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Variation of friction velocity across the surface marginal ice zone in the East Greenland Sea.

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NAVAL POSTGRADUATE SCHOOL
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VARIATION OF FRICTION VELOCITY ACROSS THE SURFACE MARGINAL ICE ZONE IN THE EAST GREENLAND SEA

by

Roberta Melvina Runge

December 1985

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Variation of Friction Velocity Across the Surface Marginal Ice Zone in the East Greenland Sea

by

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Submitted in partial fulfillment of the requirements for the degree of

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from the

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December 1985

ABSTRACT

The Marginal Ice Zone Experiment (MIZEX) took place in the summer of 1984. All data presented in this thesis are from the 15 June - 15 July time frame of the MIZEX. Of primary concern in the marginal ice zone is the surface stress, which contributes to changing the upper part of the ocean, to ocean eddy formation and dissipation and to ice movement. This thesis investigates the surface layer wind, temperature and, in particular, the variation of the surface stress in the open water along the marginal ice zone. The stress values were obtained using the dissipation method. These values will be compared to the Large and Pond bulk-formulated drag coefficients, which are open water values. From this comparison, a realistic estimate of atmospheric forcing in the marginal ice zone can be obtained.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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I. INTRODUCTION

The Arctic is of strategic importance to the United States for two main reasons. Primarily, the Soviet Union and the United States share a common ocean border. Second, the Arctic Ocean serves as a barrier to attack from the north. The Arctic is becoming a very important area of forward deployment, due to the threat of Soviet submarines and the importance of maintaining "choke points" such as the Bering Strait and the Greenland-Iceland-United Kingdom gap free of Soviet vessel movement. Soviet submarine-launched ballistic missiles represent a major threat since submarines are now being deployed in the waters of the Barents Sea and adjacent marginal ice zones (MIZ) of the Arctic Ocean. After leaving their home port of Murmansk, Soviet nuclear submarines can pass south of Spitzbergen and proceed under the arctic ice cap north of Greenland, providing the Soviets with an excellent position for targeting the United States and Canada. Missiles fired from this location would take 15 minutes to reach their U.S. destinations instead of the 30 minutes required if the missiles were fired from a Soviet base. (Johnson, et. al., 1982)

An important region of the Arctic is the marginal ice zone (MIZ). This is the area of broken ice separating the open ocean from the fast ice along the coast. It is in a state of constant change caused by ocean currents and the synoptic weather pattern. Of particular interest in this thesis is the East Greenland Sea MIZ. Knowledge of its synoptic and mesoscale meteorological conditions and features are minimal due to a lack of _in situ_ observations. Within the MIZ, atmospheric forcing is of primary importance in the interpretation of upper ocean mixing, ice movement and acoustic properties.

The Marginal Ice Zone Experiment (MIZEX) took place in the summers of 1983 and 1984. This thesis considers 1984 data only. Preliminary results from these experiments have been summarized by Johannessen (1985).

MIZEX was a six week study of the atmospheric, oceanic and ice properties of the marginal ice zone and was conducted by scientific groups from West Germany, France, Denmark, Finland, Norway, Switzerland, Ireland, Canada, England and the United States. This represented the largest internationally coordinated Arctic experiment ever attempted. The experimental area covered 125 square miles of the East Greenland Sea and is illustrated in Fig. 1.

The MIZEX research program was intended to increase the understanding of the transition zone from the fast ice along the coast of Greenland to the open ocean (Johannessen, et. al., 1983). The objectives of the meteorological studies during the MIZEX are as follows:

1. To characterize surface layer forcing of the ice and upper ocean which contributes to mesoscale atmospheric cyclogenesis adjacent to the MIZ.

2. To understand how the vertical and horizontal structure of mesoscale atmospheric features are related to the surface conditions.

3. To relate atmospheric features to changing ice and ocean conditions remotely sensed from surface (roughness) and tropospheric (cloud) properties.

