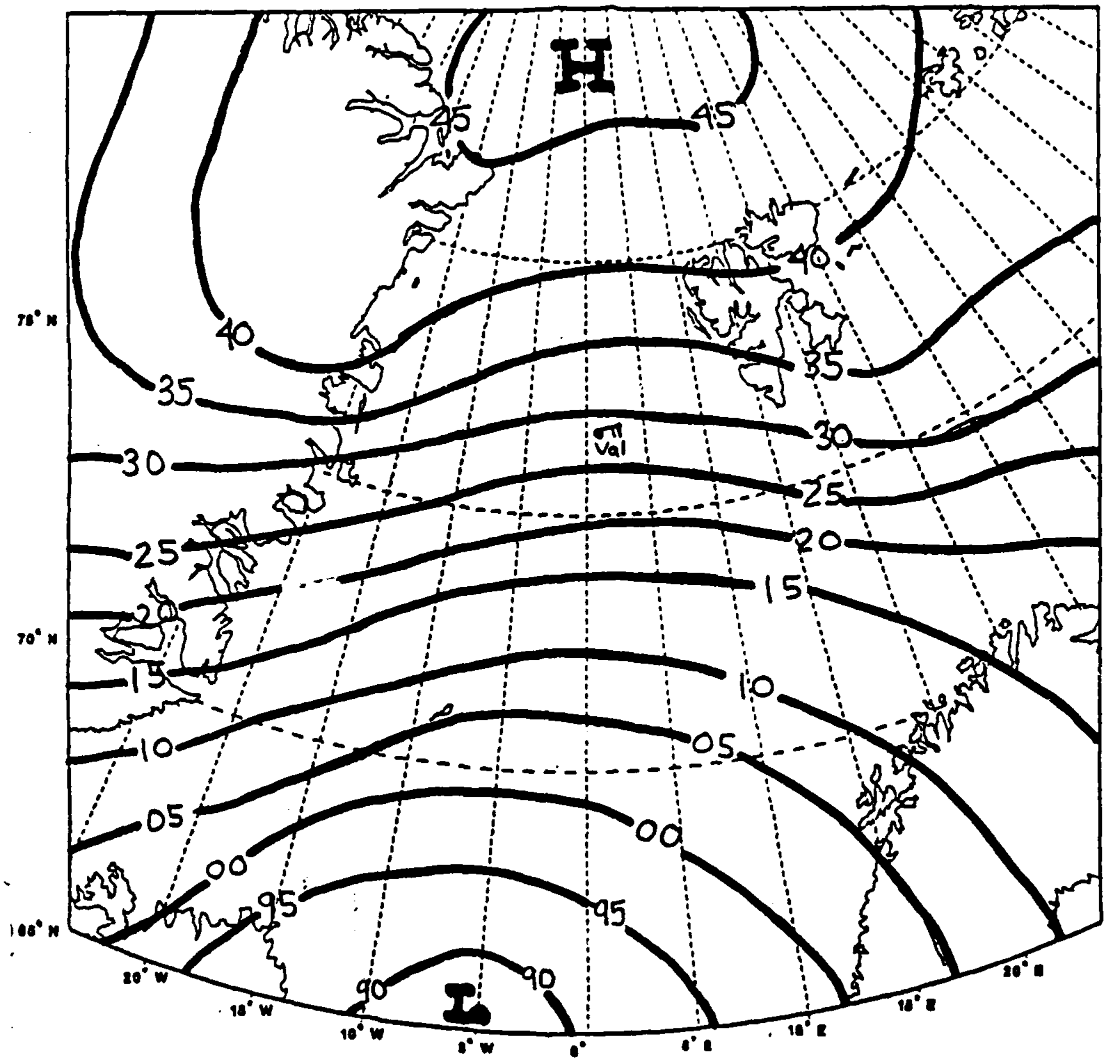



Fig. 3.2 Sea-Level Pressure Analysis, 12 UT 21 March 1987.

and Hakon Mosby arrived in the MIZ vicinity late on 23 March after transiting from Tromso, Norway with high easterly winds and seas (Fig. 3.4) while the Valdivia, 350 km to the northwest measured weaker winds from the west. The Polar Circle and Hakon Mosby measured, during the transit, winds approaching 20 m $s^{-1}$ on 23 March. During the latter part of this period (22 - 23 March), all three ships measured (Fig. 3.4) a gradual decrease in the winds to less than 5 m $s^{-1}$, remaining from an easterly direction, accompanied by an increase in the low and middle level clouds.

The 500 mb contour analysis for 12 UT 21 March (Fig. 3.5) shows a high directly over the Fram Strait region. Valdivia's rawinsonde 500 mb height taken in the

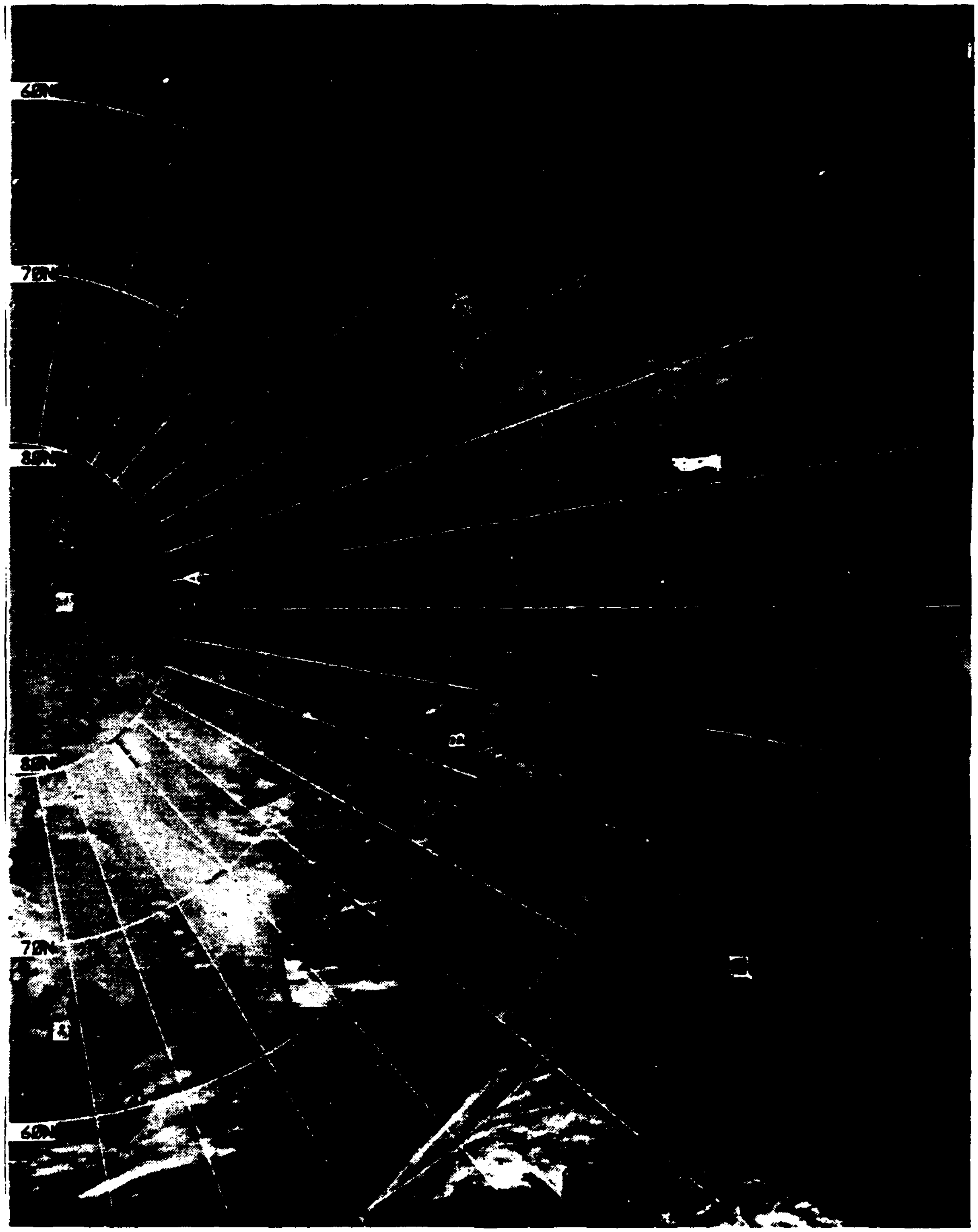



Fig. 3.3 DMSP Composite IR Imagery
Centered at 1201 UT 21 March 1987.

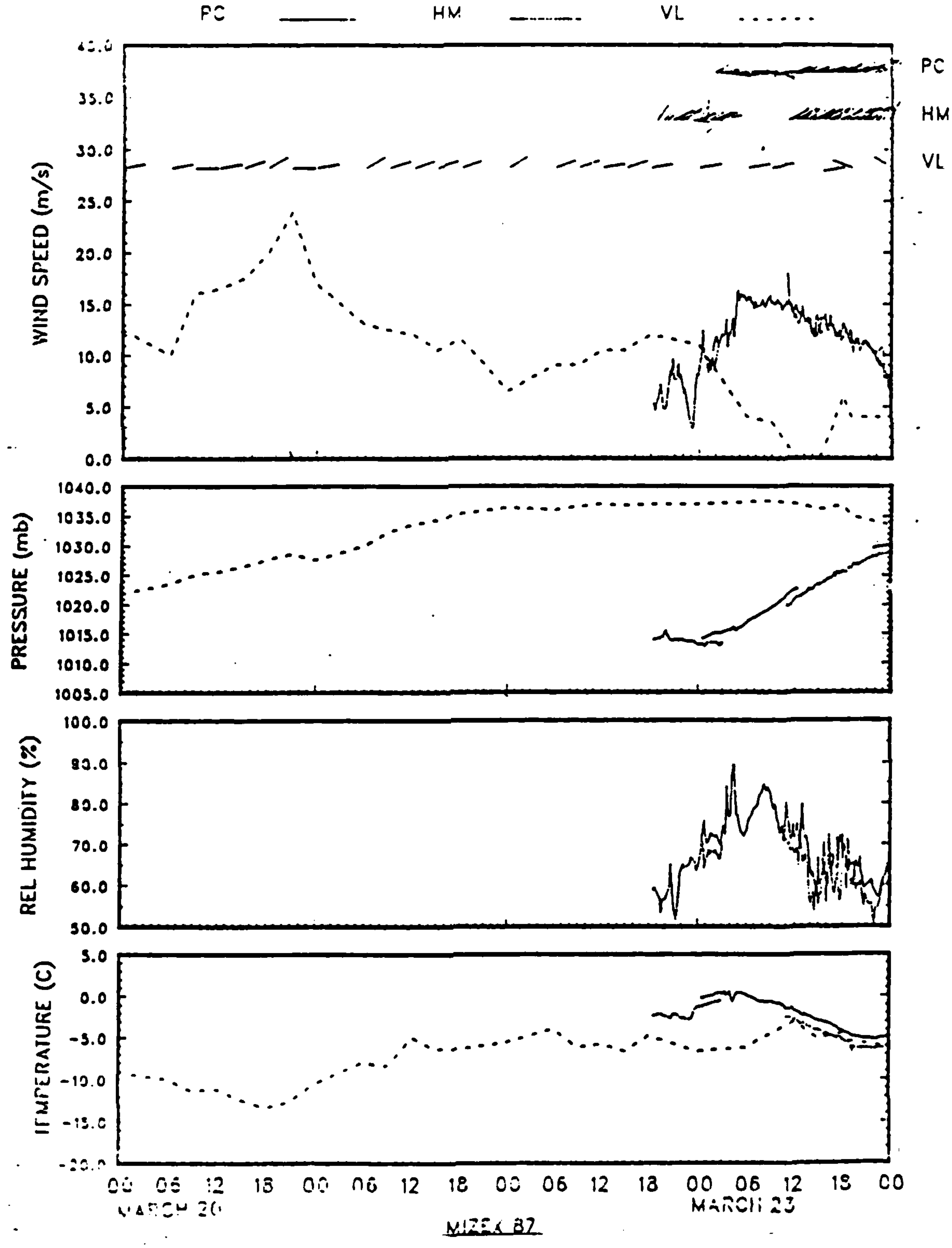



Fig. 3.4 MIZEX 1987 Ships Surface Layer Time Series
20 - 23 March 1987.

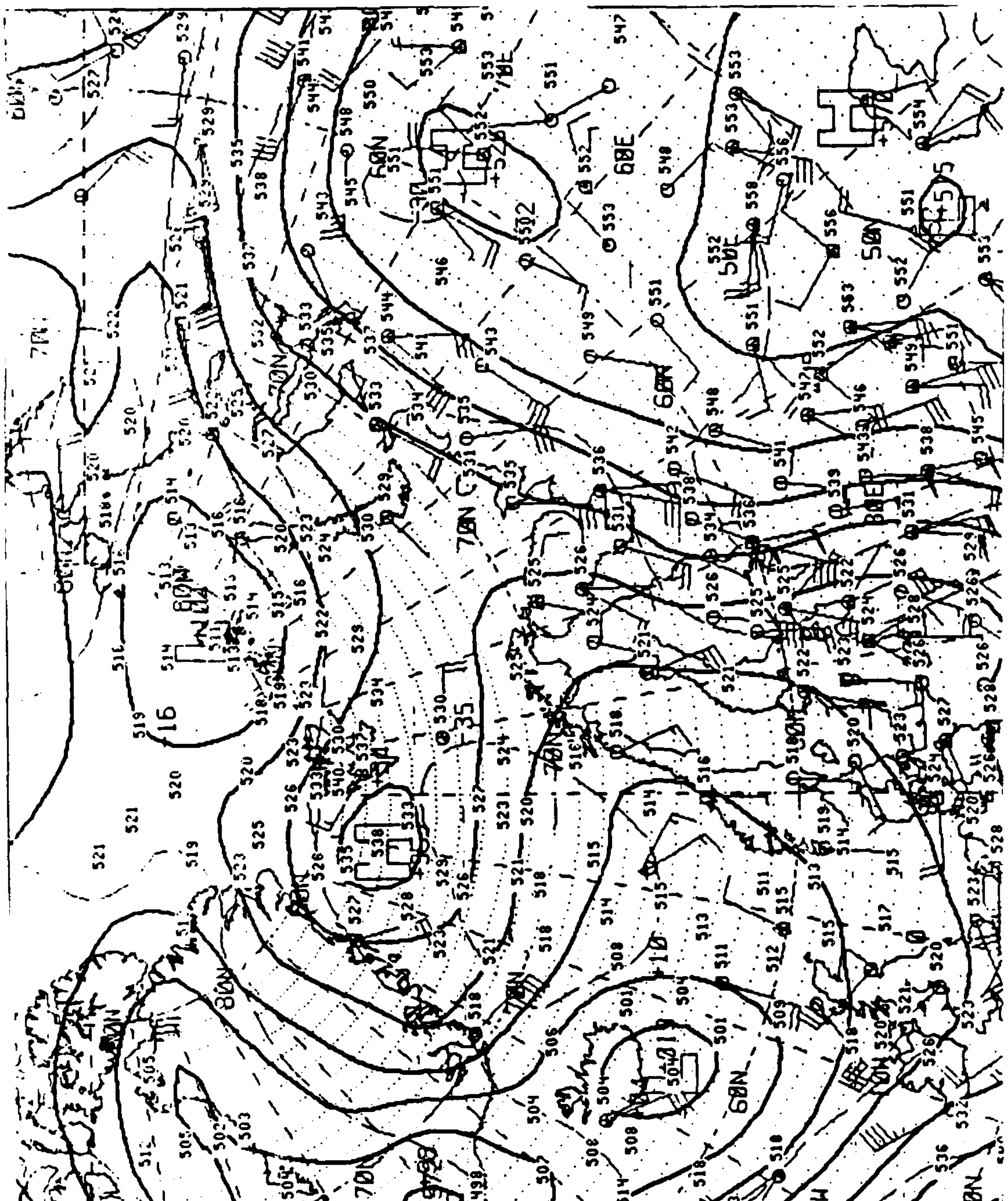


Fig. 3.5 500 mb Contour Analysis, 12 UT 21 March 1987.

Fram Strait (77.1° N, 10.0° E) at 1207 UT 21 March was 531 dm which supports the analysis of the 500 mb high although this level was 2 to 7 dm lower than the accompanying satellite soundings and 9 dm lower than the height at the Svalbard Islands. The Polar Circle and Hakon Mosby were not in the MIZ region and their rawinsonde 500 mb heights were not available for this period. The Svalbard Islands reported associated upper-level winds from the northwest of 8 m $s^{-1}$ which supports the analysis of an upper, as well as a lower-level, high over the region.

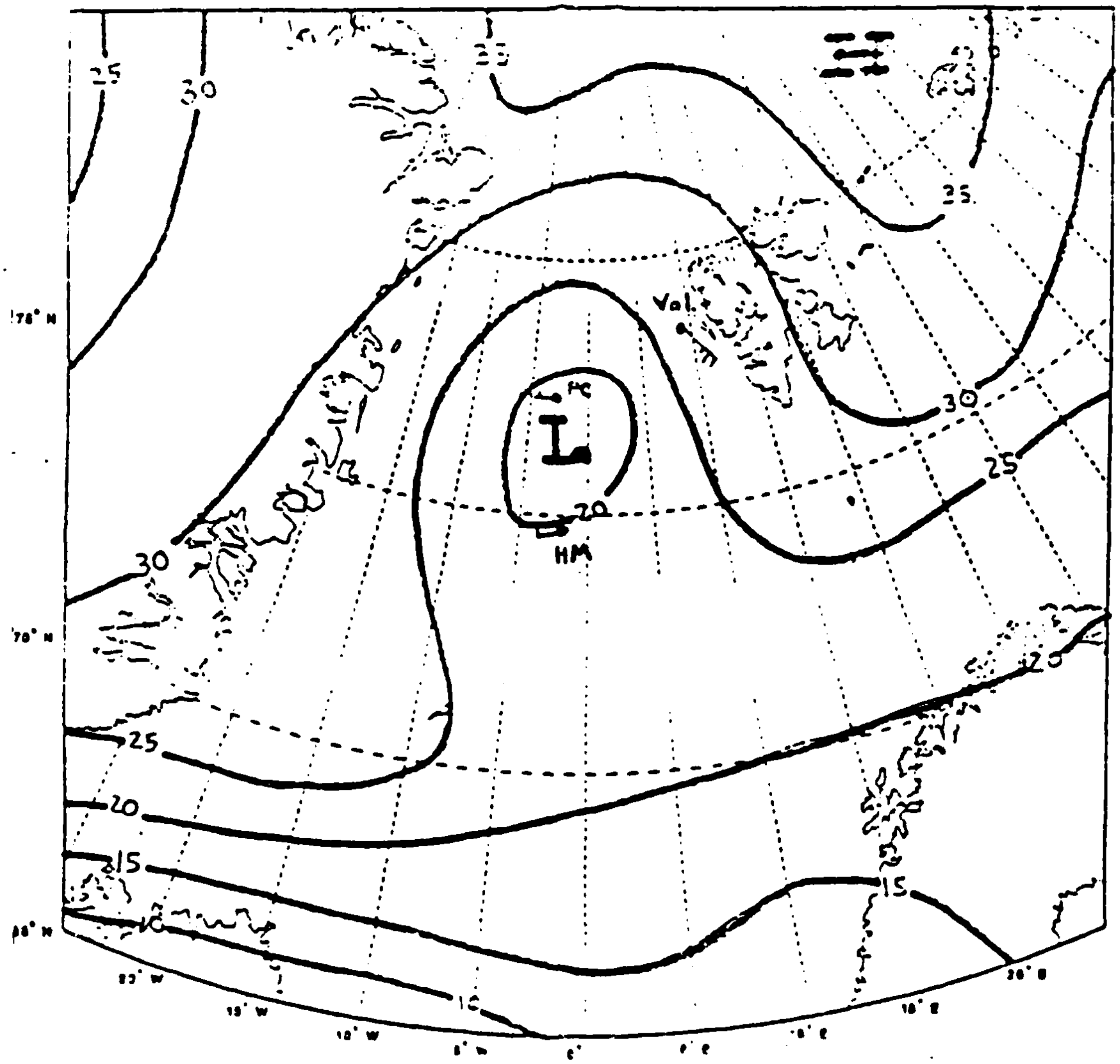



Fig. 3.6 Sea-Level Pressure Analysis, 12 UT 25 March 1987.

Fig. 3.7 NOAA 10 IR Satellite Imagery, 1039 UT 25 March 1987.