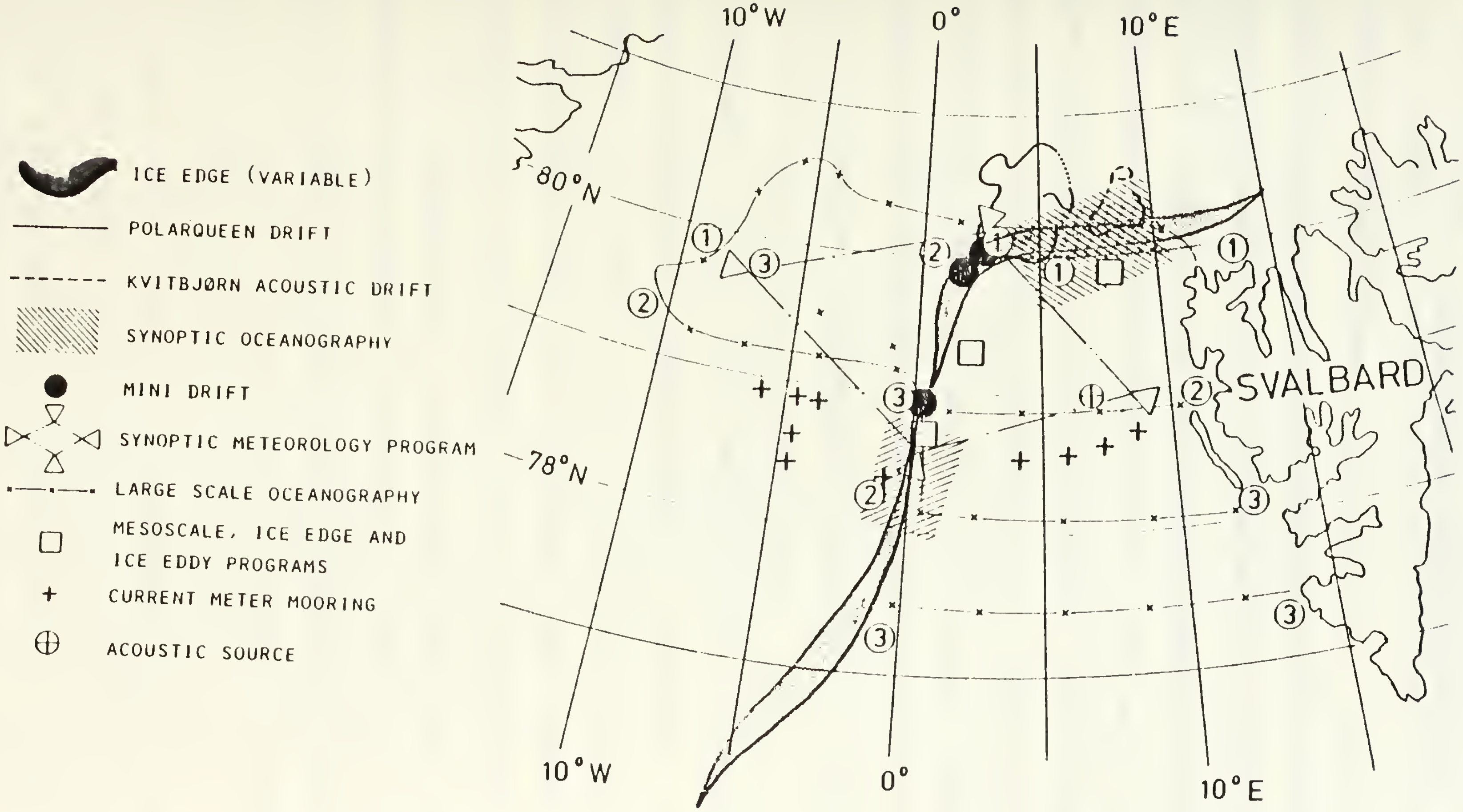

Figure 1. MIZEX 84 Program Overview

Of primary meteorological concern in the marginal ice zone is the surface stress, which contributes to changing the upper part of the ocean, to ocean eddy formation and dissipation and to ice movement. It is unrealistic when estimating the atmospheric forcing in the MIZ, to assume that wind speeds and atmospheric boundary layer structures are the same over the ice, the ice edge and the open ocean. The transition from ice to ocean is characterized by large changes in surface roughness and temperature. In addition, considerable changes in the relationship between pressure gradient and surface wind velocity occur either due to changes in the boundary layer height or through baroclinic effects caused by horizontal atmospheric temperature gradients or a sloping inversion. (Mikhalevsky, et. al. 1985)

In this thesis, the surface layer wind, temperature and, in particular, the variation of surface stress in the open water along the marginal ice zone, during MIZEX, will be discussed. The stress values were obtained using the dissipation method described in Chapter 2. From these values the neutral drag coefficients were obtained and will be compared to the bulk-derived open ocean drag coefficients of Large and Pond (1981). Variations in the surface stress will be related to synoptic scale changes.

II. OBSERVATIONS AND CALCULATIONS

A. GENERAL MEASUREMENTS

The meteorological experiments of MIZEX 84 were designed to investigate variations in atmospheric forcing in the MIZ. Mesoscale forcing seems to be the most important scale of forcing in this region of large horizontal gradients in thermal and roughness conditions. It is believed that both microscale (surface layer) and synoptic-scale (upper-level) properties and processes are important in determining the MIZ mesoscale features. Fig. 2 depicts the MIZEX organizational view of the importance of various scales, processes and available data for meteorological description of the marginal ice zone.

The ships involved in taking meteorological measurements during the MIZEX are listed in Table 1. The days the measurements were taken are also listed. The Polar Queen and Haakon Mosby meteorology measurements were made by Naval Postgraduate School investigators in addition to R. W. Lindsay onboard the Polar Queen. The positioning of the ships within the ice, at the ice edge, in the open water off the ice edge, and the coordinated surface and upper level measurements, yielded a data set which can be interpreted for mesoscale features and their effect on surface phenomena (acoustic, ice and ocean).

Numerous meteorological measurements were taken onboard the R/V Haakon Mosby from 15 June to 15 July 1984. These measurements and the systems or sensors used are listed in Table 2. Fig. 3 indicates the location of the sensors onboard the

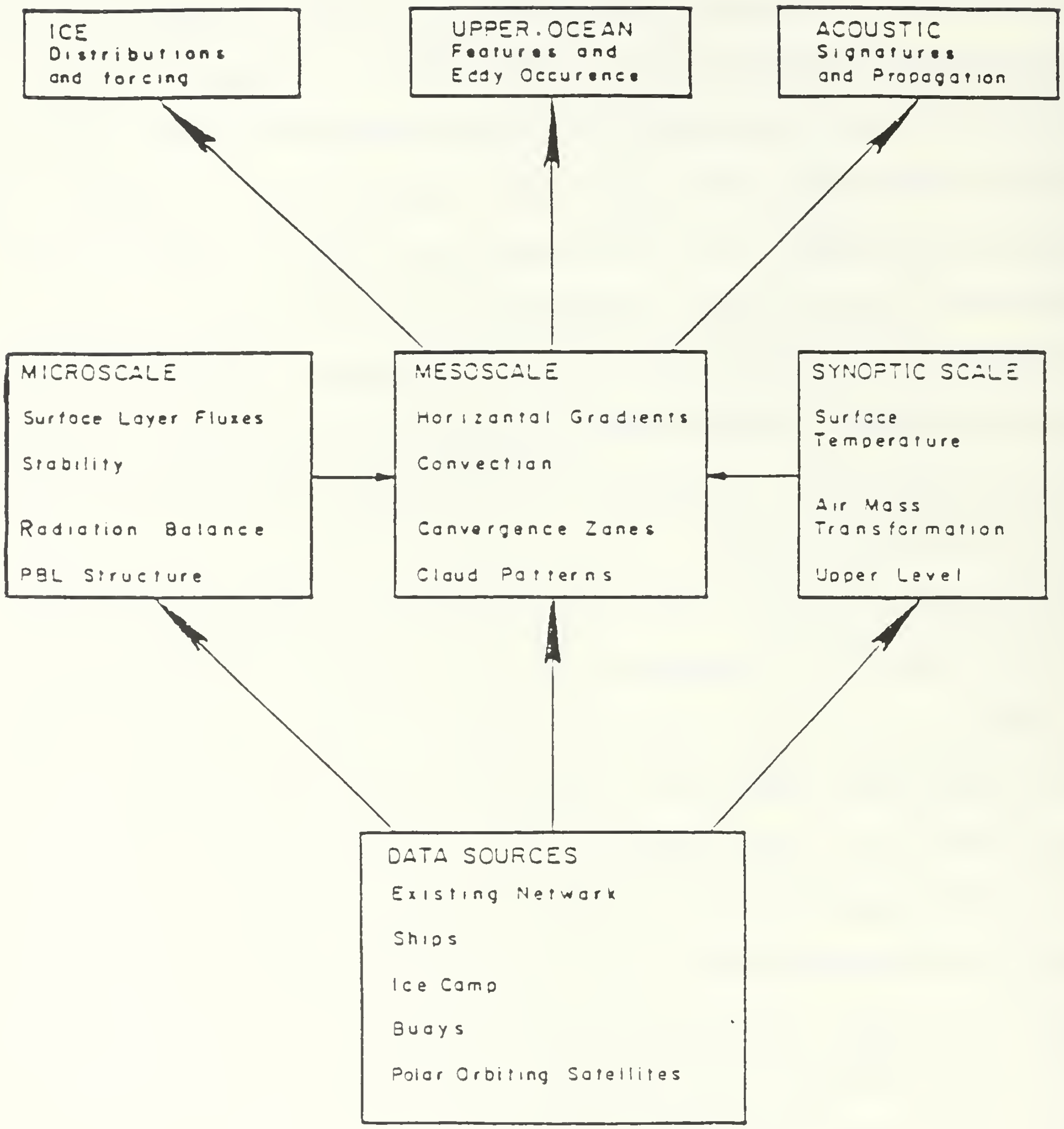

Figure 2. Atmospheric Processes

TABLE I

SHIPS IN MIZEX 84 WHICH COLLECTED METEOROLOGICAL DATA

SHIPS	PERIOD
USNS LYNCH	MAY 18 - JUNE 28
MV POLAR QUEEN	MAY 29 - JULY 29
MV KVITBJORN	MAY 30 - JULY 30
MS HAAKON MOSBY	JUNE 12 - JULY 15
FS POLARSTERN	JUNE 11 - JULY 18
FS VALDIVIA	JUNE 20 - JULY 18

TABLE II

METEOROLOGICAL MEASUREMENTS/OBSERVATIONS ON THE R/V HAAKON MOSBY

Measurements	Sensor/System	Frequency
Radiation (down and reflected)	Long/short wave radiometers	Continuous
Sea Surface Temperature	Floating thermister	Continuous
Mean surface layer:		
Wind (speed, direction)	Cup anemometer, vane	Continuous
Temperature	Resistance thermometer	Continuous
Humidity	Dew cell (cool mirror)	Continuous
Aerosols	Optical Counters (.3 to 300)	Continuous
Turbulent Kinetic Energy Dissipation Rate	Hot film/ Miniature	Continuous
Inversion Height	Sodar	Continuous
Temperature, Humidity, and Wind Profiles	Vaisala (MIZEX-84 schedule) Radiosonde	Continuous 4 or 8/day
Sky and Sea Conditions	Visual observations	Hourly