### 2. Easterly Wave in the Fram Strait (24 - 27 March 1987)

During this period the Fram Strait region saw a front develop 100 km west of the Svalbard Islands which moved westward across the strait while an upper-level high continued to dominate above. The sea-level pressure analysis for 12 UT 25 March (Fig. 3.6) has a surface low 300 km off the west coast of the Svalbard Islands associated with the development and movement of a boundary-layer front just west of the Svalbard Islands. This mesoscale feature will be examined in more detail in Chapter IV.

Before this period, the Greenland High had weakened considerably with an associated development of high pressure located 300 km to the northeast of the Svalbard Islands. Significantly, the boundary-layer front off the west coast of the Svalbard Islands (A) moved rapidly westward on 25 March until it reached the MIZ (B to C) where it stalled and dissipated. A north to south band of cumulus clouds in the satellite imagery for 1039 UT 25 March (Fig. 3.7) indicates that the position of the boundary-layer front is 100 km west of the Svalbard Islands. Realignment of the cloud streets to the southeast of the Svalbard Islands further indicates that winds were beginning to shift to a more easterly direction.

The time series data for all three ships (Fig. 3.8) shows that associated with this frontal movement were increases in the wind speed and a clockwise turning of winds to the southeast behind the front (east side). Ships on the west side of the front reported lower wind speeds than the Valdivia, east of the front, and from a westerly direction. Specifically, at 12 UT 25 March the Valdivia measured southeasterly winds at 12 m $s^{-1}$ while the Hakon Mosby on the west side of the front, measured northwesterly winds at less than 10 m $s^{-1}$. The pressure difference across the front was minimal with the Valdivia reporting 1025.4 mb and the Hakon Mosby reporting 1023.2 mb and falling. However, a marked contrast in temperature was evident across the front. The Valdivia, on the east side of the front, reported -10.5° C while the Hakon Mosby, west of the front, reported only -5.7° C. This may be due to the relative positions of the ships in relation to the front. The Valdivia, on the east side of the front, was influenced by the cold Arctic air outbreak. The Hakon Mosby, on the west side of the front, was under the influence of the ocean waters. Examination of these surface ship reports supports the analysis of the existence of the boundary-layer trough in the middle of the Fram Strait. Thus, the sea-level pressure analysis (Fig. 3.6) should indicate the presence of a front rather than a surface low.

The 500 mb contour analysis for 12 UT 25 March (Fig. 3.9) shows that the upper-level high over the Fram Strait had weakened from 12 UT 21 March although the associated 500 mb winds over the Svalbard Islands increased to 15 m $s^{-1}$ and turned clockwise to have northerly flow off the ice pack. It is possible that this upper-level high pattern was responsible for the lack or absence of Polar Lows during MIZEX 1987. Shapiro, *et al.*, (1987), observed for the February 1984 Polar Low Project case that an upper-level low existed over the boundary-layer front during the development of a Polar Low. In MIZEX 1987, the upper-level high may have

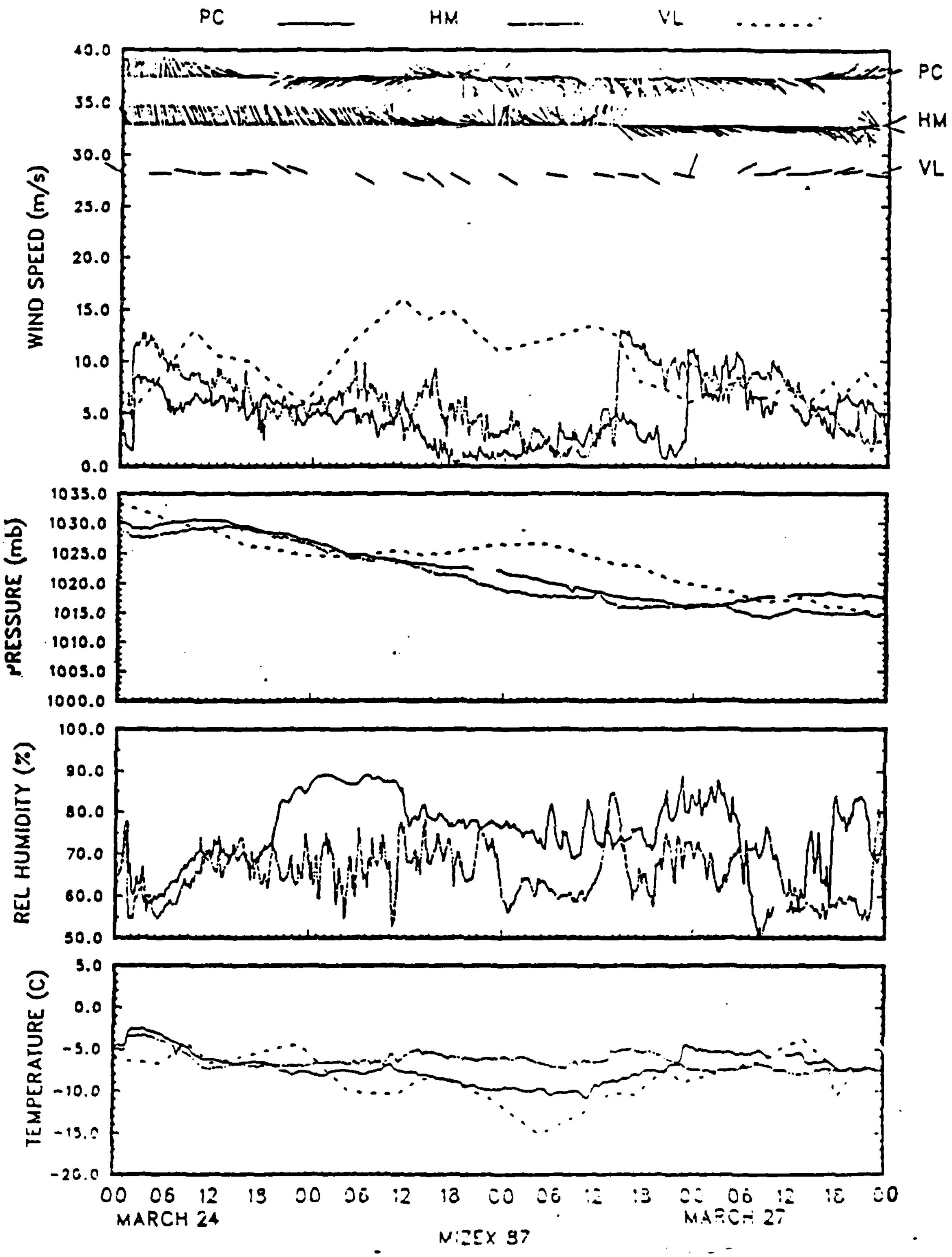



Fig. 3.8 MIZEX 1987 Ships Surface Layer Time Series 24 - 27 March.

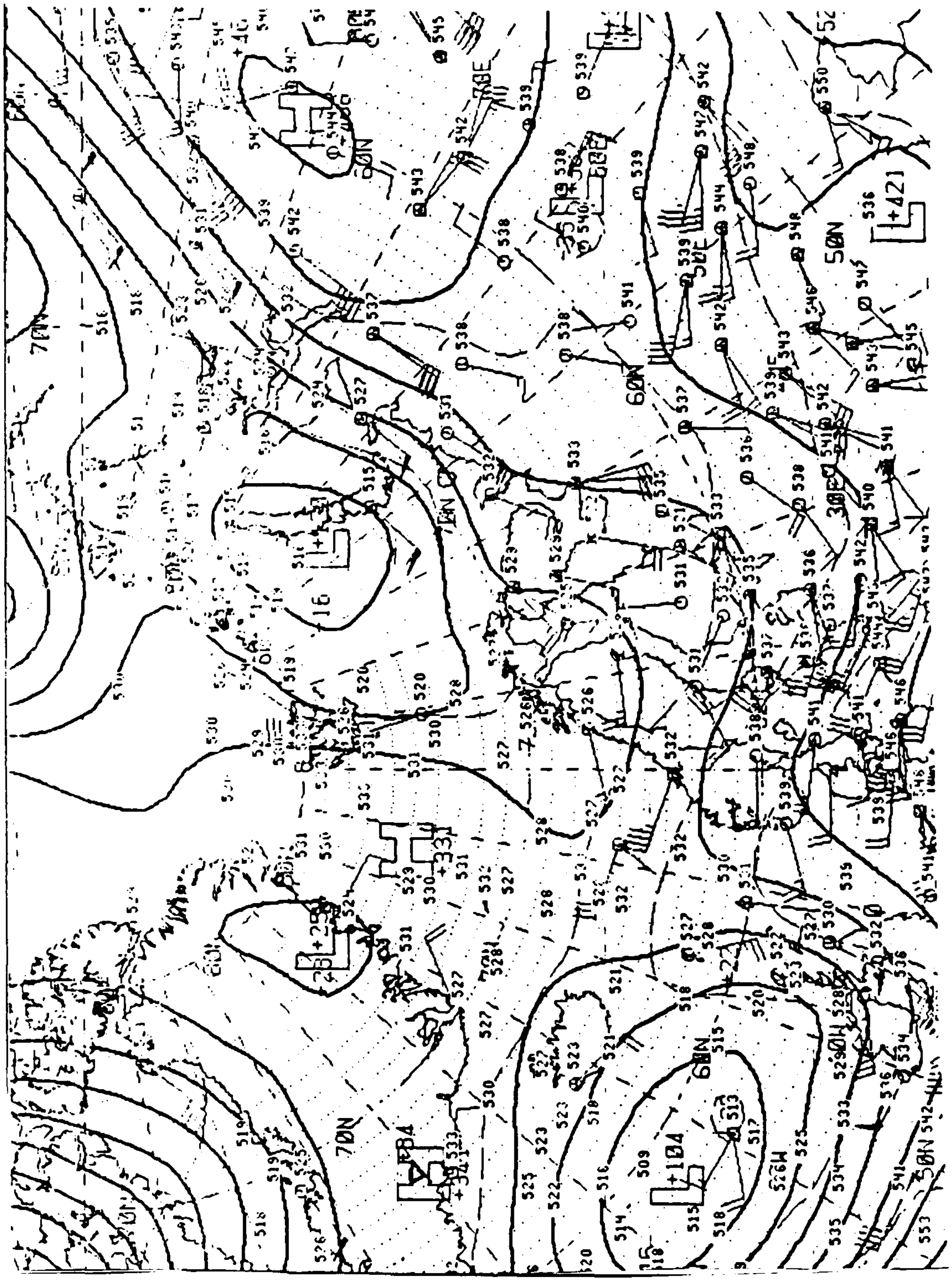


Fig. 3.9 500 mb Contour Analysis, 12 UT 25 March 1987.

prevented any development. The influence of upper-level patterns on Polar Low developments has been postulated by Businger (1985). The 500 mb low, over Iceland, moved south and the low northeast of the Svalbard Islands also moved south to a position 500 km east of the Svalbard Islands. This led to a situation where a northerly upper-level flow overlies the easterly surface flow in the eastern portion of the Fram Strait. Valdivia and Polar Circle rawinsonde profiles, located in the Fram strait measured northeasterly flow of 10 m $s^{-1}$, indicating the 500 mb analysis had perhaps undercalculated the strength of the low 500 km east of the Svalbard Islands. The easterly surface flow was reported by both the Valdivia and on the Svalbard Islands. Valdivia's rawinsonde 500 mb height was 525 dm at 1659 UT 25 March in the Fram Strait region (77.4° N, 10.0° E). This was 2 to 4 dm less than the surrounding satellite profiles and supports the analysis of a persisting but weakened high from 1207 UT 21 March. Polar Circle's rawinsonde 500 mb height was 530 dm at 1652 UT 25 March in the western Fram Strait region (76.2° N, 2.2° W). This agreed closely with the surrounding satellite soundings and further supports the analysis of a persisting high at 500 mb.

### 3. Weak Stationary Surface Low (28 - 31 March 1987)

This period had a weak surface low develop over the Fram strait while the upper-level low over the region remained but weakened. The sea-level pressure analysis for 12 UT 28 March (Fig. 3.10) reveals that during this period the high northeast of the Svalbard Islands maintained its position although it weakened. The Greenland surface high has strengthened and moved southeast over the southeast coast of Greenland. After the dissipation of the front near the Greenland Sea MIZ on 27 March, a small weak surface low dominated the Fram Strait and remained stationary. This was analyzed by the Norwegian Meteorological Institute as an inverted trough over the MIZEX 1987 region.

The NOAA 10 IR satellite imagery for 1120 UT 28 March (Fig. 3.11) has west of the Svalbard Islands (A) two bands of north-south cumulus clouds (B and C) over the Fram Strait region. The DMSP IR satellite imagery (Fig. 3.12) taken at an earlier time than the NOAA 10 imagery and for a larger area, shows southeast of the Svalbard Islands (A) a cloud vortex (B) associated with the surface low 100 km off of the west coast of Norway (C).

During this period, the Hakon Mosby measured (Fig. 3.13) light northerly winds of 10 m $s^{-1}$. A pressure fall from 1029.0 mb at 12 UT 24 March to 1011.4 mb

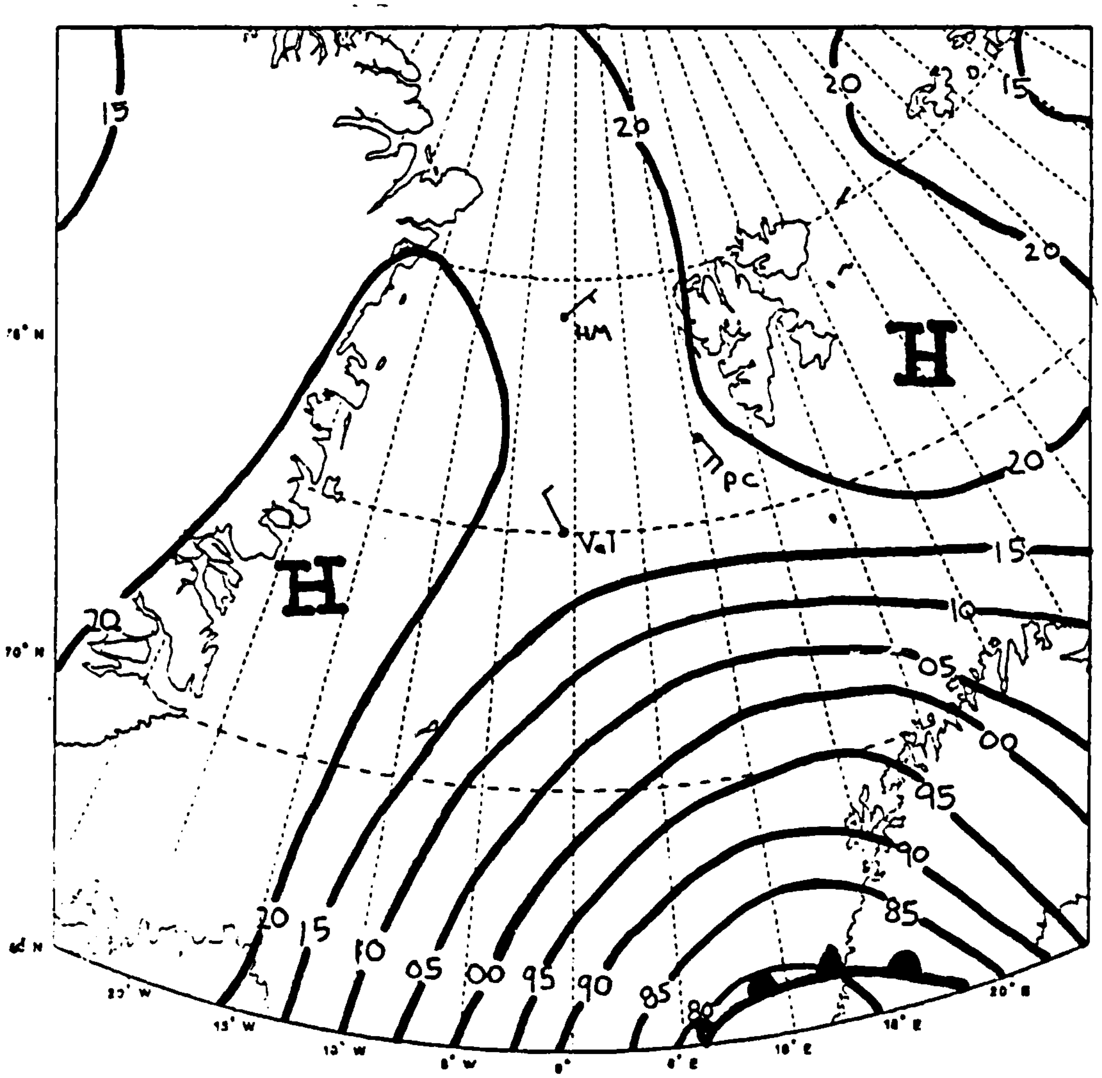



Fig. 3.10 Sea-Level Pressure Analysis, 12 UT 28 March 1987.

at 12 UT 28 March, measured by the Hakon Mosby, indicated the weakening of the Greenland High. Pressure drops were also recorded on the Polar Circle and the Valdivia, further supporting the analysis of the weakening of the high. Both Hakon Mosby and Polar Circle, stationed near each other, recorded temperatures of -9.1° C at 03 UT 28 March. The Polar Circle reported northeasterly winds of 5 m $s^{-1}$ at 00 UT 28 March shifting to northerly winds of 7 to 8 m $s^{-1}$ at 12 UT 30 March. During the last two days of this period the Hakon Mosby recorded a sea-level pressure rise of 13 mb, from 1010.0 mb at 06 UT 29 March to 1023 mb at 18 UT 30 March. The Polar Circle and the Valdivia also recoreded similar rises in pressure. The Valdivia, 500 km farther south and farther away from the MIZ, recorded at 12 UT 30 March northerly winds at 6 m $s^{-1}$, a sea-level pressure of 1012.5 mb and a temperature at -5.4° C.

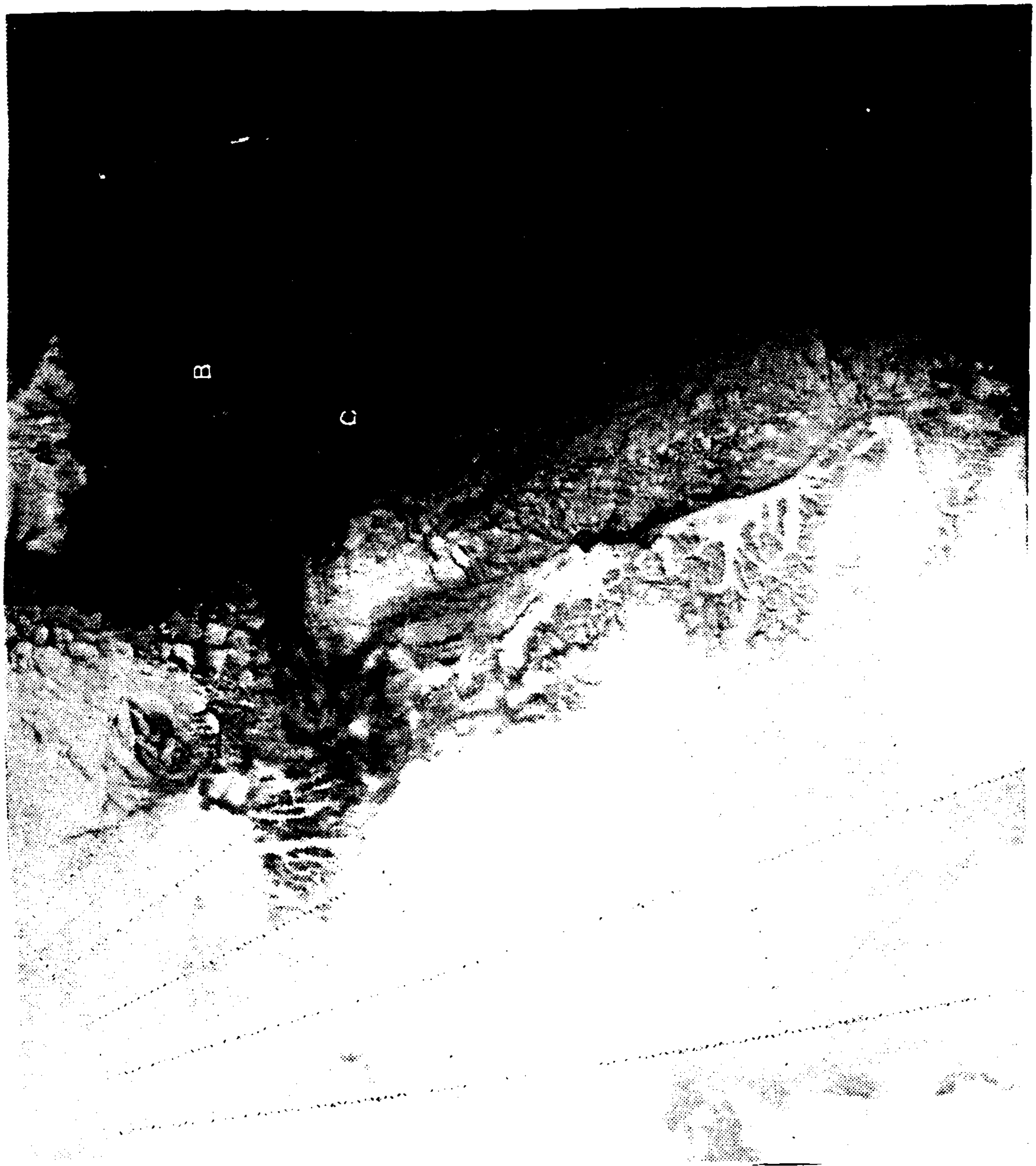



Fig. 3.11 NOAA 10 IR Satellite Imagery, 1120 UT 28 March 1987.

The 500 mb contour analysis for 12 UT 28 March (Fig. 3.14) shows a persisting upper-level high pressure system over the Fram Strait. A ridge intensified over Iceland and a strong upper-level low moved over central Norway. The low, which was 500 km east of the Svalbard Islands deepened slightly and remained stationary so upper-level westerly flow continued over both the Fram Strait and the Barents Sea. Valdivia's rawinsonde 500 mb height was 514 dm at 1118 UT 28 March in the southern Fram Strait region (75.0° N, 0.2° E). This was 4 dm less than the surrounding

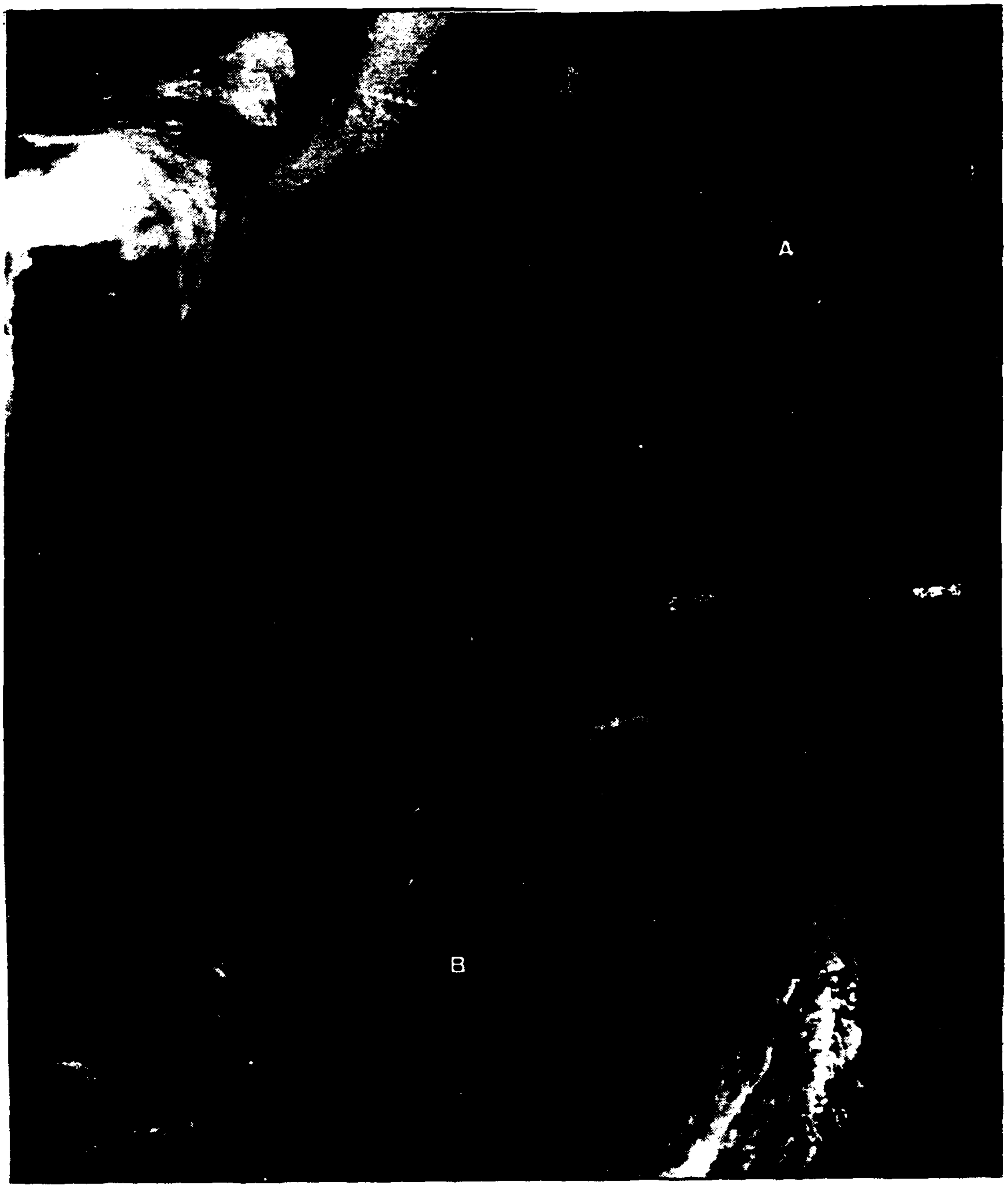



Fig. 3.12 DMSP IR Satellite Imagery, 0418 UT 28 March 1987.

satellite soundings and supports the analysis of the ridge over the Fram strait. The Polar Circle's rawinsonde 500mb height was 515 dm at 1052 UT 28 March in the western Fram Strait region (78.4° N, 1.1° E). This height was included in the 12 UT contour analysis (Fig. 3.14).

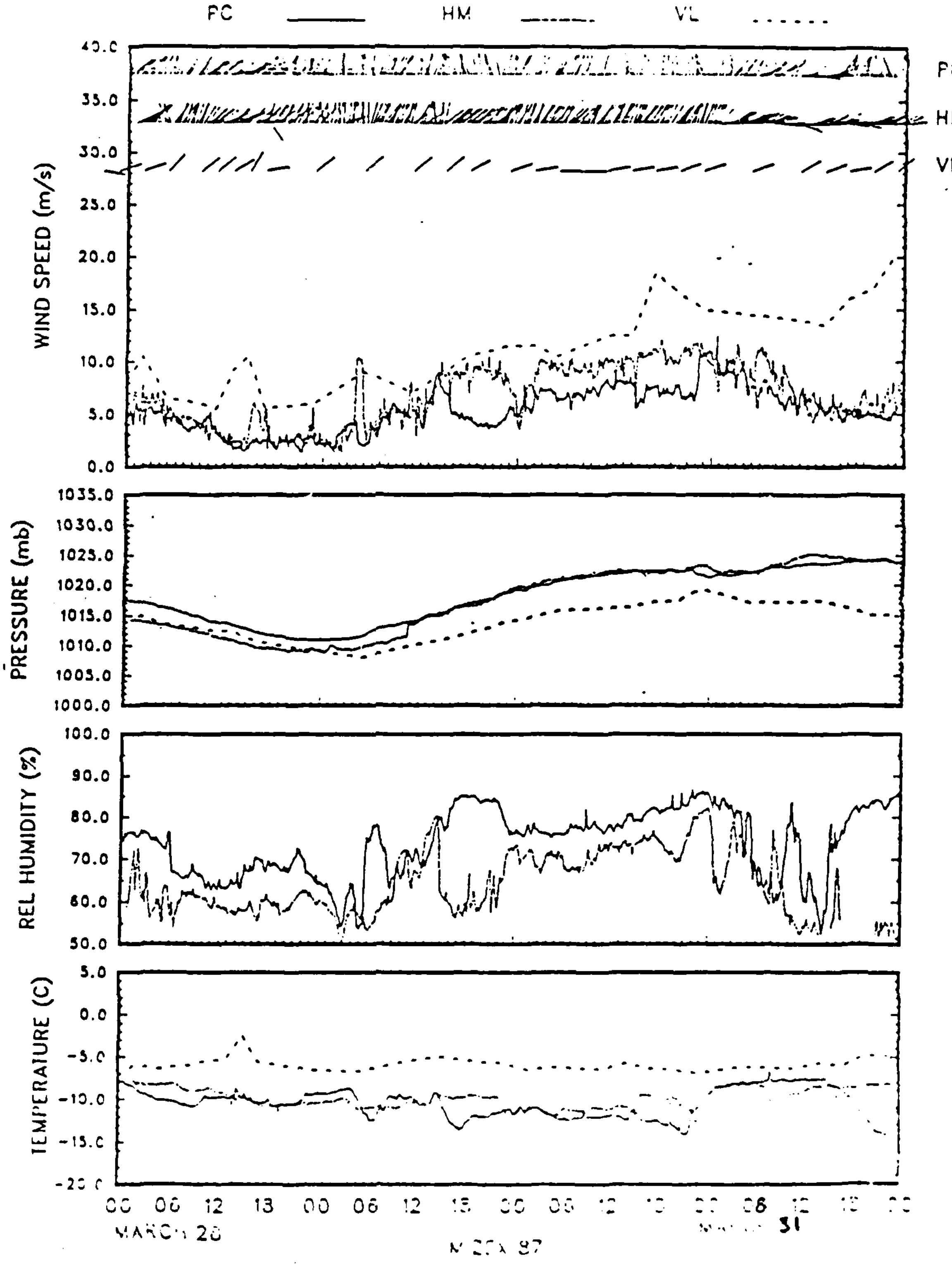



Fig. 3.13 MIZEX 1987 Ships Surface Layer Time Series
28 - 31 March 1987.

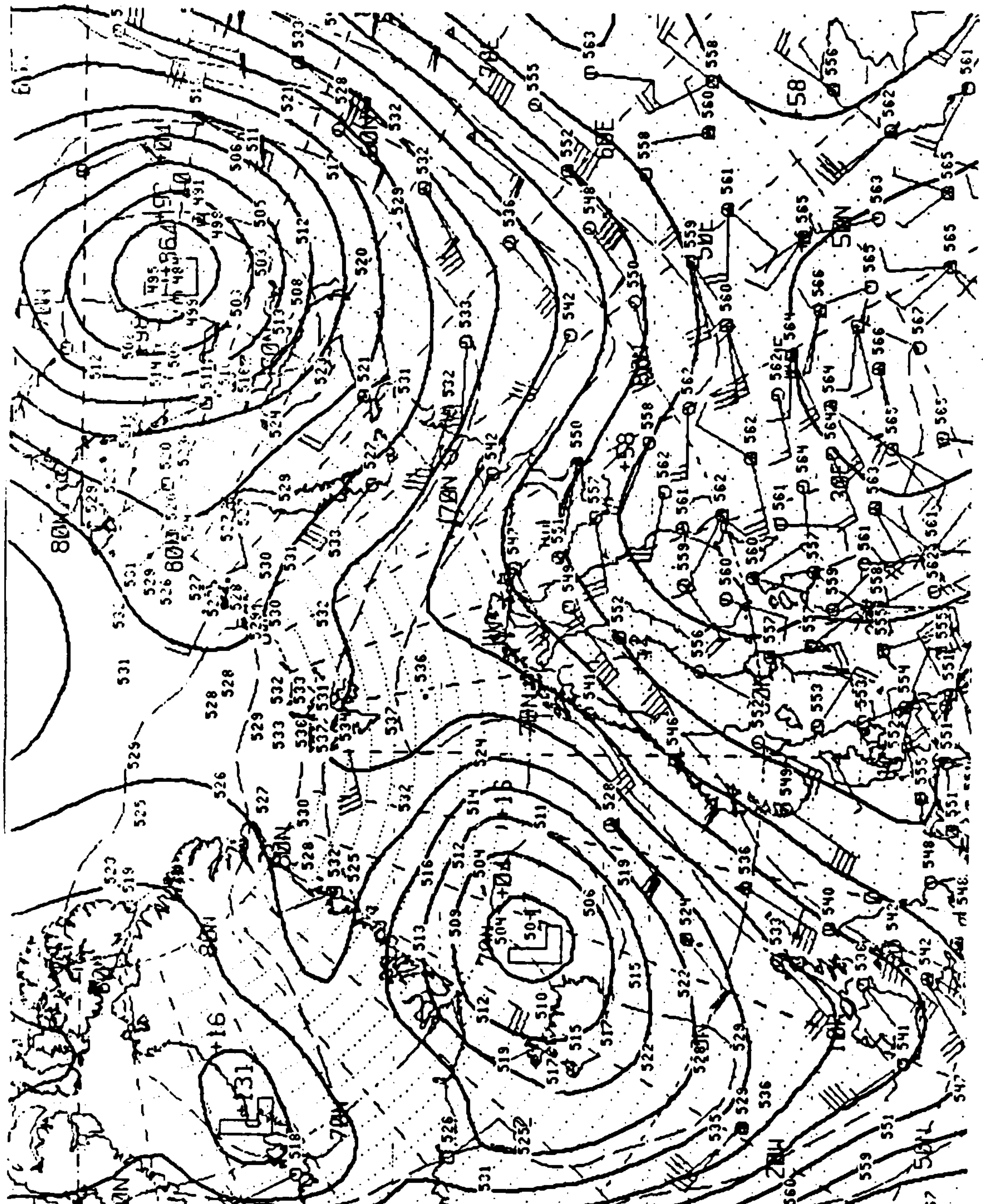


Fig. 3.14 500 mb Contour Analysis, 12 UT 28 March 1987.

4. **First Approaching Synoptic Scale Low (1 - 3 April 1987)**

The fourth synoptic period of MIZEX 1987 showed the first influence of major cyclones from the south. The sea-level pressure analysis for 12 UT 1 April (Fig. 3.15) reveals that the high over Greenland and the high northeast of the Svalbard Islands maintained their relative positions. The small scale surface low also maintained its position over the Fram Strait region and was analyzed as a shallow inverted trough. During the 1 - 3 April period, a surface synoptic-scale low, to be referred to as Low A, with an initial position of 66.5° N and 013.0° W at 12 UT 1 April moved eastward. The satellite imagery for 0442 UT 1 April (Fig. 3.16) shows a cloud vortex feature (A) southwest of the Svalbard Islands (B) and north of Iceland (C) which illustrates the strength and position of Low A. By 09 UT 3 April, Low A moved into central Norway and filled. The Svalbard Islands reported steady 10 to 12 m $s^{-1}$ southeasterly surface winds throughout most of this period.

Time series data for the period 1 - 3 April appear in Fig. 3.17. The Valdivia, stationed 400 km farther south than the other ships during this time, reported northeasterly winds over 20 m $s^{-1}$, sea-level pressure of 1007.8 mb and an air temperature of -3.0° C at 06 UT 1 April. The high wind speeds occurred because the Valdivia was near the occluded front associated with Low A. The DMSP satellite imagery (Fig. 3.16) has a band of cumulus clouds associated with the occluded front close to Valdivia's postion.

The Polar Circle was well into the ice pack during this period and the Hakon Mosby maintained a position just outside the MIZ. Polar Circle's winds were northerly at 8 m $s^{-1}$ and the sea-level pressure was rising until it reached 1032 mb at 00 UT 3 April. The Polar Circle's temperature increased until it reached -2.0° C at 12 UT on 3 April. The nearby Hakon Mosby reported a similar trend in wind, pressure, relative humidity and temperature although the temperatures were higher by 2 to 3° C. The higher Hakon Mosby temperatures are most likely due to its position relative to the MIZ. Since the Polar Circle was well into the ice pack her temperatures are lower than the Hakon Mosby's, which was located outside the MIZ. This would be especially true with the northerly winds occurring. At 04 UT 3 April clockwise wind shifts from northerly to southeasterly were recorded on all three ships. Wind speeds after this shift became highly variable ranging in value from 3 to 13 m $s^{-1}$. These wind reports may be related to the distant passage of Low B, 650 km to the south.

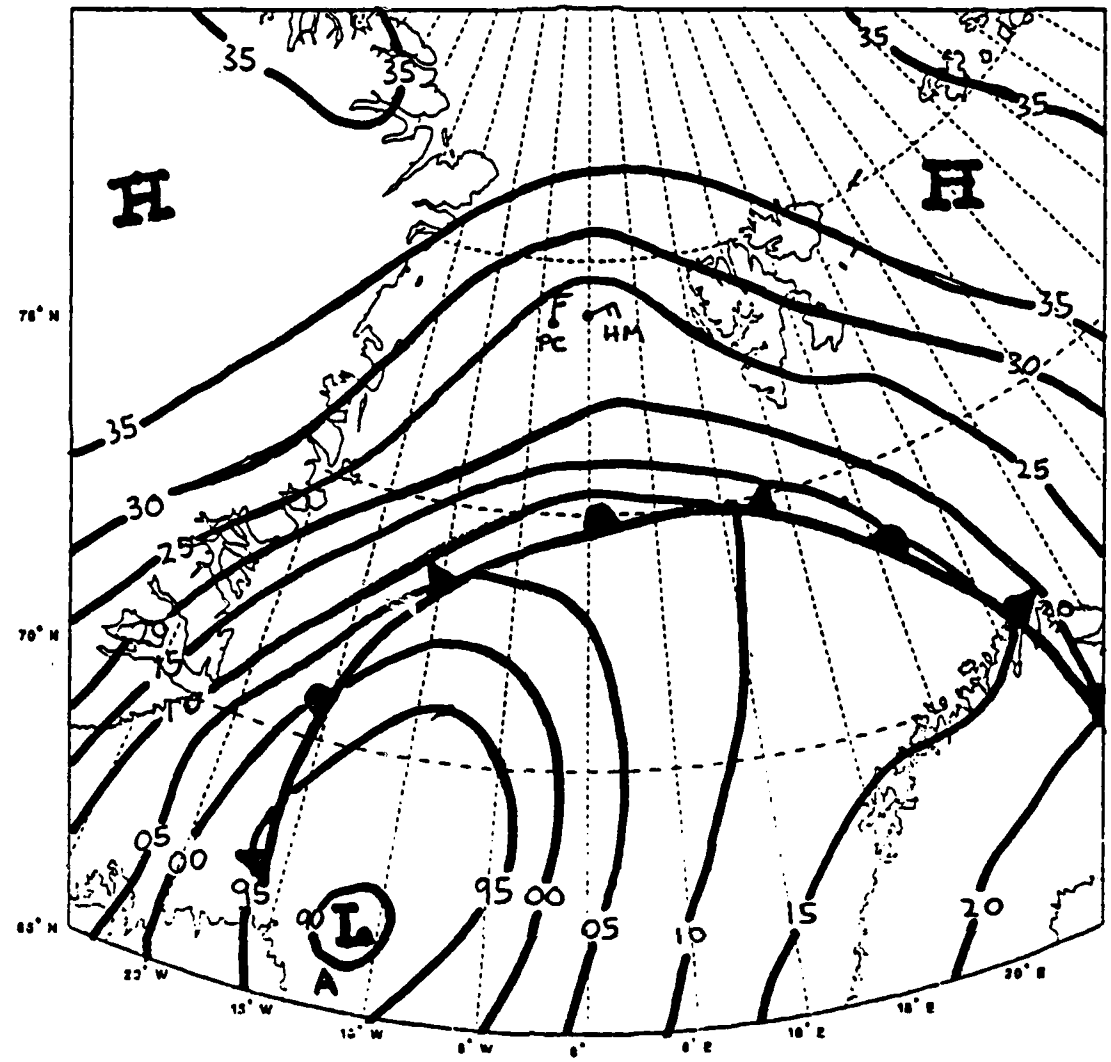



Fig. 3.15 Sea-Level Pressure Analysis, 12 UT 1 April 1987.