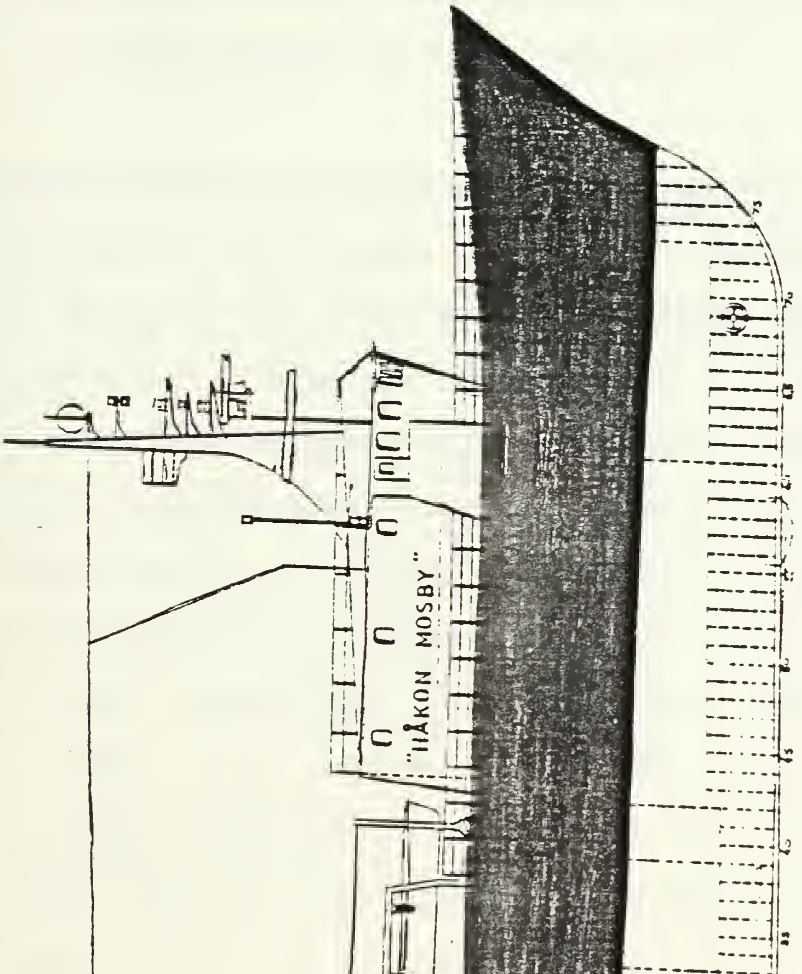

Figure 3. R/V Haakon Mosby

R/V Haakon Mosby. All measurements were taken in the ice free region of the MIZ, as can be seen from the general location of the ice edge and the path of the R/V Haakon Mosby (Figure 4).

A total of 136 successful radiosonde launches were performed on the Haakon Mosby. The normal frequency of launches was four per day with an increase to eight per day during 9 - 15 July. An onboard acoustic sounder, SODAR, was used to indicate convective activity (up to 600 meters) and the presence of inversion layers. The collection of surface layer mean and turbulent data benefited from the synoptic and mesoscale CTD station procedures in which the ship was oriented into the wind and uninterrupted data were obtained for 30-60 minute periods. The transit patterns enabled measurements along tracks with various orientations to the ice edge and oceanic fronts. Data collected adjacent to the ice edge were often adversely affected by icing of turbulent wind sensors when fog was present, which was 30% of the time.