The 500 mb contour analysis for 12 UT 1 April (Fig. 3.18) has a ridge extending from northern Norway to over the Fram Strait. The Svalbard Islands' 500 mb winds were coming from the southwest at 18 m $s^{-1}$. A strong 500 mb low exists 100 km north of Iceland associated with the position of a surface synoptic-scale low in Fig. 3.15. The relative positions of the 500 mb and surface lows suggests that Low A sloped westward with height indicating a developing system. Valdivia's rawinsonde 500 mb height was 531 dm at 1655 UT 1 April in the southern Fram Strait region (75.2° N, 2.1° W). This supports the analysis of a ridge over the Fram strait region. The Polar Circle's rawinsonde 500 mb height was 532 dm at 1055 UT 1 April in the western

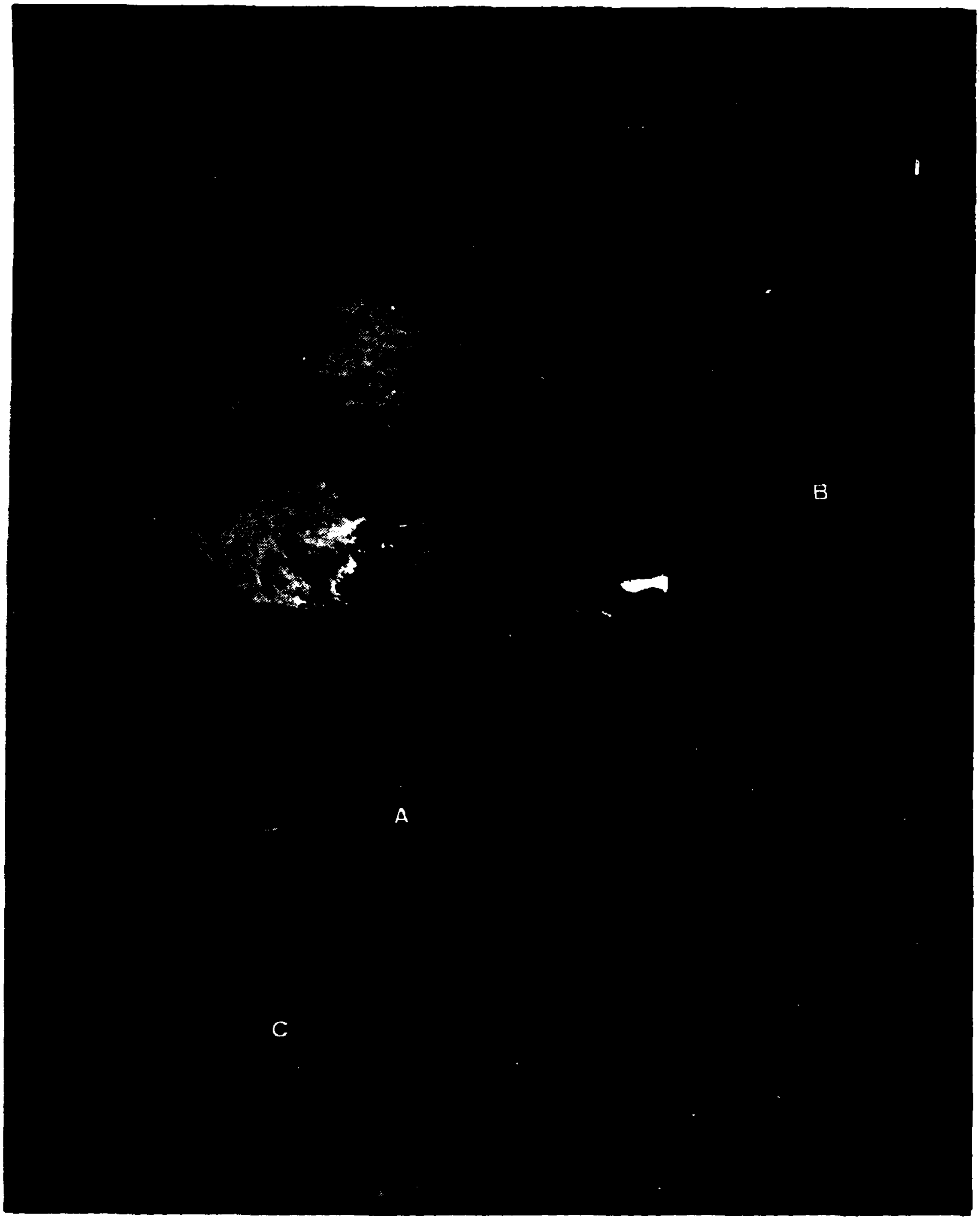



Fig. 3.16 DMSP IR Satellite Imagery, 0442 UT 1 April 1987.

Fram Strait region (78.1° N, 3.5° W). This height indicates that the ridge in the 12 UT contour analysis for 1 April (Fig. 3.18) should be even stronger. With this additional 500 mb height information an extension of the 530 dm contour northwestward to cover the entire Fram Strait region would be required.

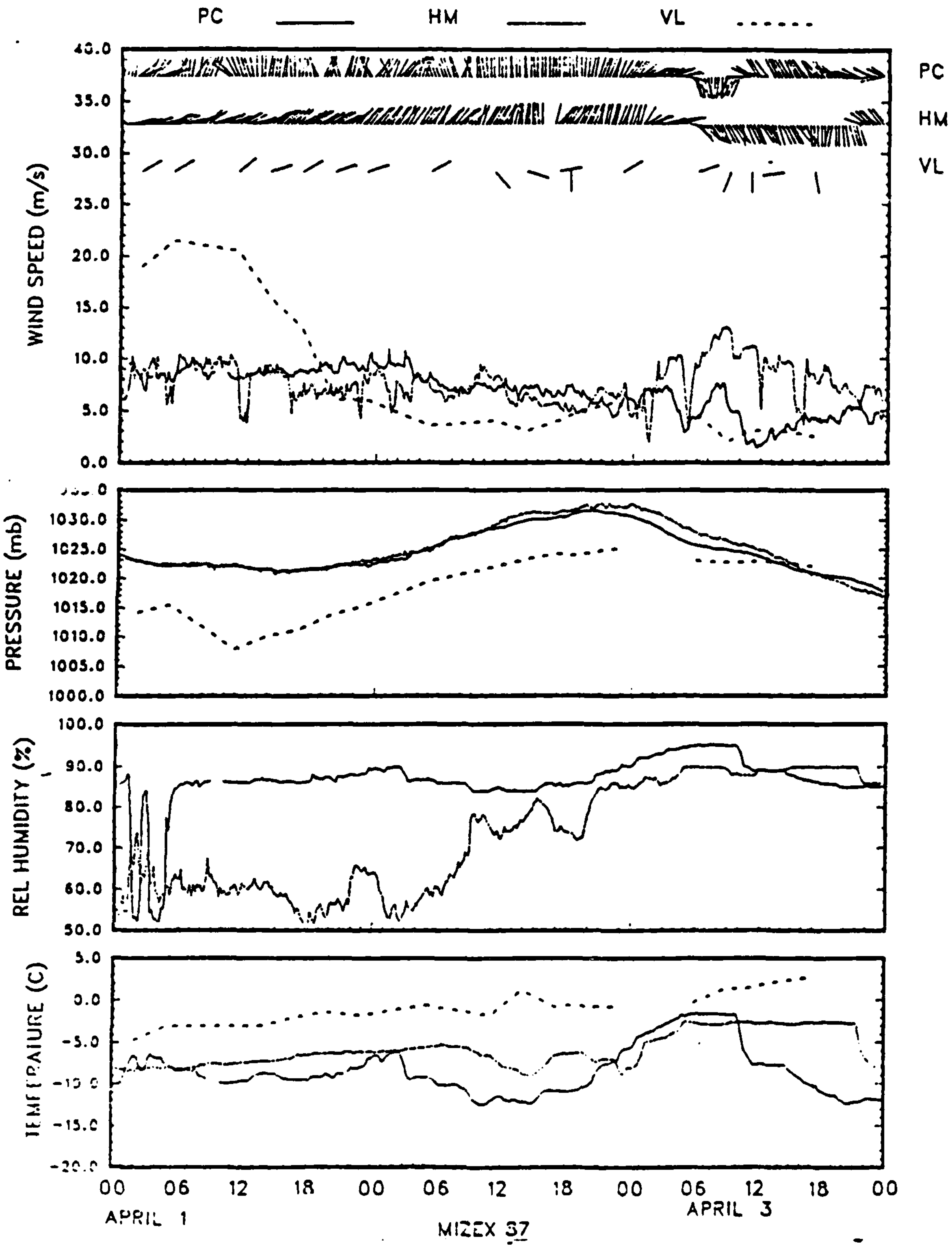



Fig. 3.17 MIZEX 1987 Ships Surface Layer Time Series
1 - 3 April 1987.

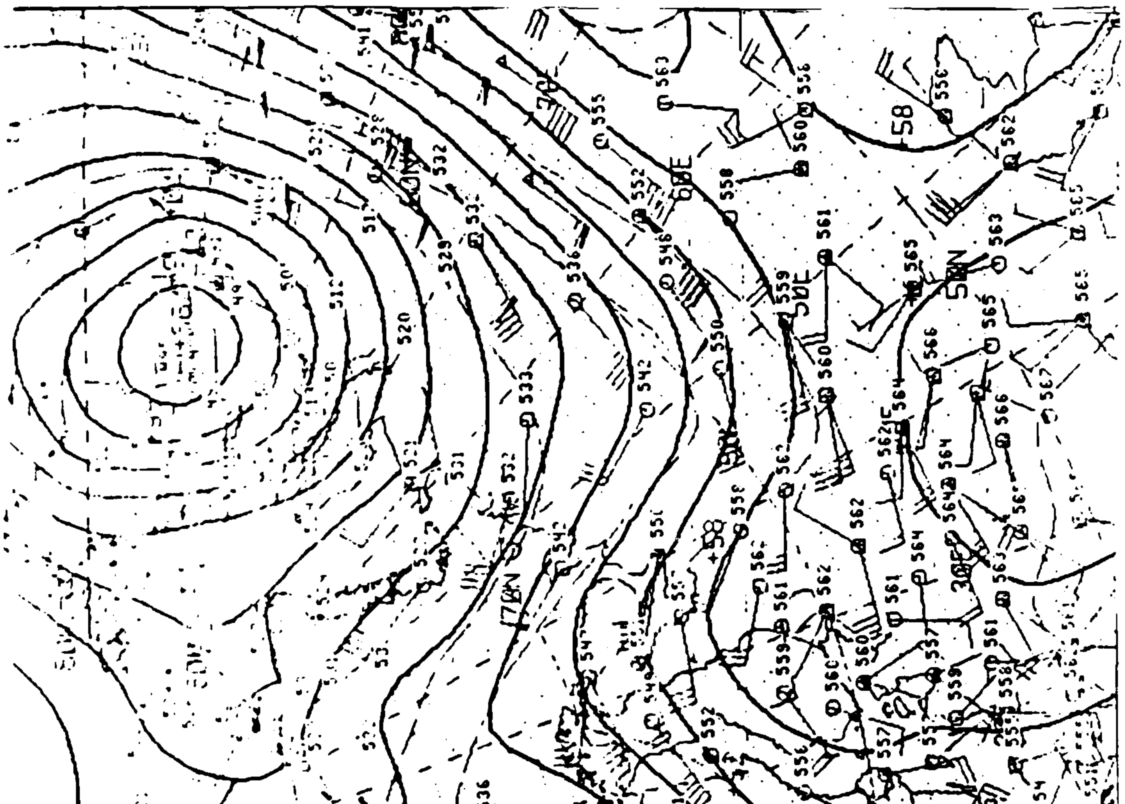


Fig. 3.18 500 mb Contour Analysis, 12 UT 1 April 1987.

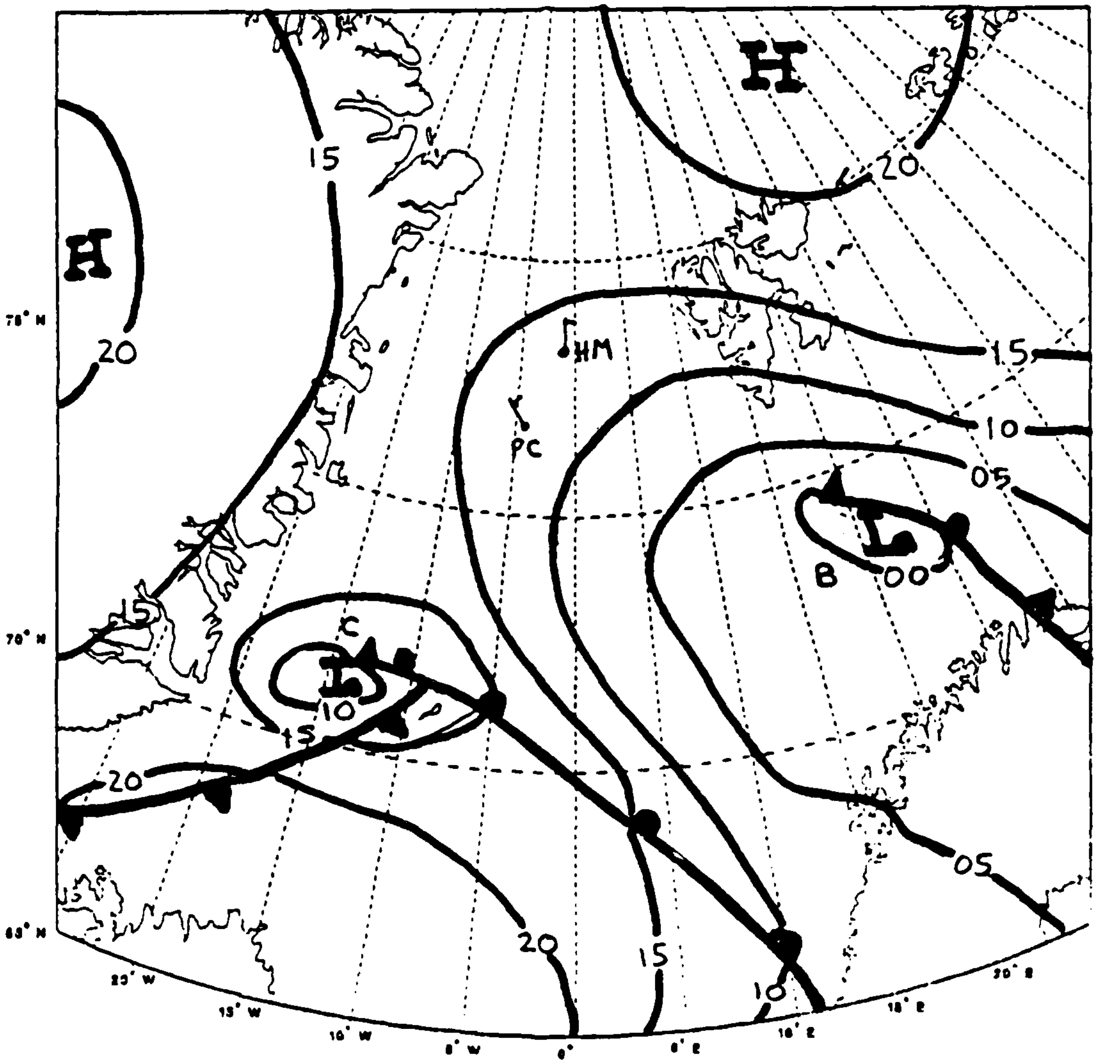



Fig. 3.19 Sea-Level Pressure Analysis, 12 UT 5 April 1987.

5. **Second and Third Synoptic Scale Lows (4 - 10 April 1987)**

The final period during MIZEX 1987 showed the influence of two more major cyclones from the south. The sea-level pressure analysis for 12 UT 5 April (Fig. 3.19) shows a second synoptic-scale low, Low B, which formed very rapidly at the beginning of this period. At 06 UT 3 April the low was 100 km off the east coast of Greenland at 72.5° N and 9.0° W. It moved rapidly northeast and stalled at a position 100 km southwest of the Svalbard Islands at 12 UT 5 April (73.0° N, 20.0° E). Low B followed the secondary storm track in the April climatology presented previously in Fig 2.4. A third low, referred to as Low C, formed near the original position of Low B at 06 UT 4 April at 71.0° N and 015° W. Low C followed in the wake of Low B and moved rapidly northeast, merging with the stalled Low B on 8 April at a position 200 km southwest of the Svalbard Islands. In the satellite imagery for 1637 UT 5 April (Fig. 3.20) the near-surface features are not visible due to the presence of very bright high level clouds associated with the development of Low C (A) off the east coast of Greenland (B) and southeast of the Svalbard Islands (C).


Fig. 3.20 NOAA 10 IR Satellite Imagery, 1637 UT 5 April, 1987.

The Valdivia left the MIZ on 2 April and so her data in this time series were collected enroute to Tromso, Norway (Fig. 3.21). The time series data for the period 4 - 7 April, Fig. 3.21, shows a near constant surface pressure of 1015.0 mb measured by all three ships throughout this period. Wind direction on the Hakon Mosby and Polar Circle was mainly northeasterly at 5 to 10 m $s^{-1}$ until 06 UT 6 April where erratic winds were measured, eventually settling out to northerly winds of 6 to 11 m $s^{-1}$ at 18 UT on 6 April. Relative humidity measured by the Polar Circle remained between 80 and 90 percent throughout this period while on the Hakon Mosby it remained near 80 percent until 00 UT 6 April when it became erratic, eventually settling out at 65 percent at 06 UT 7 April. Temperatures on both ships dropped at the beginning of this period reaching a low value of -18° C at 21 UT 4 April for the Polar Circle and a value of -17° C at 17 UT 4 April for the Hakon Mosby. Temperatures measured gradually rose on both ships until a value -5.0° C was recorded at 12 UT 6 April. The change in wind vector, relative humidity and temperature parameters late on 6 April indicates the passage of Low C.

The 500 mb contour analysis for 12 UT 5 April (Fig. 3.22) shows Low B 100 km off the north coast of Norway. The relative positions of the 500 mb and surface Low B suggests a near vertical structure for the system indicating its mature nature. The position of the low caused southeast winds to occur north of it at the Svalbard Islands. A 500 mb high exists over central Norway and over Iceland. The second low (Low B) off the east coast of Greenland does not show up on the 500 mb contour analysis, presumably due to lack of data. Polar Circle's rawinsonde 500 mb height was 530 dm at 1054 UT 5 April in the southern Fram Strait region and this height was included in the 12 UT 500 mb contour analysis (Fig. 3.22).

Fig. 3.23 shows sea-level pressure analysis pattern after Low C had overtaken Low B. Low C merged with the stationary low B over the Fram Strait region creating a larger, more intense system, to be referred to as Low D. The satellite imagery at 1202 UT 9 April (Fig. 3.24) reveals that the larger Low D has associated high level clouds over the Fram Strait region (A). Further major cyclone activity (B) continues southeast of the Fram Strait.

Time series for the Hakon Mosby and Polar Circle for the period 8 - 11 April are shown in Fig. 3.25. The Hakon Mosby and Polar Circle also left the West Fram Strait ice edge late on 6 April and were enroute to the Barents Sea when Low D and its associated front overtook them. Before the frontal passage, winds reported by the

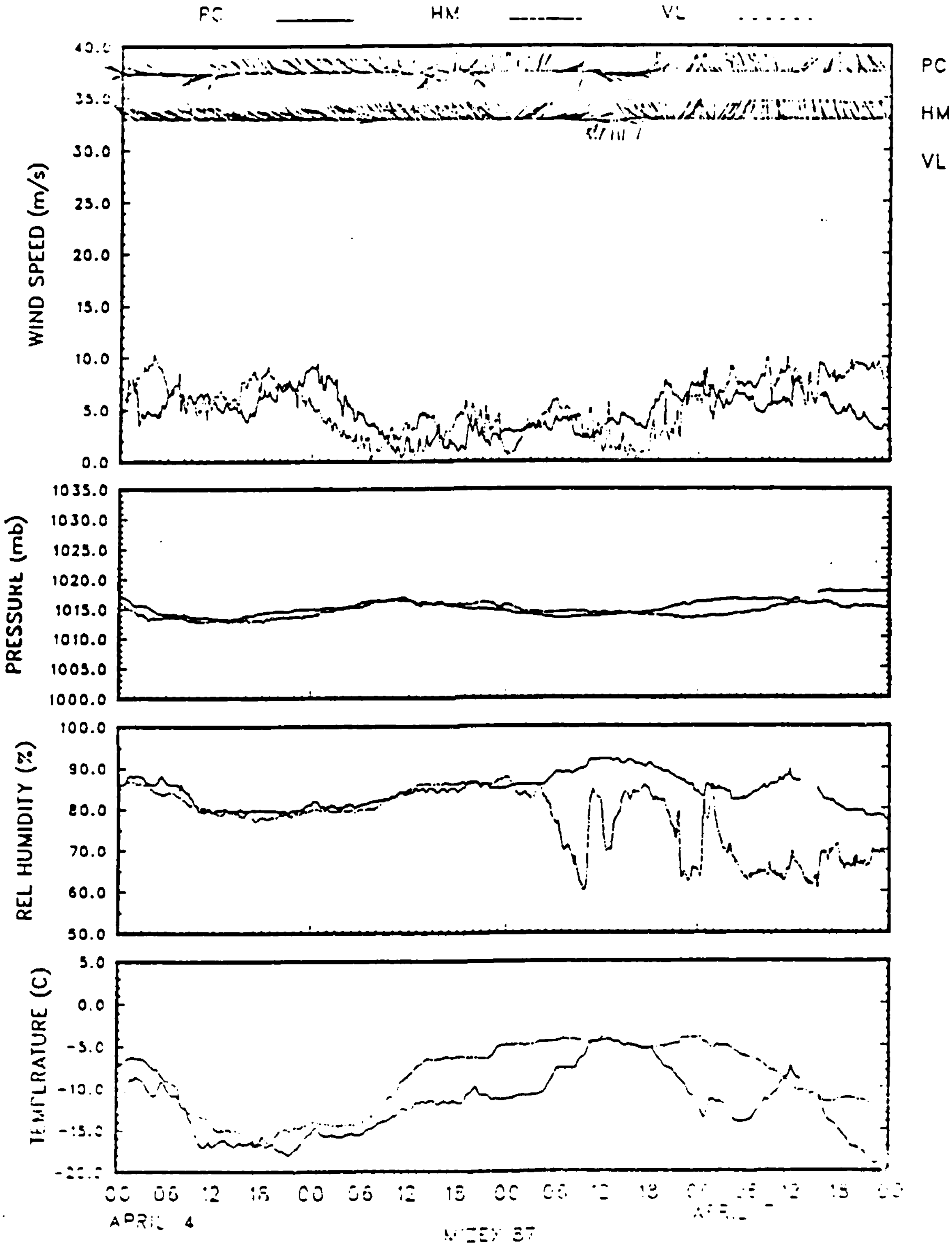



Fig. 3.21 MIZEX 1987 Ships Surface Layer Time Series
4 - 7 April 1987.

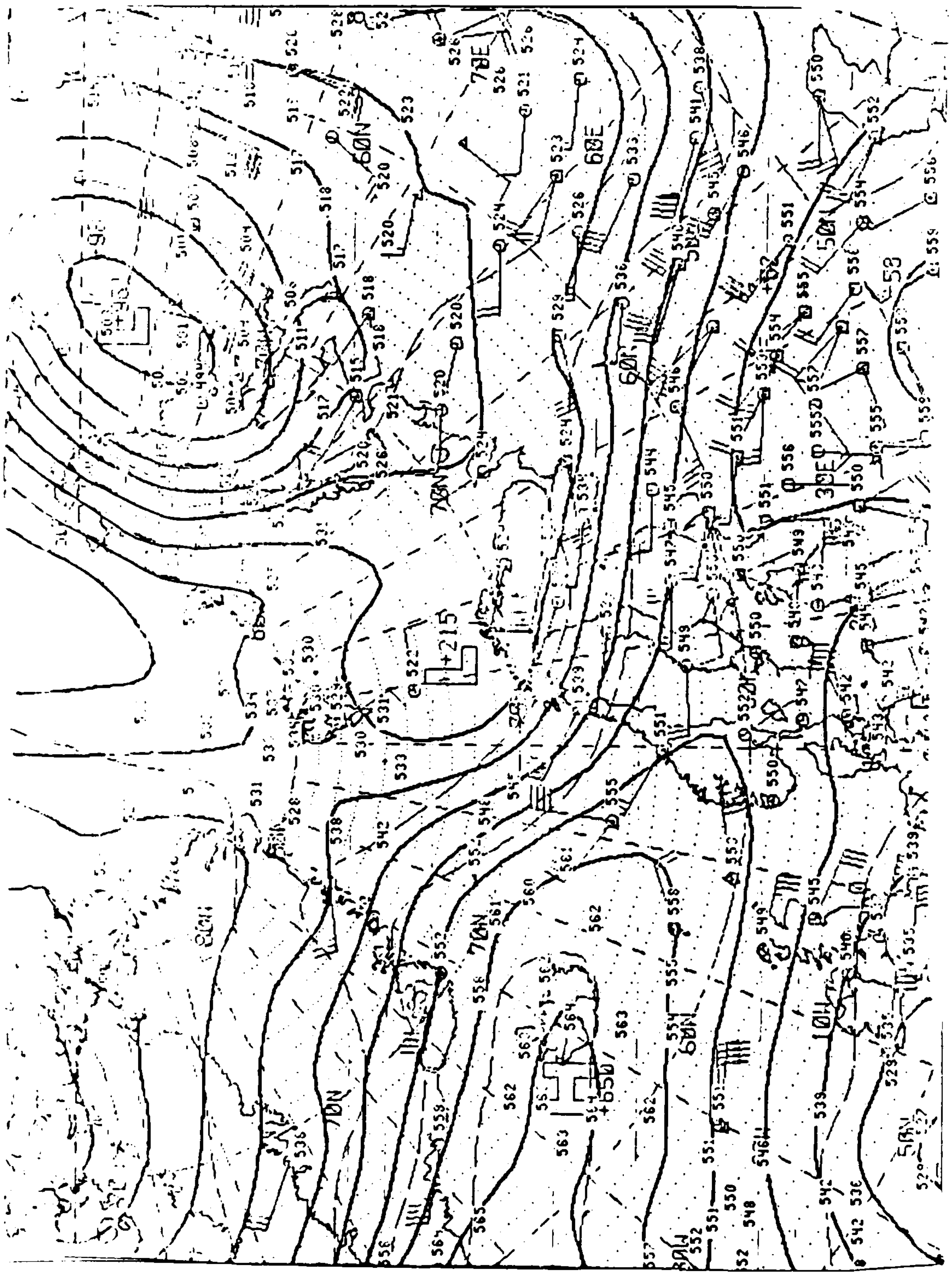


Fig. 3.22 500 mb Contour Analysis, 12 UT 5 April 1987.

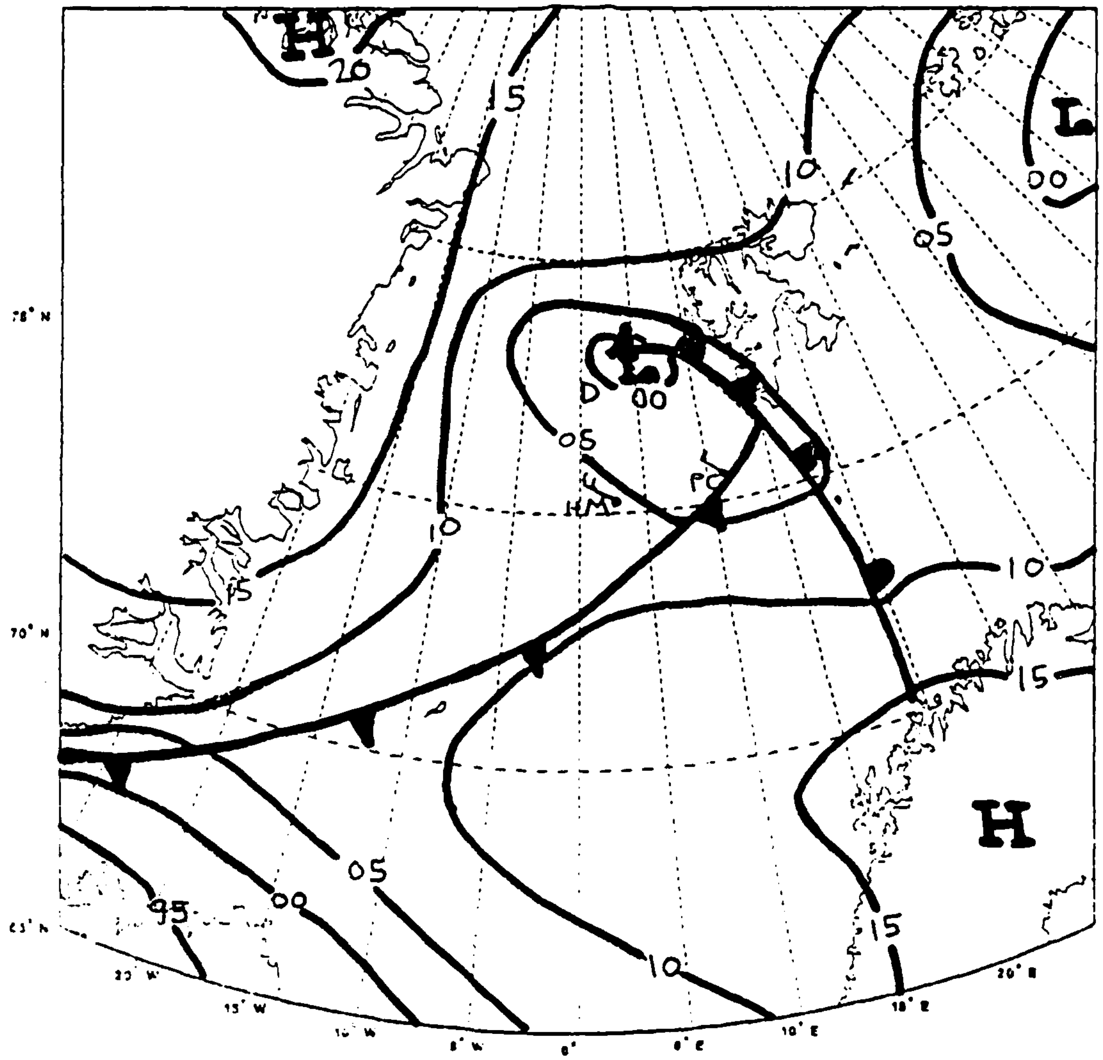
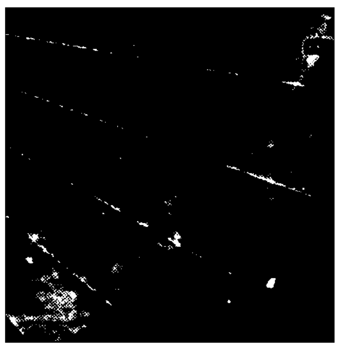


Fig. 3.23 Sea-Level Pressure Analysis, 12 UT 9 April 1987.

Polar Circle were northerly at 2 m $s^{-1}$. This does not conform with the pre-frontal position and could have been due to the strength of the inversion which decoupled the surface from the overlying geostrophic wind pattern. The Polar Circle recorded a significant counter-clockwise wind shift at 12 UT on 9 April which correlated well with the passage of the front associated with Low D.

The 500 mb contour analysis for 12 UT 9 April (Fig. 3.26) has a 500 mb low 300 km east of Low D's position while no upper-level support is evident over Low D. The lack of upper-level support may be due to lack of data input into the NOGAPS model run. Strong upper-level northwest winds exists over much of the Fram Strait along with a high over central Norway. Polar Circle's rawinsonde 500 mb height was



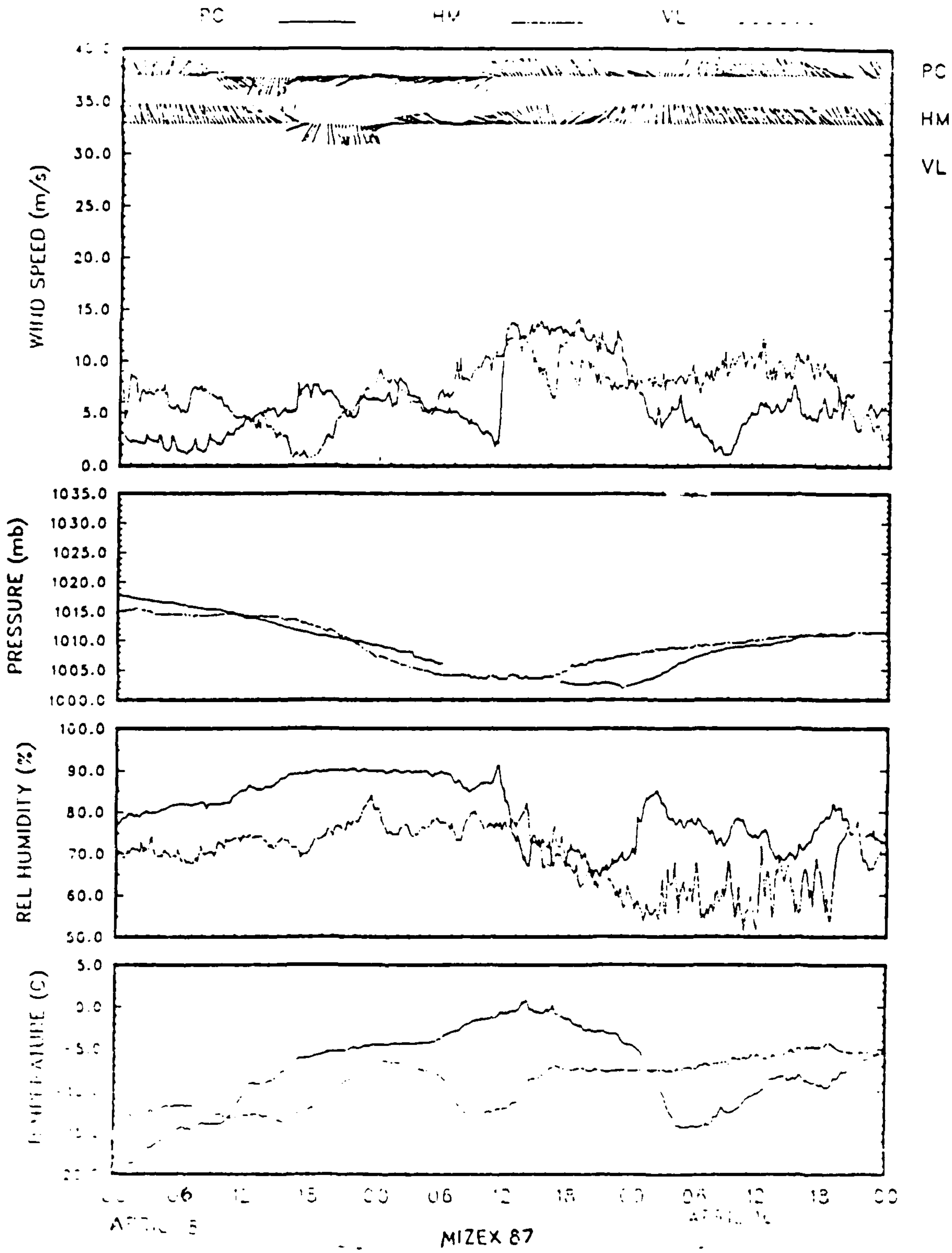



Fig. 3.25 MIZEX Ships Surface Layer Time Series
8 - 10 April 1987.

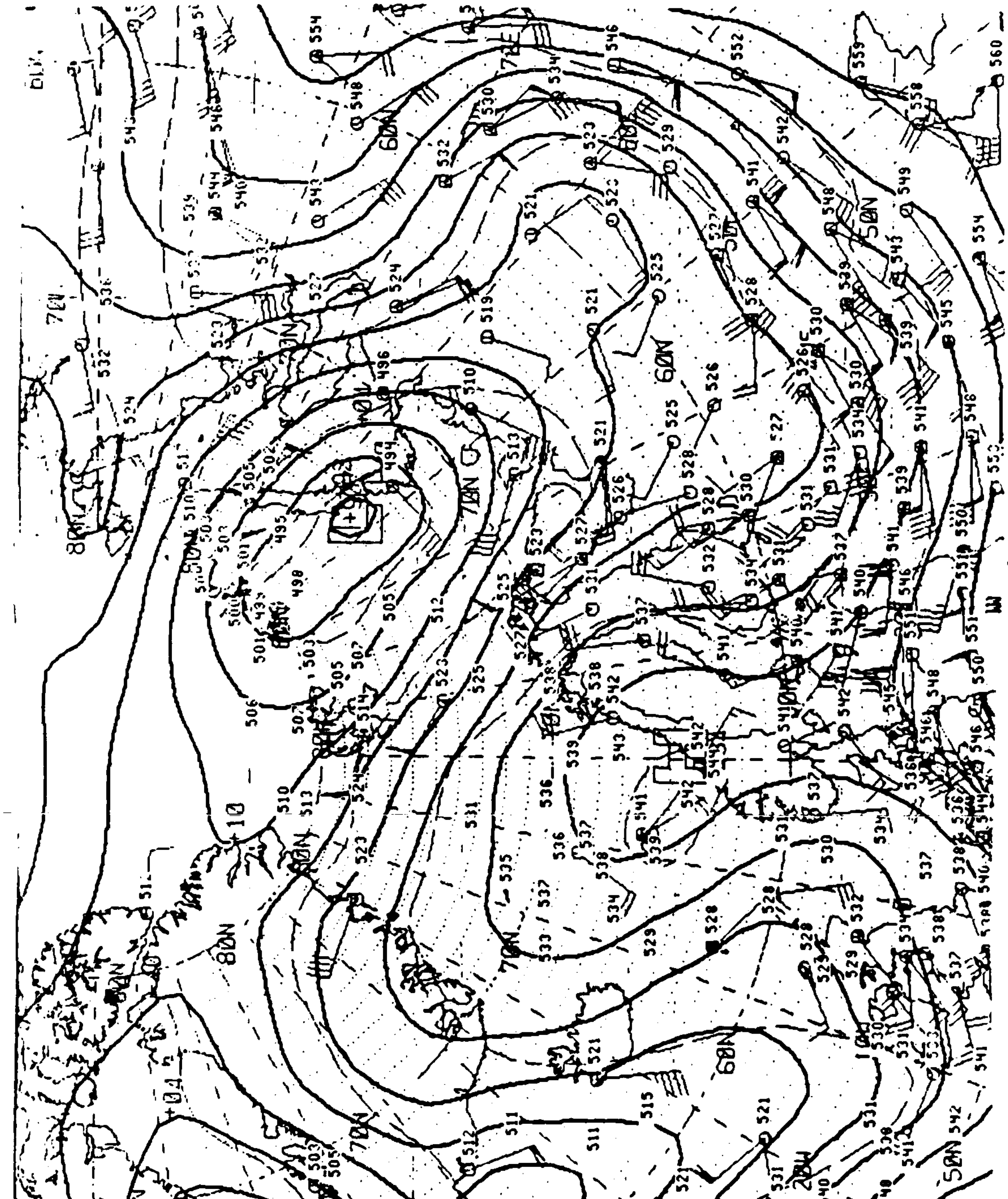


Fig. 3.26 500 mb Contour Analysis, 12 UT 9 April 1987.

# IV. EASTERLY WAVE IN THE FRAM STRAIT

## A. OVERVIEW

This section presents a more detailed description of the westward movement of an boundary-layer front which formed off the coast of the Svalbard Islands on 24 March 1987. The period was described from a synoptic-scale perspective in Part 2, Section C, of Chapter III. This more detailed description will include information from rawinsondes launched from all three MIZEX ships and more detailed analyses of satellite imagery. The time series data for the period 24 to 27 March, presented in Fig. 3.8 of Chapter III, will be referenced in greater detail.

This front was clearly evident on NOAA 9 and 10 satellite imagery during its several stages. It was associated with the outbreak of cold arctic air advected southward by north winds east of the Svalbard Islands. On 25 March, winds east of the Svalbard Islands shifted from northerly to northeasterly then to easterly. This wind shift was immediately followed by the rapid movement of the boundary-layer front westward across the open waters of the Fram Strait. During 26 March the front reached the MIZ in the western part of the Fram Strait and started to lose its organization. On 27 March, the front gradually disappeared in the vicinity of the MIZ.

There are two reasons why this event was chosen for a more detailed examination. First, there is evidence that the boundary-layer type front is associated with the formation of Polar Lows. For example, in Shapiro's, *et al.*, (1987) study, the Polar Low formed at the southern tip of the ice edge boundary-layer front. Rasmussen (1985) also described a Polar Low formation at the southern tip of an ice edge boundary-layer front. However, in both these studies no discussion is made of the the front being the cause of the Polar Low formation. In the 1984 Polar Low Project aircraft flights across the front, Shapiro, *et al.*, (1987), provided the only detailed description of structure in an ice edge front. The MIZEX 1987 front appears to be different to that described by Shapiro, *et al.* (1987). Second, measurements in MIZEX 1987 were taken while this front traveled from its origination point, westward across the Fram Strait. This movement is surprising since this type of front is thought to be closely associated with the ice edge and, therefore, presumably of a stationary nature.