B. HOT FILM MEASUREMENTS

A key measurement in this analysis is the hot film measured high frequency fluctuations of wind speed from which surface stress, τ, will be calculated. Measurement of the stress is difficult to do directly onboard a ship. However, by measuring high frequency velocity fluctuations and calculating the turbulent kinetic energy dissipation rate, an estimate of τ can be obtained. The fluctuations of wind speed at high frequencies were measured using a hot film anemometer. Because the response of the hot film anemometer voltage to wind speed is affected

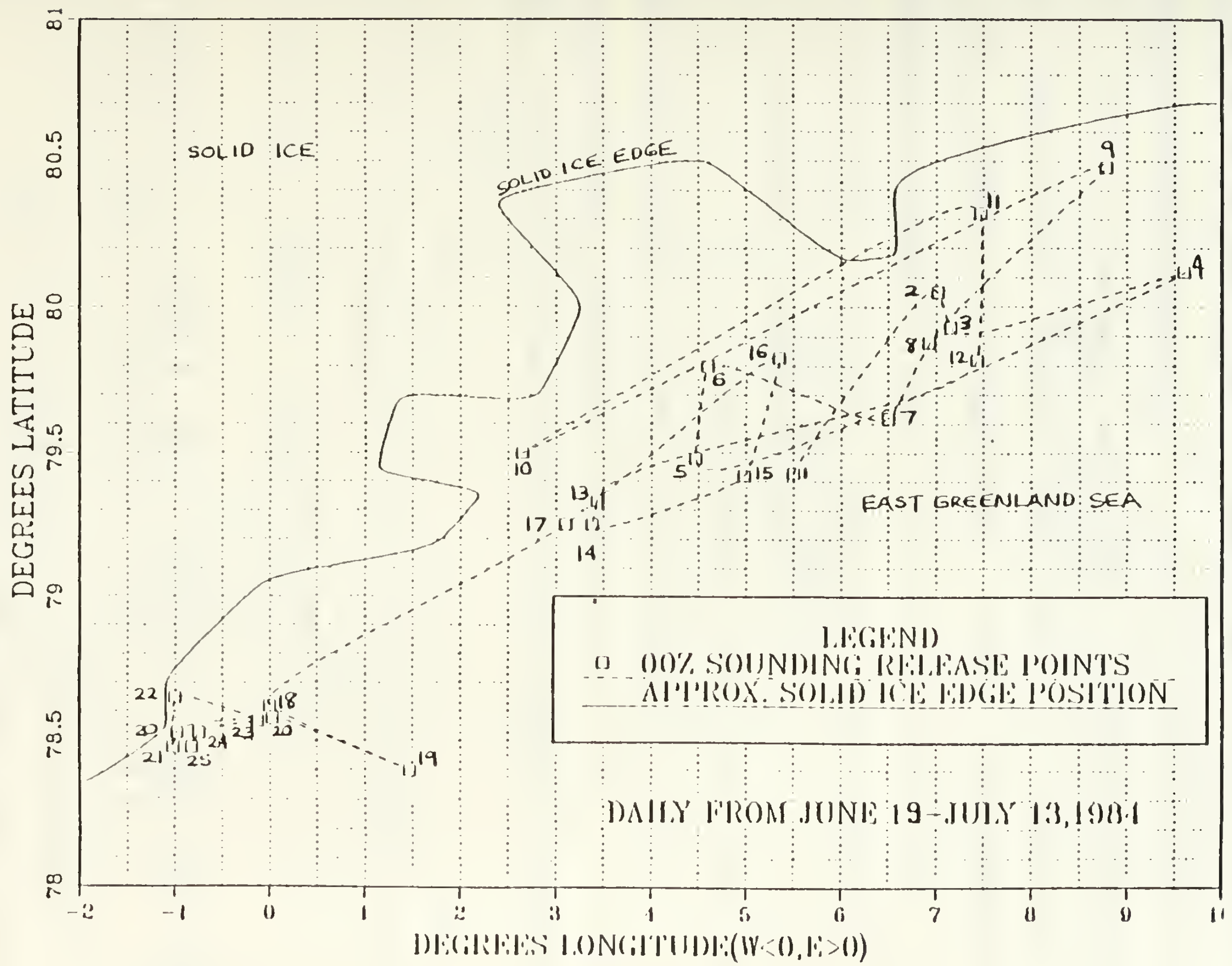

Figure 4. Ice Edge and Haakon Mosby Locations

by the environment, <u>in situ</u> calibration of the hot film anemometer was performed. This was done by calculating a least squares best fit between the hot film anemometer voltages, and the cup anemometer wind speed for several ten minute averages.