This mesoscale system displayed three major phases. These phases are coincident with the general events described above. The first phase, from 00 UT 24 March to 00 UT 25 March, is when the front became organized and clarified in satellite imagery at its initial stationary position 100 km west of the Svalbard Islands. The second phase, from 00 UT 25 March to 18 UT 26 March, begins when the wind on the east side of the front shifts from northerly to easterly and the front travels across the Fram Strait and ends when the front reached the Greenland ice pack after crossing the open water of the Fram Strait. The third phase, from 18 UT 26 March to 12 UT 27 March, describes the weakening of the front over the MIZ. Coincident with this last phase, a smaller boundary-layer front was observed to be forming on NOAA 10 satellite imagery 100 km west of the Svalbard Islands in the same longitude as the original front but in a more northern position.

## B. FRONT DEVELOPMENT PHASE (00 UT 24 - 00 UT 25 MARCH 1987)

During this phase, the boundary-layer front became distinct on the satellite imagery and became elongated (northward) while remaining stationary 100 km west of the Svalbard Islands (see dashed lines in Fig. 4.1) Northerly flow, east of the Svalbard Islands, resulted in an outbreak of Arctic air to the east of Fram Strait. The wind direction in this region is evident in satellite imagery for 1100 UT 24 March, Fig. 4.1, where distinctive north to south cloud streets are formed southeast of the Svalbard Islands when cold, off ice flows over warm oceanic waters. The bands of convective clouds which form are parallel to the direction of the gradient wind. The streamline analysis (Fig. 4.1) yields a large anticyclonic vortex associated with the low-level clouds over the Fram Strait. The eastern boundary of this vortex joins the ice edge boundary-layer front (dashed line from A to B) 100 km west of the Svalbard Islands (C). The flow on the east side of the front is from the south and east while on the west side of the front the flow is from the north. These flow conditions are a different situation than in Shapiro's, *et al.*, (1987) case study where the ice edge boundary-layer front formed with flow from the north.

During this phase, all three MIZEX ships were on the west side of the front and were reporting westerly or northwesterly winds (Fig. 3.8). All had wind speeds less than 10 m $s^{-1}$ and had temperatures which ranged from -5.2° C to -7.1° C.

All rawinsonde profiles in this thesis have the following key. Bold solid line is $\theta$. Dashed line is $\theta_d$. Both of these use the bottom scale in ° C. Light solid line is specific humidity using the top scale in g/kg. Valdivia rawinsonde profiles (Fig. 4.2) during this phase reveals a strong inversion between 600 to 900 m. The Polar Circle's rawinsonde profiles (Fig. 4.3) and Hakon Mosby's rawinsonde profiles (Fig. 4.4) for a location farther west than the Valdivia's, also shows a strong inversion at a height of 800 m due to convective mixing. The vector wind profiles for all three ships show no significant features.

Reasons for the actual formation of the front is not clear but may be associated with the outbreak of cold Arctic air to the southeast which could set up a zone of low-level baroclinicity at the ice edge along the west coast of the Svalbard Islands.

## C. FRONTAL MOVEMENT PHASE (00 UT 25 - 18 UT 26 MARCH 1987)

At the beginning of this phase, east of the Svalbard Islands, the wind shifted to a more easterly direction and the boundary-layer front began to move rapidly westward. This wind shift is evident by a comparison of Figs. 4.1 and 4.5. On 24 March (Fig. 4.1) the cloud streets to the southeast of the Svalbard Islands are aligned north-south indicating off ice flow along the northwest to southeast ice edge south of the Svalbard Islands. However, on 25 March, the cloud streets southeast of the Svalbard Islands have aligned more northeast-northwest indicating more easterly flow. During the frontal movement, occurring with the wind shift, the Valdivia measured the frontal passage between 03 UT and 06 UT 25 March at a postion 200 km west of the Svalbard Islands, as indicated in Fig. 3.8. Winds shifted rapidly clockwise to become southeasterly and increased in speed to over 15 m $s^{-1}$. A temperature decrease from a -4.5° C to a -10.5° C occurred. Surprisingly, only a minimal pressure change was noted during the frontal passage with an increase of only 0.8 mb, from 1026.2 mb to 1025.4 mb. The streamline analysis in Fig. 4.5 corresponds to a time just after the Valdivia's recording of the frontal passage with the front being indicated by the dashed line from A to B.

Observable weather on the Valdivia during the frontal passage had visibility remaining at 20 km throughout 24 March. Amount of low-level clouds decreased as the front passed, going from a pre-frontal overcast to 2/8 at 18 UT 24 March and increasing again to overcast as the front moved on by 00 UT 25 March. This change is perhaps due to the Valdivia's position being close to the ice edge which did not allow the cold post-frontal air opportunity to gain moisture from the relatively short time over water. Significant wave heights went from 1/4 to 1/2 m at 06 UT 24 March to 2 m at frontal passage (09 UT 24 March) dropping again to 1/4 to 1 2 m at the end of the day.

Fig. 4.1 Satellite Imagery and Streamlines, 1100 UT 24 March, 1987.

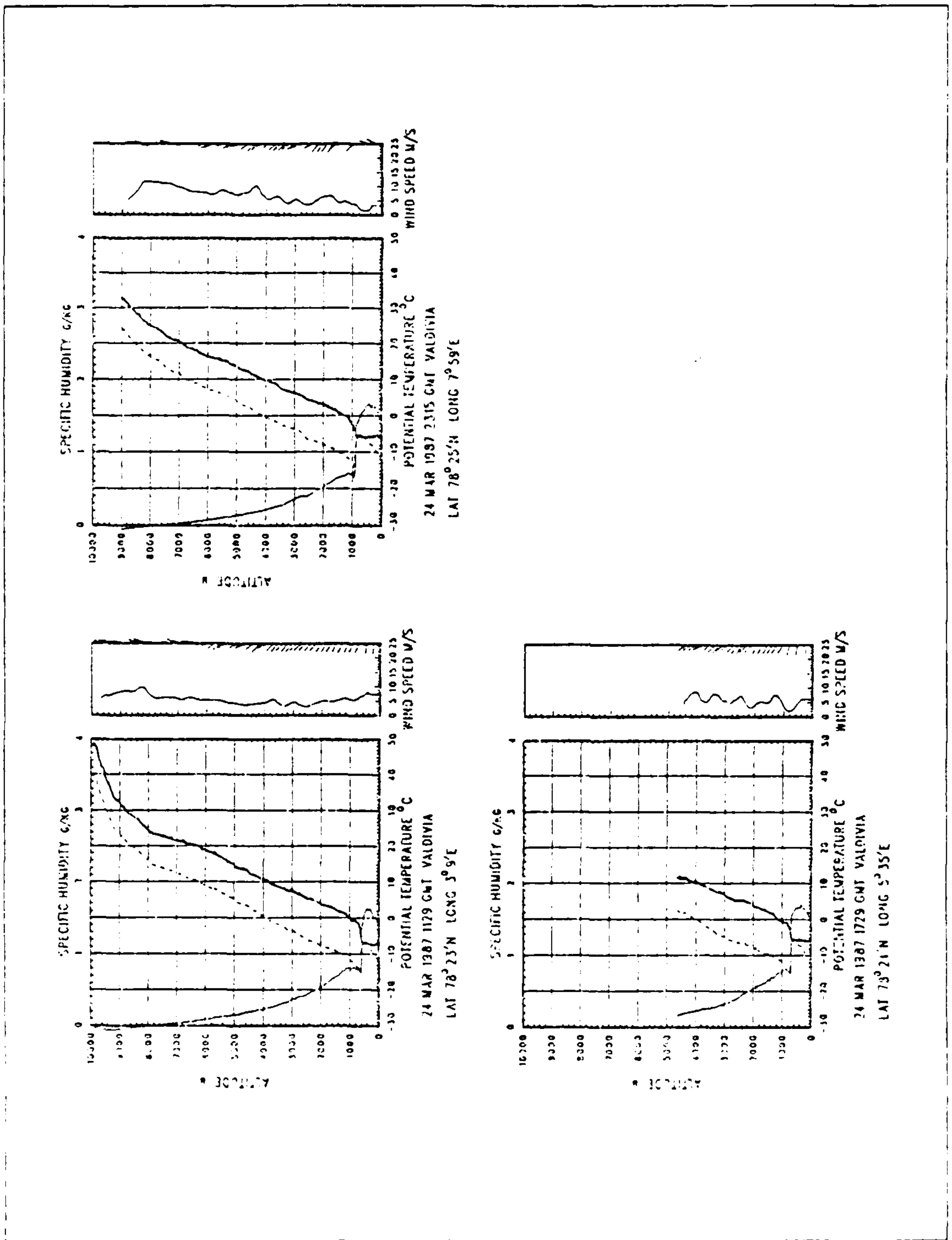



Fig. 4.2 Valdivia Rawinsonde Profiles, 24 March 1987
(a) 1129 UT, (b) 1729 UT, (c) 2315 UT.

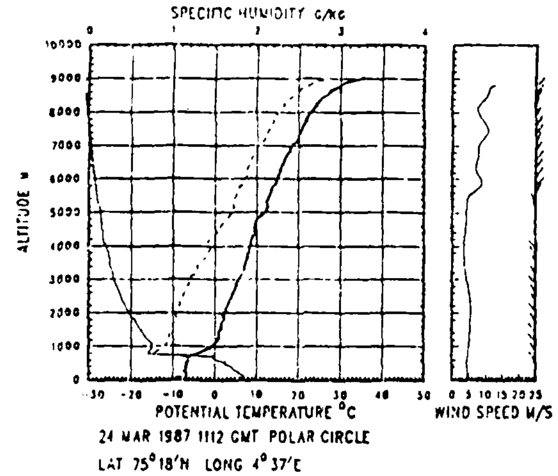



Fig. 4.3 Polar Circle Rawinsonde Profiles, 24 March 1987
(a) 1112 UT.

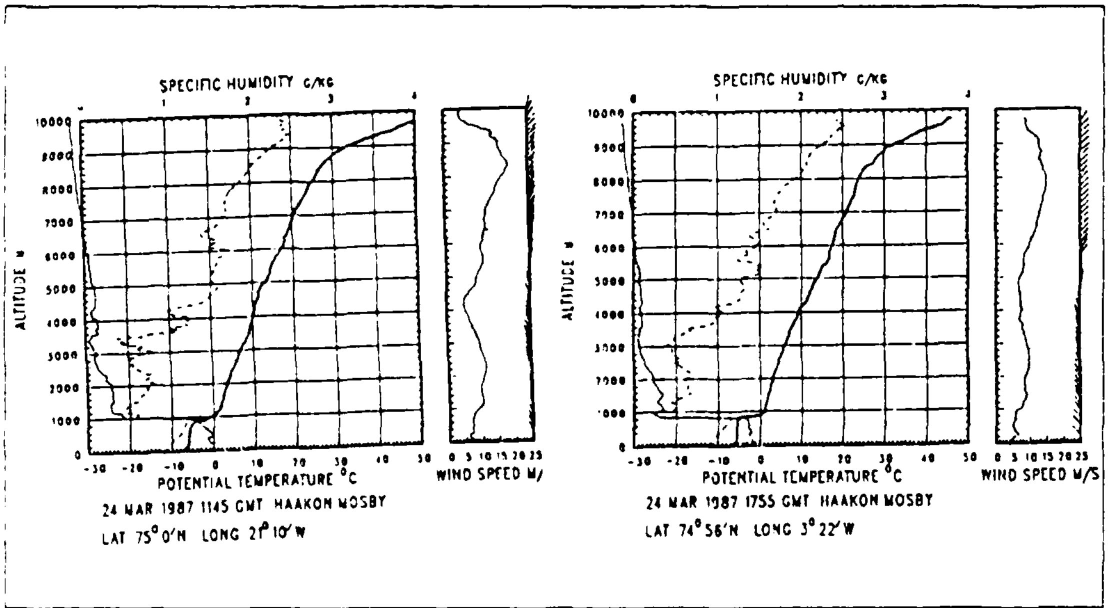



Fig. 4.4 Hakon Mosby Rawinsonde Profiles, 24 March 1987
(a) 1145 UT, (b) 1755 UT.

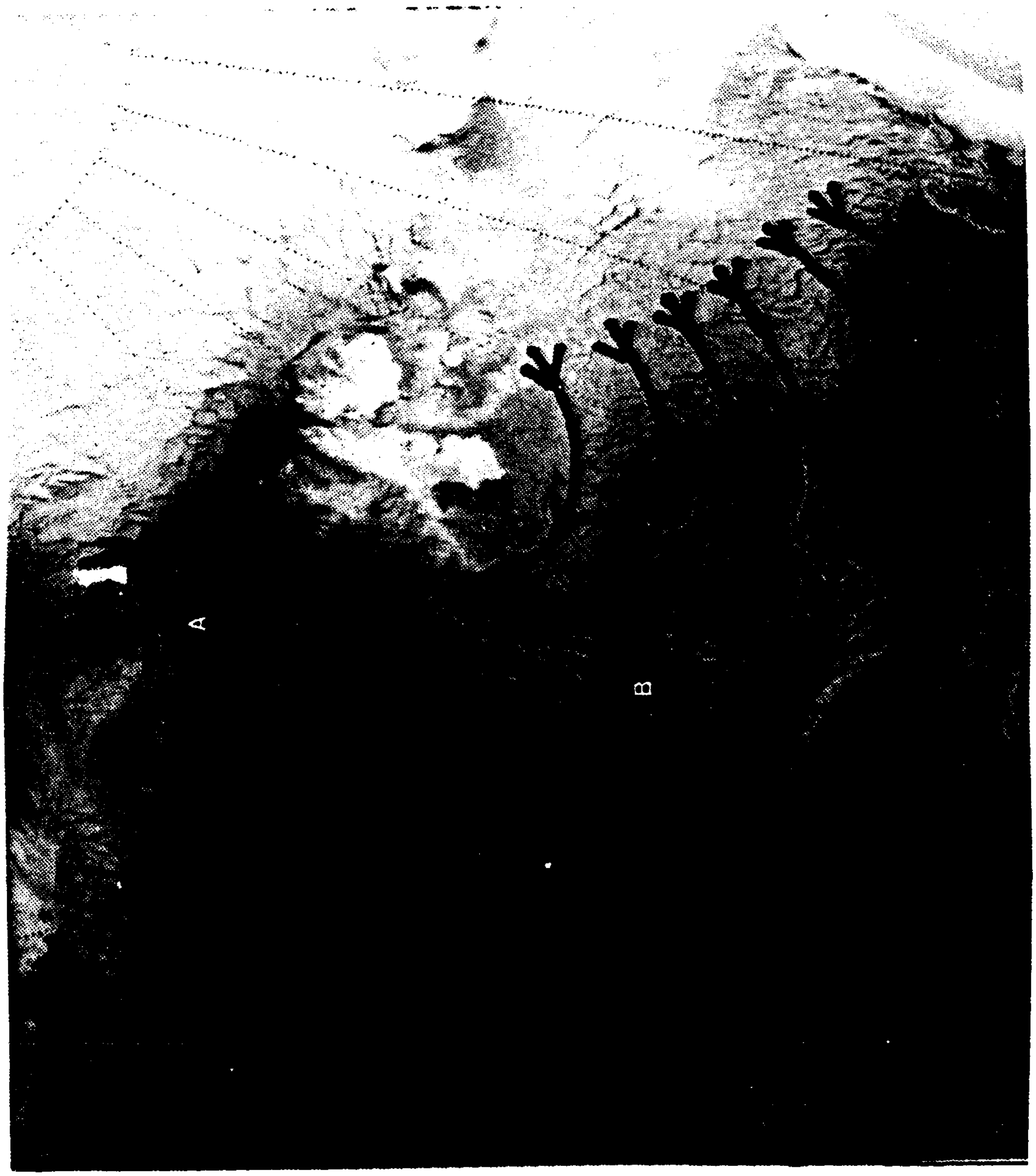



Fig. 4.5 Satellite Imagery and Streamlines, 1110 UT 25 March 1987.

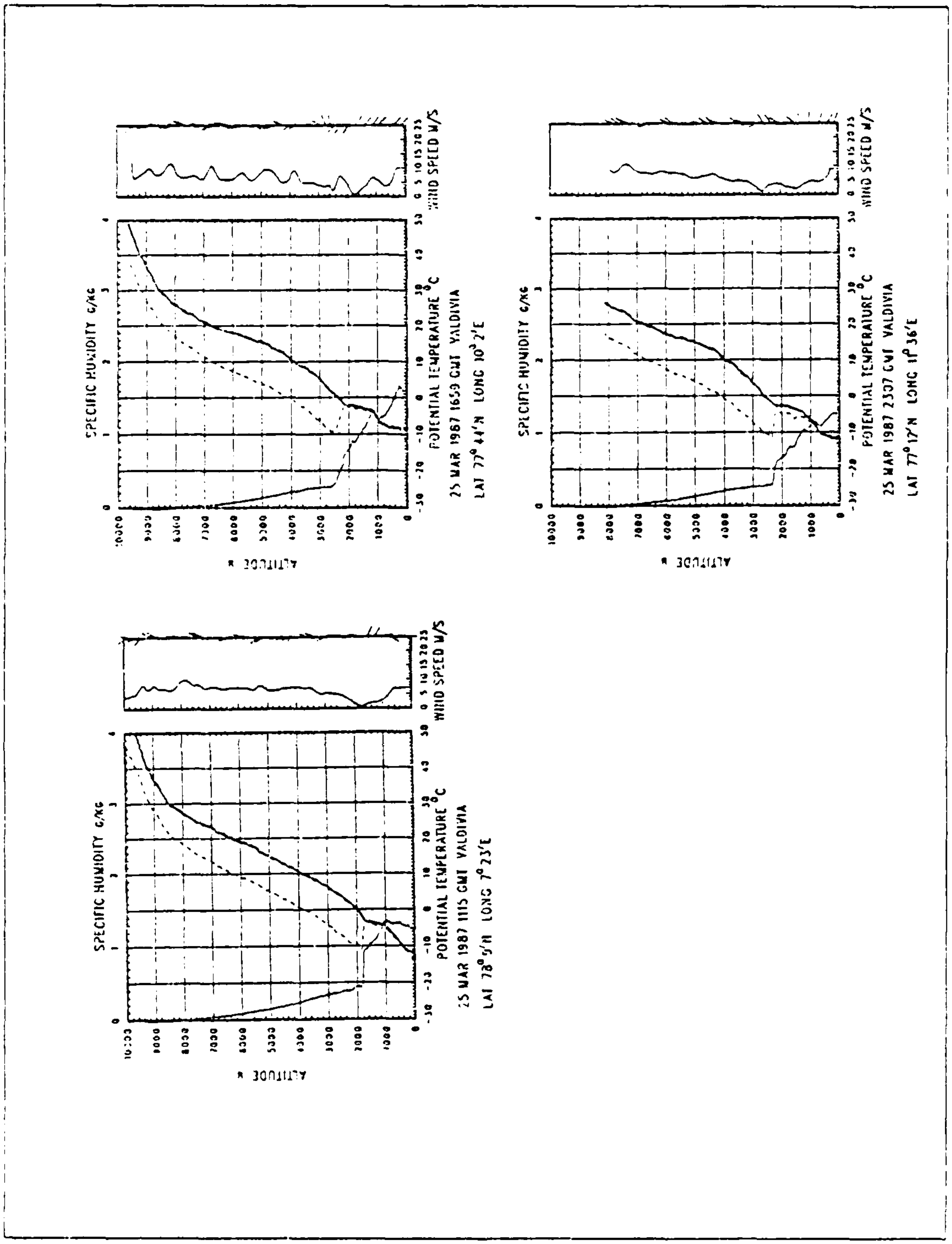



Fig. 4.6 Valdivia Rawinsonde Profiles, 25 March 1987
(a) 1115 UT, (b) 1659 UT, (c) 2307 UT.