Periods of light wind (<4m/s), rain, drizzle, sleet, snow and radio interference all had a significant effect on the hot film anemometer voltage. Any water droplets striking the hot film surface result in latent heat release. This causes a sudden cooling, inducing a jump in voltage and producing spikes in the data. This contaminates the high frequencies and results in large erroneous drag coefficient estimates. Periods of light winds do not cool the film surface sufficiently to prevent convection, producing erratic drag coefficient values. Flow distortion around the ship's structure is also a problem with light or moderate winds. Radio transmissions sometimes produce frequencies in the inertial subrange resulting in erroneous drag coefficient values.

C. STRESS ESTIMATES FROM HOT FILM MEASUREMENTS

The turbulent kinetic energy (T.K.E.) balance can be expressed as follows:

$$\frac{\partial e}{\partial t} = u_*^2 \frac{\partial \bar{u}}{\partial z} + g\frac{\overline{w'T_v'}}{T_o} - \frac{\partial}{\partial z}\left(\overline{w'e} + \frac{1}{\rho}\overline{w'p'}\right) - \varepsilon \quad (1)$$

T_v = virtual temperature

T_o = surface layer temperature

U_* = surface friction velocity where

$\partial e/\partial t$ = the local time rate of change of T.K.E.

$u_*^2(\partial \bar{u}/\partial z)$ = the wind shear production of T.K.E.

$g(\overline{w'T_v'}/T_o)$ = the buoyancy production of T.K.E.

$\partial/\partial z(\overline{w'e} + \frac{1}{\rho}\overline{w'p'})$ = redistribution of T.K.E.

ε = rate of dissipation of T.K.E.

If a steady state is assumed and the divergence term is assumed to be relatively small compared to the other terms, the T.K.E. balance can be expressed as:

$$U_*^2 \frac{\partial \bar{u}}{\partial z} + g\frac{\overline{w'T_v'}}{T_o} - \varepsilon = 0 \qquad (2)$$

The mean surface layer wind flux profile must also be used and is defined as follows:

$$\frac{\partial \bar{u}}{\partial z} = \frac{U_*}{kz}\,\phi_M(z/L) \qquad (3)$$

$\partial \bar{u}/\partial z$ = the vertical gradient of the wind speed

k = von Karman constant (.4)

$\phi_M(z/L)$ = dimensionless stability function based on surface fluxes

The stability parameter is a function of z/L, where z is the height above the surface and L is the Monin-Obukov length.

$$z/L = -g\frac{kz\,(\overline{w'T_v'})}{T_o U_*^3} \qquad (4)$$

By combining the above three equations, the friction velocity can now be written in terms of ε and z/L as:

$$U_* = \left(\frac{\varepsilon k z}{\phi_M(z/L) - z/L}\right)^{1/3} \qquad (5)$$

The denominator is replaced by $\phi_\varepsilon(z/L)$ on the basis of empirical formulations. This function adjusts for the stability of the layer. By definition:

unstable $\phi_\xi = \left[(1 - 16\, z/L)^{-.25}\right] - z/L$

stable $\phi_\xi = \left[1 + 2.31 (z/L)^{.667}\right]^{1.5}$

neutral $\phi_\xi = 1$

At this stage, given z/L (stability), ξ must be determined to obtain a U* value. The Kolmogoroff theory for the energy density spectrum in the inertial subrange is used to calculate a value for the kinetic energy dissipation rate. With this method, the following one dimensional power spectrum is assumed to represent the fluctuations of the wind velocity at high frequencies in the inertial subrange. No energy is produced or dissipated in this subrange. (Lumley and Panofsky, 1964)