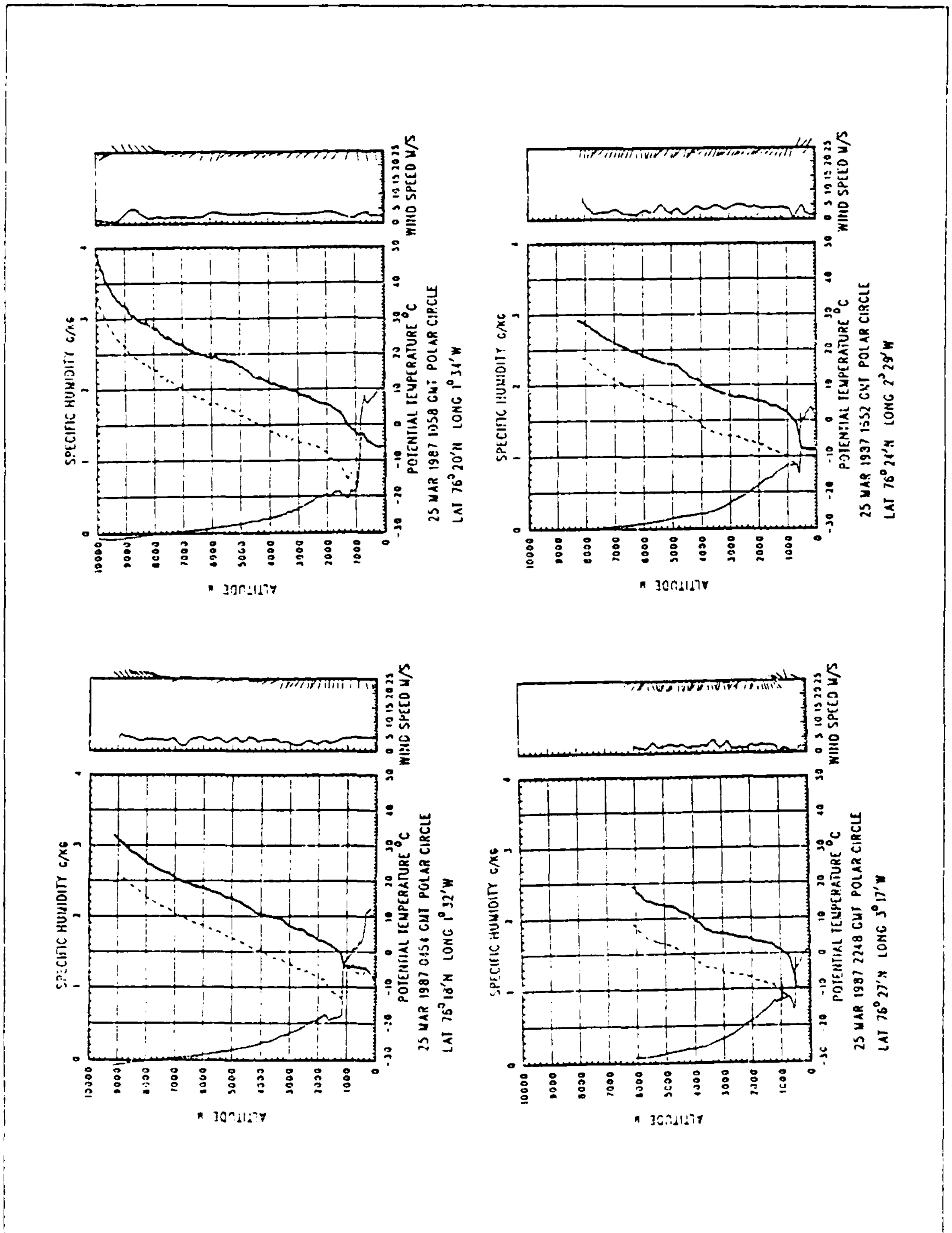



Fig. 4.7 Polar Circle Rawinsonde Profiles, 25 March 1987
(a) 0454 UT, (b) 1058 UT, (c) 1652 UT, (d) 2248 UT.

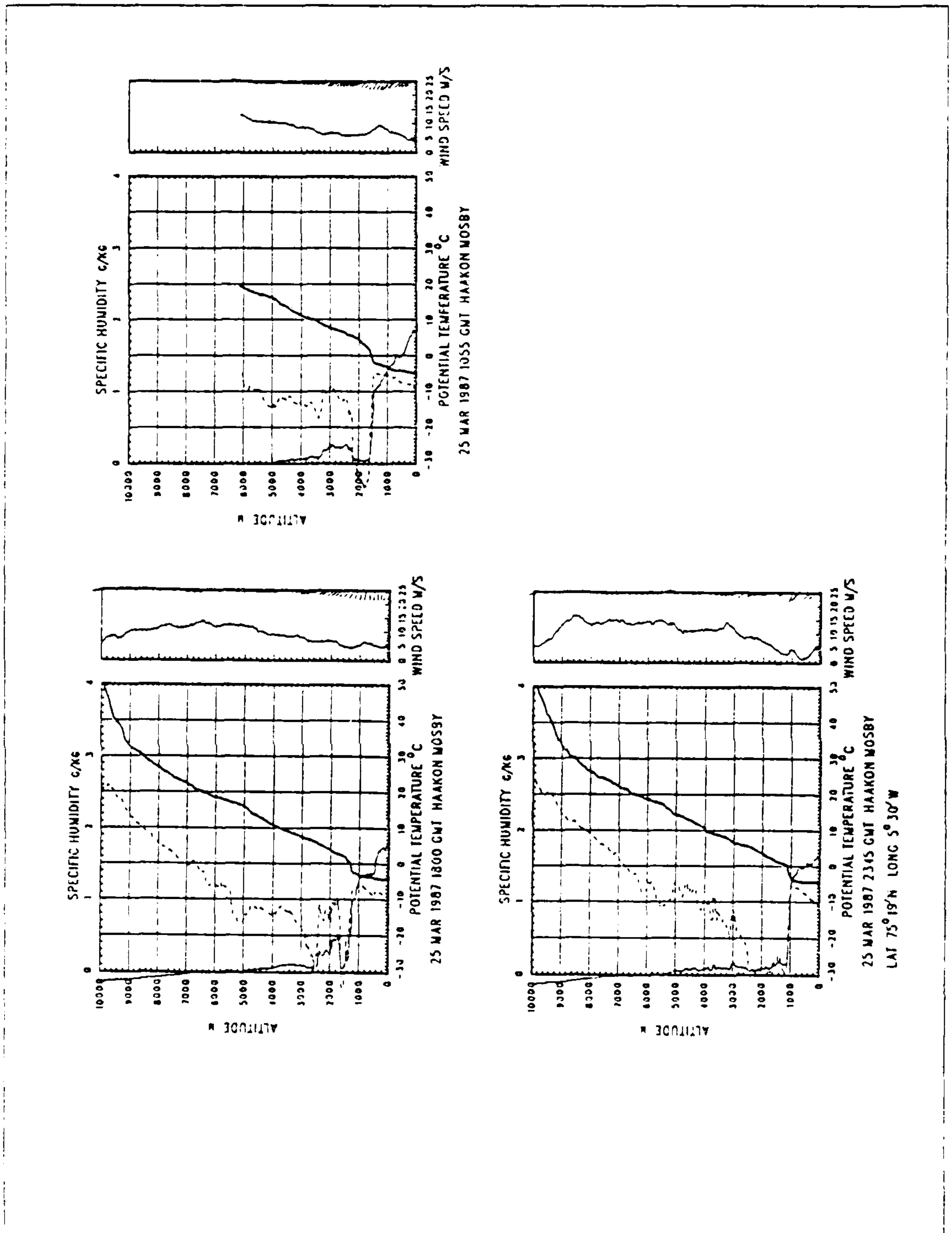



Fig. 4.8 Hakon Mosby Rawinsonde Profiles, 25 March 1987
(a) 1055 UT, (b) 1800 UT, (c) 2345 UT.

Valdivia's rawinsonde profiles during this phase (Fig. 4.6) reveals an inversion layer at 1000 m at 1115 UT, Fig. 4.6(a), evolving into a 800 m well mixed layer by 1659 UT (Fig. 4.6(b)). The 800 - 1000 m mixed layer had existed before at 2315 UT 24 March, before the frontal passage. After the frontal passage another inversion appeared near 2000 m. This inversion may have been the earlier pre-frontal inversion which is now lifted and weakened as the cold Arctic air pushed underneath it. Also evident in Fig. 4.6(a) is the clockwise turning of the wind and its slowing to near calm at 1400 m. This may be due to the thermal wind effects associated with the front. The Polar Circle and Hakon Mosby, both farther west, did not experience the frontal passage until later on 26 March. During the time that Valdivia observed the frontal passage both the Polar Circle and Hakon Mosby continued to report westerly winds under 5 m $s^{-1}$ and surface temperatures higher than -7.5° C. Polar Circle rawinsonde profiles (Fig. 4.7) and Hakon Mosby rawinsonde profiles (Fig. 4.8) continued to exhibit pre-frontal features with an inversion layer at 1000 m but no inversion at 2000 m. Hakon Mosby's and Polar Circle's upper-level winds during this phase exhibit no significant features. Analysis of the NOAA 10 AVHRR imagery in Fig 3.7 had cloud top temperature values ranging from -20.0° to -12° C.

As the front moved westward on 26 March, well past the Valdivia, the Valdivia reported that wind speeds decreased, below 10 m $s^{-1}$ (Fig. 3.8). However the direction was still easterly to southeasterly. Valdivia rawinsonde profiles (Fig. 4.10) for this time period are similar to the pre-frontal profiles (24 March, Fig. 4.2) with a new mixed layer extending up to 1000 m but no inversion at 2000 m.

The Hakon Mosby experienced the frontal passage next as evident in satellite imagery, Fig. 4.9, with the position of the front being indicated by the dashed line from A to B. The frontal passage is also evident the Hakon Mosby's time series (Fig. 3.8). Changes associated with the passage occur between 08 UT 26 March to 15 UT 26 March. At 08 UT 26 March the Hakon Mosby's reported the wind speed increases to greater than 10 m $s^{-1}$ and a clockwise wind direction shift from westerly to southeasterly. Only a small increase was observed in temperature, 1° C from -6.6° to -5.6° C, and pressure, 1 mb from 1018.7 mb to 1017.7 mb. Hence the frontal passage was primarily noticeable in the surface layer wind shift which was quite distinct and correlated well with the satellite imagery position. The temperature and pressure differences being minimal was perhaps due to the front's travel across the relatively warm waters of the Fram Strait.

Observable weather on the Hakon Mosby experienced a drop in visibility with the frontal passage from 20 km at 06 UT 26 March to 2 km at 15 UT 26 March increasing again to 10 km by 03 UT 27 March. Clouds increased from 2/8 coverage of low-level clouds at 06 UT 26 March to overcast by 15 UT 26 March. At 15 UT 26 March the Hakon Mosby recorded intermittent moderate snowfall which lasted until 18 UT 26 March. Significant wave heights during this phase increased from 1 to 1.5 m at 06 UT 26 March to a peak at 15 UT of 3 to 4 m. After the frontal passage the significant wave heights dropped to 1 to 1.5 m by 12 UT 27 March.

The Polar Circle was the last MIZEX ship to measure changes associated with the passage of the front. This occurred after 18 UT 26 March with distinct wind direction and speed changes, from westerly at less than 1 m $s^{-1}$ to easterly at 10 m $s^{-1}$. Similar to the Hakon Mosby, the pressure and temperature changes were small. An increase in temperature, -8.0° C to -4.5° C was observed which is opposite to the decreases observed by the Valdivia and Hakon Mosby. This could have been due to the in-ice location of the Polar Circle at the time of the frontal passage. Since the Polar Circle was well into the Greenland ice pack, westerly, pre-frontal winds would cause low temperatures. With the frontal wind shift to easterly, the Polar Circle, at a post-frontal location, was now affected by air which had been warmed when crossing the warmer open waters of the Fram Strait. With the frontal passage, the pressure dropped 1.5 mb, from 1017.3 mb to 1015.8 mb. The Valdivia, much farther east, continued to have strong easterly winds of greater than 10 m $s^{-1}$ but a strong inversion had reestablished itself at 1100 m (Fig. 4.10). Polar Circle upper-level winds show a significant direction shift at the top of the well mixed layer while the Valdivia's upper-level winds (Fig. 4.10) show no significant features. Hakon Mosby's rawinsonde profile (Fig. 4.12) shows an increase in the well mixed layer height in the 1705 UT profile to 2500 m.

Observable weather conditions during the Polar Circle's frontal passage were as follows. Visibility did not change throughout the passage, remaining near 10 km. Clouds increased from 4/8 coverage from low-level clouds at 18 UT 26 March to overcast by 00 UT 27 March. Intermittent moderate snowfall was recorded on the Polar Circle at 00 UT 27 March which stopped by 06 UT 27 March. Since the Polar Circle was well into the ice pack at the time of the frontal passage no sea wave height information was possible.

Fig. 4.9 Satellite Imagery and Streamlines, 0601 UT 26 March 1987.

Polar Circle rawinsonde profiles (Fig. 4.11) show a pre-frontal mixed layer to 1000 m (Fig. 4.11(a,b and c)) increasing to 1600 m after the frontal passage (Fig. 4.11(d)). This is similar to changes which occurred in Valdivia's profiles on 25 March although the Valdivia had two distinct layers (Fig. 4.2) with tops at 800 m and 2000 m. Hence, the pre-frontal mixed layer adjacent to the surface was higher for the Polar Circle, reaching up to 1600 m vice 800 m for the Valdivia pre-frontal mixed layer. The

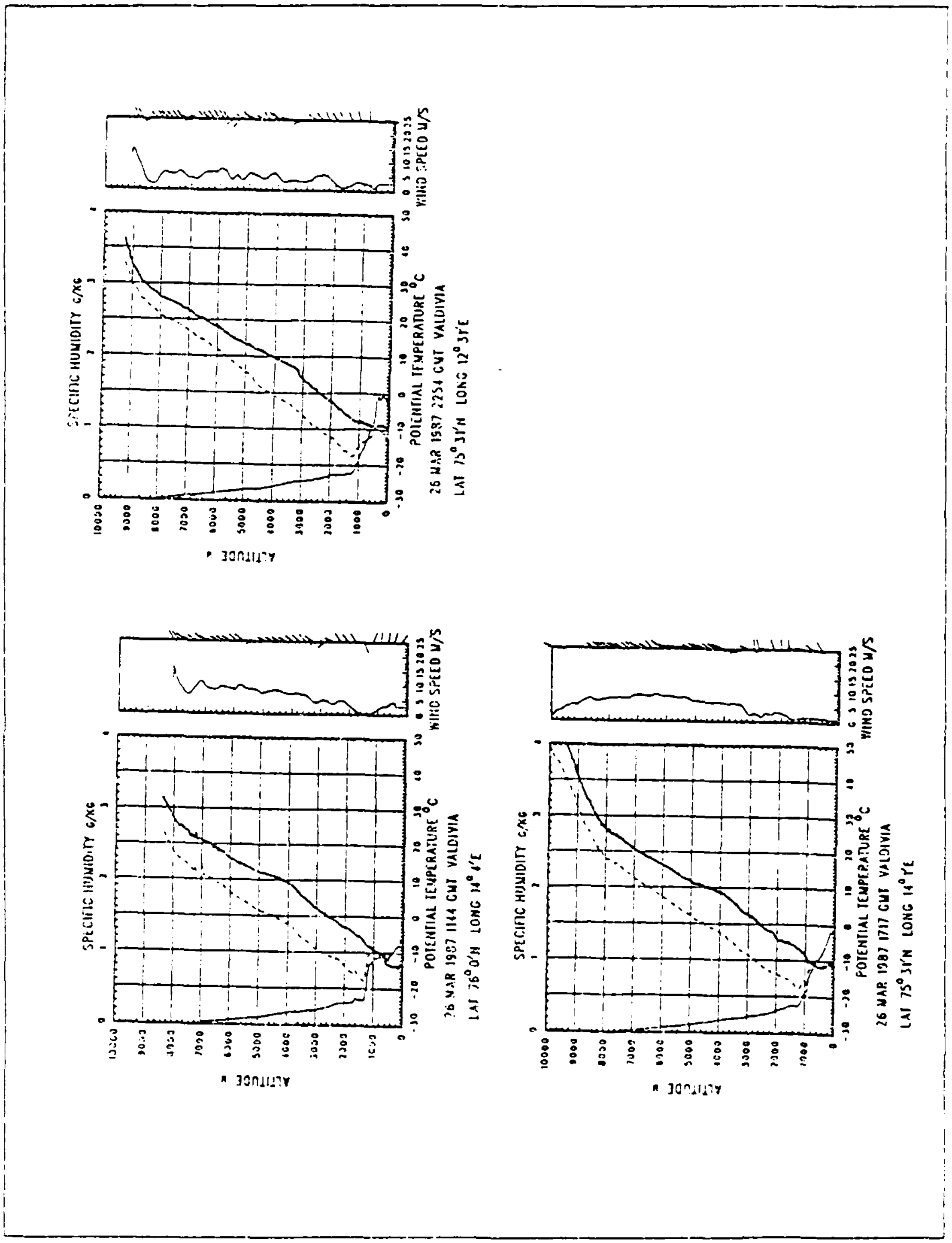



Fig. 4.10 Valdivia Rawinsonde Profiles, 26 March 1987
(a) 1144 UT, (b) 1717 UT, (c) 2254 UT.

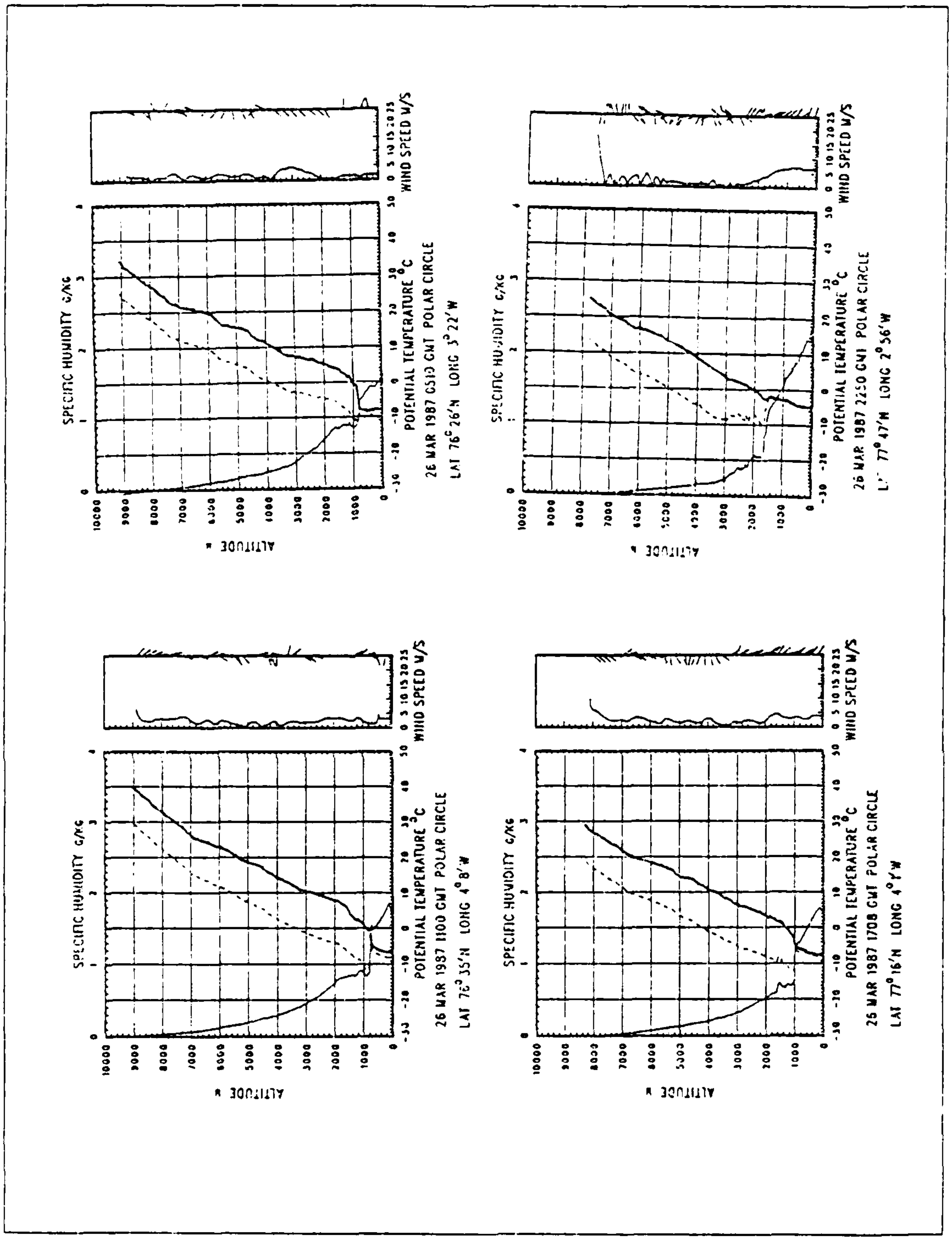



Fig. 4.11 Polar Circle Rawinsonde Profiles, 26 March 1987
(a) 0510 UT, (b) 1100 UT, (c) 1708 UT, (d) 2250 UT.

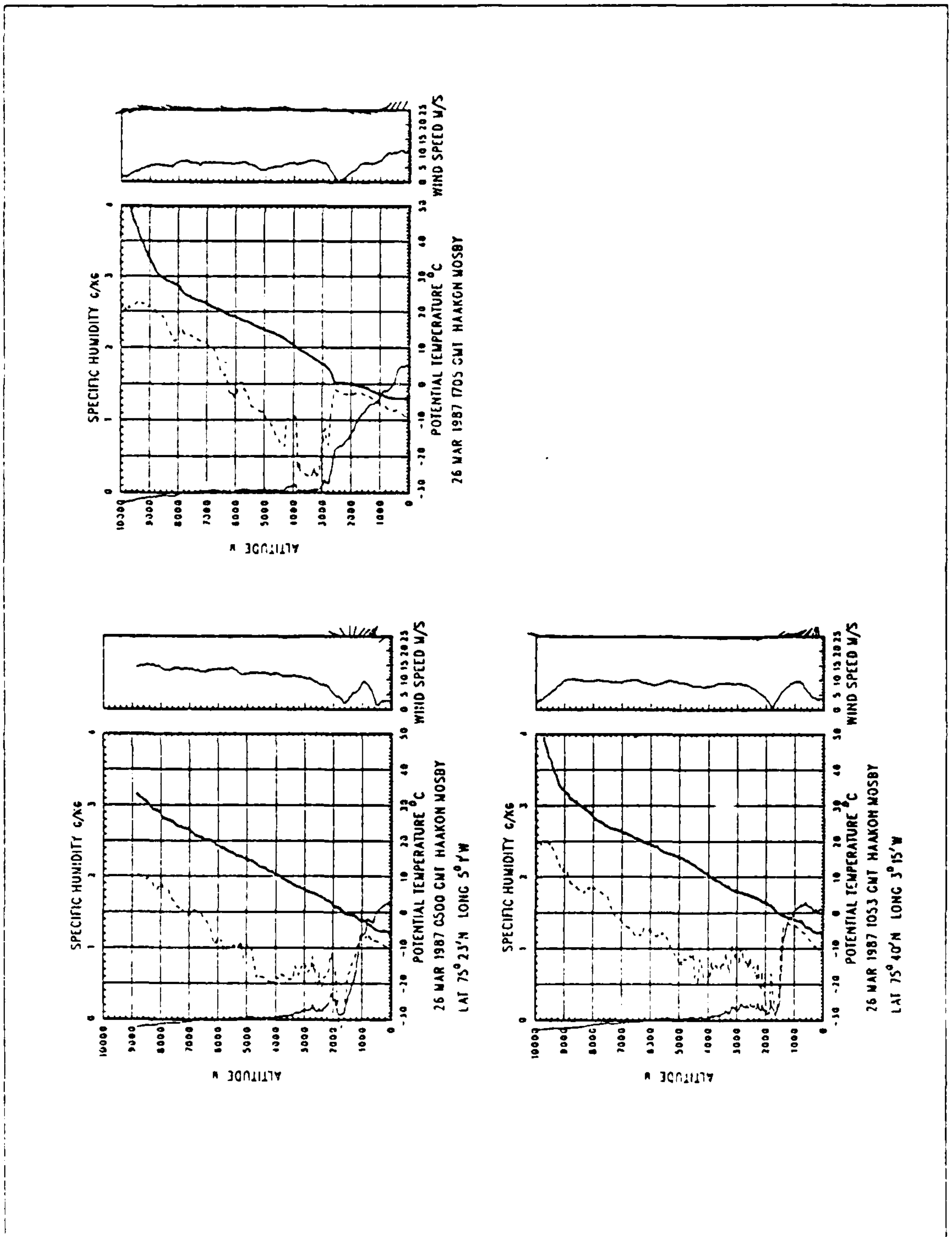



Fig. 4.12 Hakon Mosby Rawinsonde Profiles, 26 march 1987
(a) 0500 UT, (b) 1053 UT, (c) 1705 UT.

increase in the mixed layer specific humidity as the front crossed the Fram Strait is apparent in comparing Fig. 4.10(d) with Fig. 4.6(a). Post-frontal mixed layer values of specific humidity at the Valdivia, which was on the east side of the Fram Strait, were 1.5 g/kg (Fig. 4.6(a)) while post-frontal values for the Polar Circle , which was on the west side of the Fram Strait, were 2 G/Kg (Fig. 4.11(d)).

## D. FRONTAL DISSIPATION PHASE (18 UT 26 - 12 UT 27 MARCH 1987)

During this phase, the front, as established by satellite imagery (Fig. 4.13) weakened and lost its clarity while maintaining its MIZ position. The Polar Circle and Hakon Mosby continued to have southeasterly winds at 10 m $s^{-1}$ and the Valdivia, further to the east, had easterly winds of low speed.

Valdivia rawinsonde profiles (Fig. 4.14) indicate that the post-frontal mixed layer inversion had established itself at a slightly higher level, 1200 m, than the pre-frontal mixed layer, 800 m. The Polar Circle's rawinsonde profiles (Fig. 4.15) revealed the continued influence of the stalled front throughout the day on the basis of maintainance of a large well mixed-layer up to 2000 m. The distinct multiple layers with tops at 1100 and 2200 m in humidity profile at 1125 UT 27 March (Fig. 4.15(b)) are interesting but not explained. The Hakon Mosby profiles (Fig. 4.16) also show the maintainance of the well mixed layer to 2500 m throughout 27 March.

Satellite imagery for 27 March (Fig. 4.13) includes evidence of a possible second boundary-layer front beginning to form in the lee of the Svalbard Islands at a position longitudinally the same as the origin of the previous front (10° E) but at a slightly more northern postion. This completes the examination of the westward moving wave in the Fram Strait.

Fig. 4.13 Satellite Imagery and Streamlines, 0550 UT 27 March 1987.

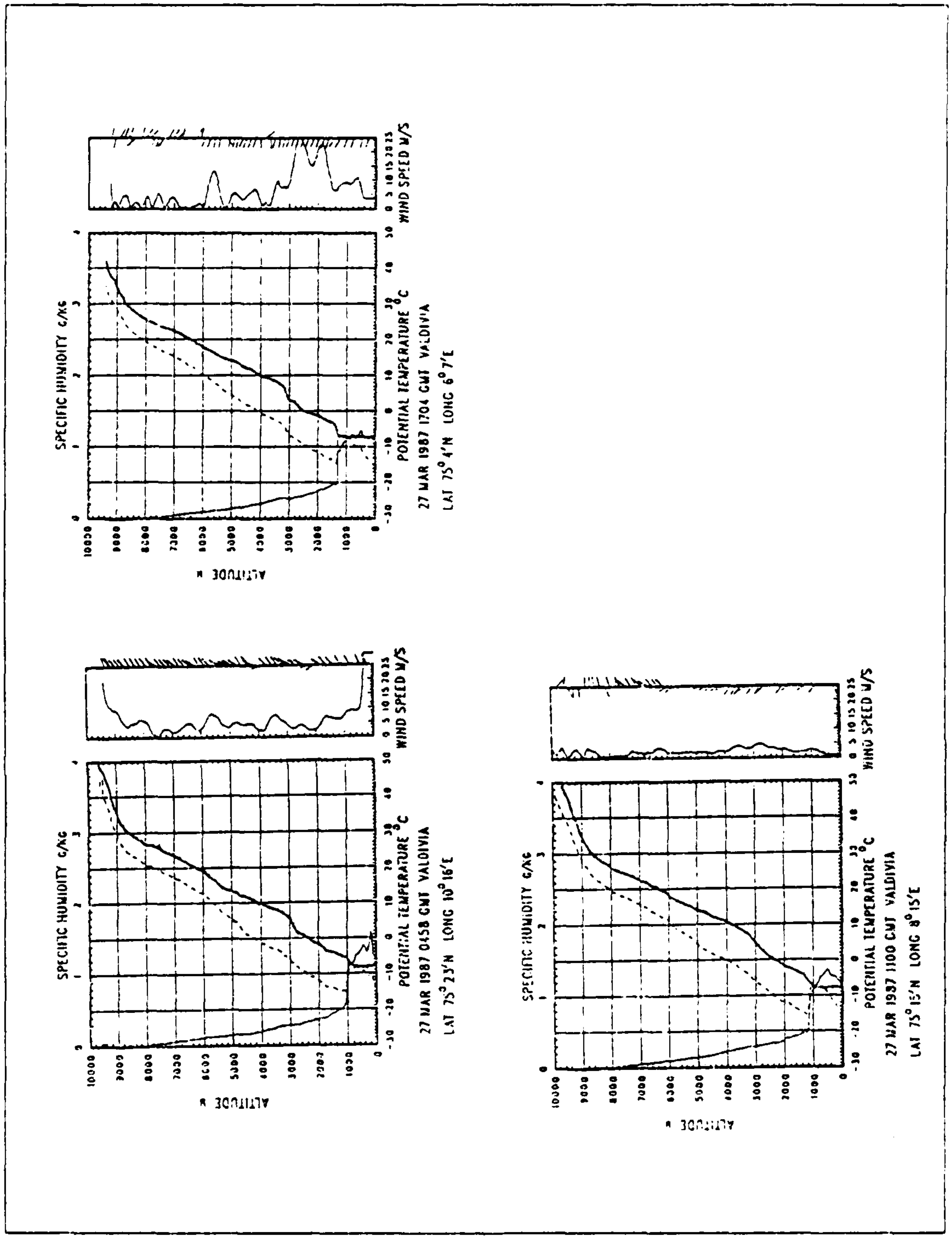



Fig. 4.14 Valdivia Rawinsonde Profiles, 27 March 1987
(a) 0458 UT, (b) 1100 UT, (c) 1704 UT.

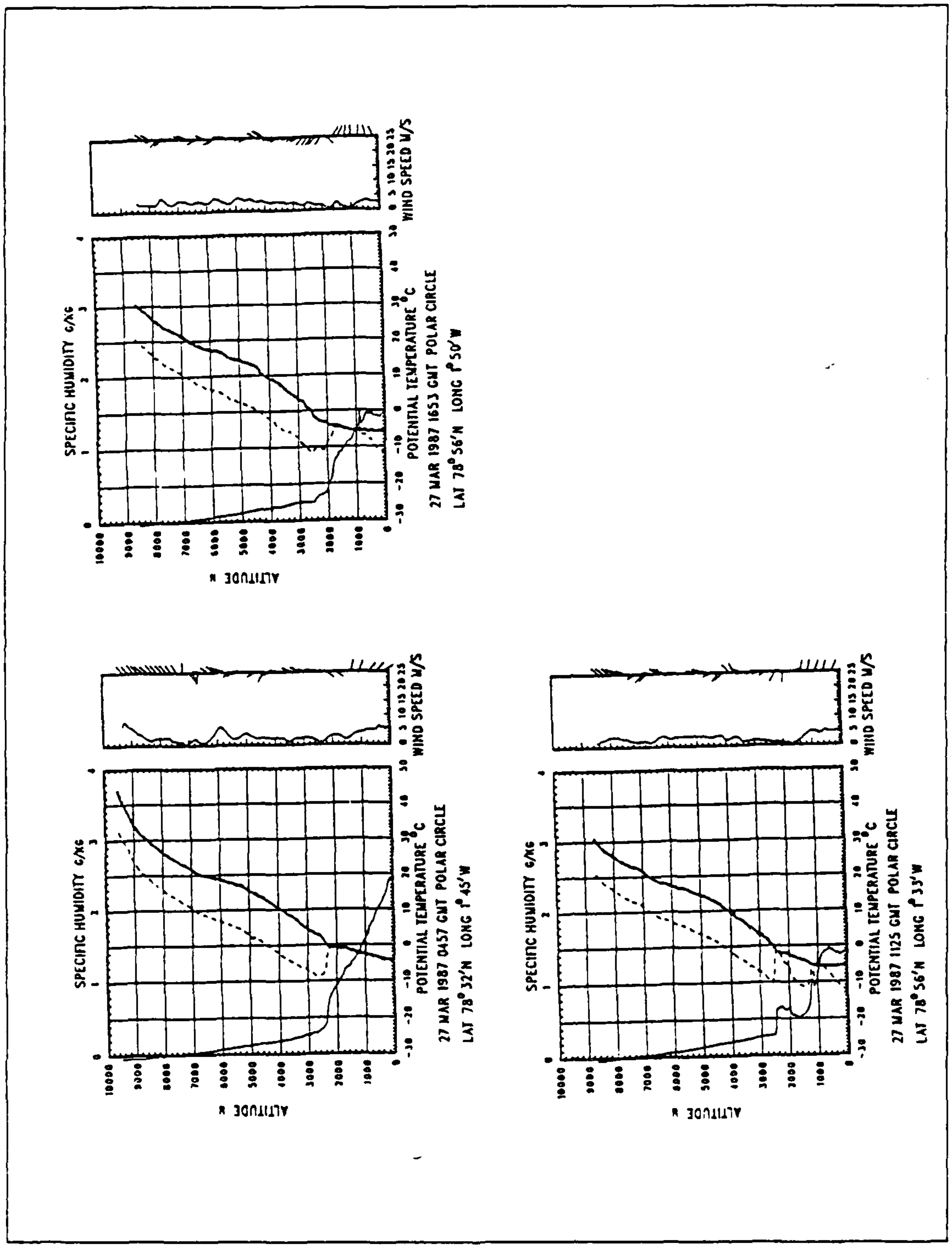


Fig. 4.15 Polar Circle Rawinsonde Profiles, 27 March 1987
(a) 0457 UT, (b) 1125 UT, (c) 1653 UT.

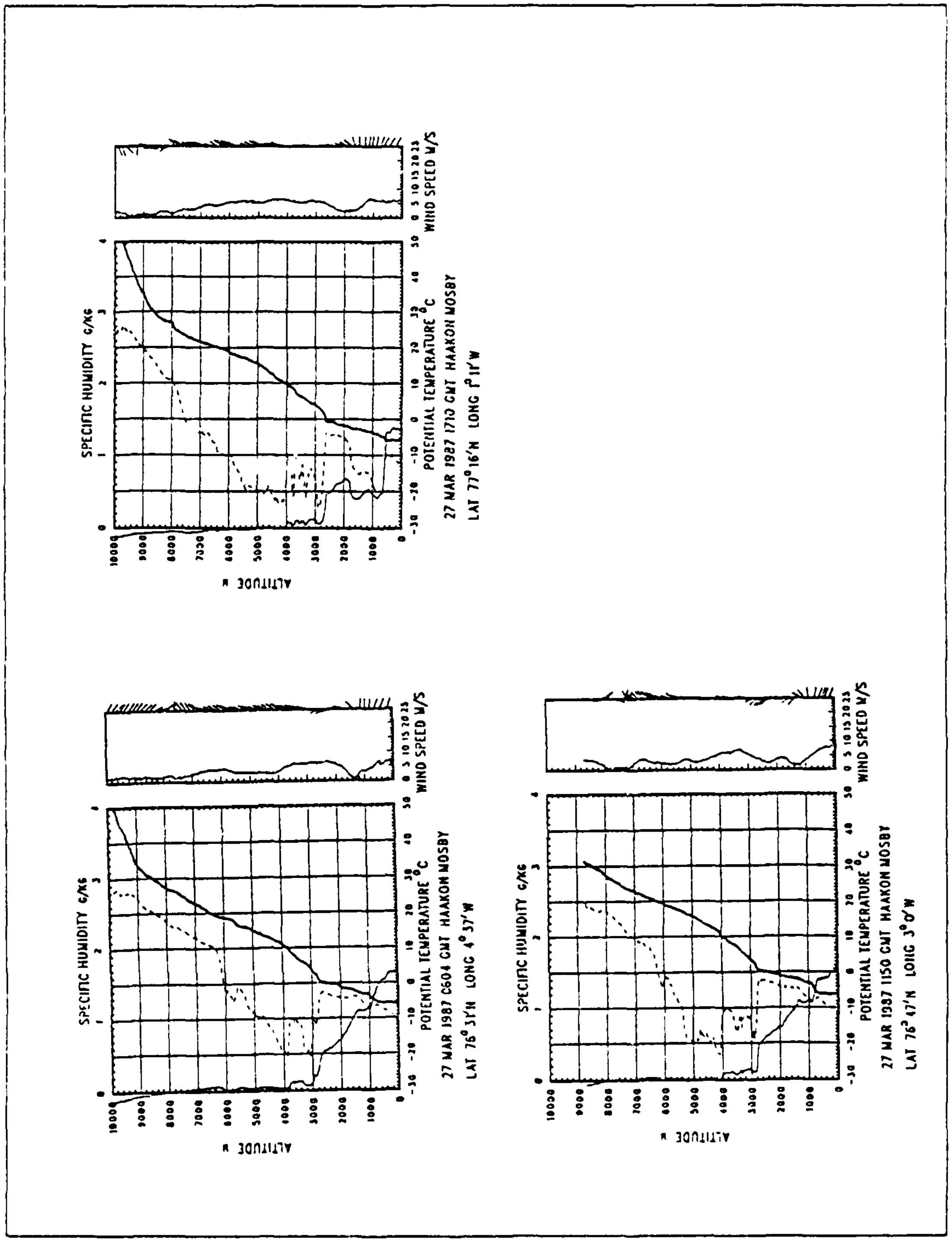


Fig. 4.16 Hakon Mosby Rawinsonde Profiles, 27 March 1987
(a) 0604 UT, (b) 1150 UT, (c) 1710 UT.

# V. SUMMARY AND RECOMMENDATIONS

## A. SUMMARY

Overall, the first half of the MIZEX 1987 period (20 March to 1 April) was dominated by local meteorological activity. The last portion (1 to 10 April) was influenced by a series of three major cyclones which entered from the south. The initial synoptic situation in MIZEX 1987 was dominated by a high pressure center over the Fram Strait MIZ region. This resulted in relatively clear skies and mild weather conditions. This high rapidly lost strength and a more typical March-April low pattern with associated stratus developed by 24 March. On 25 March the development and movement of a boundary-layer front occurred. The front formed in a position 100 km west of the Svalbard Islands and moved to a position 700 km to the west before it dissipated. MIZEX 1987 ships were in unique postions to measure the properties of this system due to their position across the front's westward path. During 27 March a return to more typical weather conditions for the Fram Strait MIZ occurred with a stationary low and a strong inversion layer at 950 mb. Throughout this period an upper-level high existed over the Fram Strait MIZ.

The last portion (1 to 10 April) of MIZEX 1987 saw a series of three synoptic-scale lows approach the MIZ from the Icelandic Low region. The first (Low A) passed well south of the MIZ and traveled into central Norway, having little direct meteorological impact on the Fram Strait. However, the second and third synoptic-scale lows (Lows B and C) passed between the Svalbard Islands and northern Norway. The second low (Low B) started from a position 100 km north of Iceland and reached a postion 100 km southwest of the Svalbard Islands where it stalled. The third, and final, low (Low C) formed later in the same region as Low B and moved along the same path. It reached the stalled Low B on 9 April and merged with it. This created an enhanced larger scale system (Low D) which extended along the entire west coast of the Svalbard Islands south to the Norwegian Sea. Again, the presence of the MIZEX 1987 ships provided valuable data collection platforms due to their postion across the frontal path even in this data collection sparse region.

A detailed study of the boundary-layer front during the 24 to 27 March period indicated its structure and features were different than in the one reported by Shapiro, *et al.*, (1987) in the Polar Low Project. Major differences noted in this thesis were that the boundary-layer front had a higher inversion layer on the east side of the front. In Shapiro's, *et al.*, (1987) case study the boundary-layer inversion was higher over the west side of the front. In this study the boundary-layer front was observed to propagate across the Fram Strait from east to west while Shapiro's, *et al.*, (1987) front was stationary. The mechanism for the frontal formation also appears to be different because no northerly flow was evident over the Svalbard Islands. Instead southerly flow existed. Another major difference was the lack of a low-level wind maximum. Ship positions did not provide sufficient resolution to analyze for a small scale structure.

## B. RECOMMENDATIONS

A full understanding of the Fram Strait MIZ will have to include an analysis of the boundary-layer phenomena since in the absence of other synoptic-scale forcing they appear to have an important role in this region's weather. Also required are understandings of the cause of the frontal features to maintain themselves after boundary-layer fronts move across the Fram Strait.

A further recommendation would be for follow-on experiments to address the occurrence of the boundary-layer fronts and, if they occur, position the ships across the front to allow data collection to be taken at mesoscale intervals. Aircraft, such as the NOAA research P-3, are necessary in these experiments. The aircraft could fly across the front dropping rawinsondes as needed, repeating as required to obtain sufficient data.

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