$$S_u(K_*) = \alpha\, \xi^{2/3}\, K_*^{-5/3} \qquad (6)$$

$$K_* = \frac{2\pi f}{U_{rel}}$$

α is a an empirical coefficient, usually set to .52. By integration of the Kolmogoroff spectrum between wavenumbers, in the inertial subrange, the friction velocity can be calculated as (Fairall, et. al., 1979):

$$U_* = 2.81\, \sigma_{u\Delta f} \left[\frac{z}{\bar{U}_{rel}\, \phi_\xi (z/L)}\right]^{1/3} \left(f_1^{-2/3} - f_2^{-2/3}\right)^{-1/2} \qquad (7)$$

f1 = 5 hz f2 = 50hz

$\sigma_{u\Delta f}$ = standard deviation of u fluctuations in the integrated inertial subrange bounded by f1 and f2.

This gives a estimate of the friction velocity based on velocity fluctuation measurements with corrections for the stability of the layer.

D. STRESS ESTIMATES FROM BULK FORMULAE

Another method for the estimation of U* involves the use of the log profile. It is useful as a comparison of the stress estimates obtained from the hot film and the wind speed ten meters above the surface.

Integration of equation 3 yields (Paulson, 1970):

$$U = \frac{U_*}{K}\left(\ln z/z_o - \Psi\right) \tag{8}$$

z_o = roughness length

Ψ = stability parameter

Ψ for the unstable case (z/L<0):

$$\Psi = 2\ln\frac{1+x}{2} + \ln\frac{1+x^2}{2} - 2\tan^{-1}x + \frac{\pi}{2} \tag{9}$$

where $x = \left(1-\beta\left(z/L\right)\right)^{1/4}$ and β = 15 or 16

for the stable case (z/L>0):

$$\Psi = \beta\left(z/L\right) \tag{10}$$

where β = 4 to 7. This will yield a log profile with stability corrections in terms of z/L. The neutral drag coefficient (C_{DN}) can now be defined as:

$$C_{DN} = \left(\frac{K}{\ln z/z_o}\right)^2 \tag{11}$$

Finally, the general equation for the drag coefficient in terms of Ψ and C_{DN} can be written as:

$$C_D = \left(C_{DN}^{-1/2} - \frac{\Psi}{K}\right)^{-2} \tag{12}$$

The Large and Pond (1981) drag coefficients were determined from open water measurements. These conditions are in contrast with the surface in the marginal ice zone of the East Greenland Sea. A comparison of the two drag coefficients should produce some insight to the forcing mechanisms found in the MIZ and how they differ with those found in the open ocean.

III. GENERAL SYNOPTIC CONDITIONS

The summer synoptic-scale circulation patterns in the East Greenland Sea are fairly weak throughout the troposphere. A westerly flow pattern is generally present a 500 mb with a low centered over the Arctic Ocean. A persistent low-level inversion occurs over ice covered areas preventing an intrusion of upper level winds. Stratus clouds are frequently found in the vicinity of the ice edge. Cyclones tend to originate over Greenland and the Urals of Russia. Storms tend to occlude near Iceland or Baffin Bay. High pressure systems are usually present over Greenland, the Canadian Archipelago and just north of Russia.

In addition to the major synoptic changes, the Greenland ice mass exerts a mesoscale effect on the East Greenland Sea due to katabatic winds flowing off the ice cap. These winds however do not extend more than 15.0 km from the coast.

A. OVERVIEW OF 15 JUNE TO 15 JULY WEATHER PATTERN

Time series of true wind speed and direction, air and sea temperature, and surface pressure, are shown in Fig. 5. These measurements were taken onboard the R/V Haakon Mosby from 15 June to 15 July and define the synoptic events occurring during MIZEX. Periods of high wind speed will be investigated along with the changes in surface pressure and the stability of the layer. In addition to the time series, synoptic charts of the MIZEX area from 15 June to 15 July are also presented in this chapter.

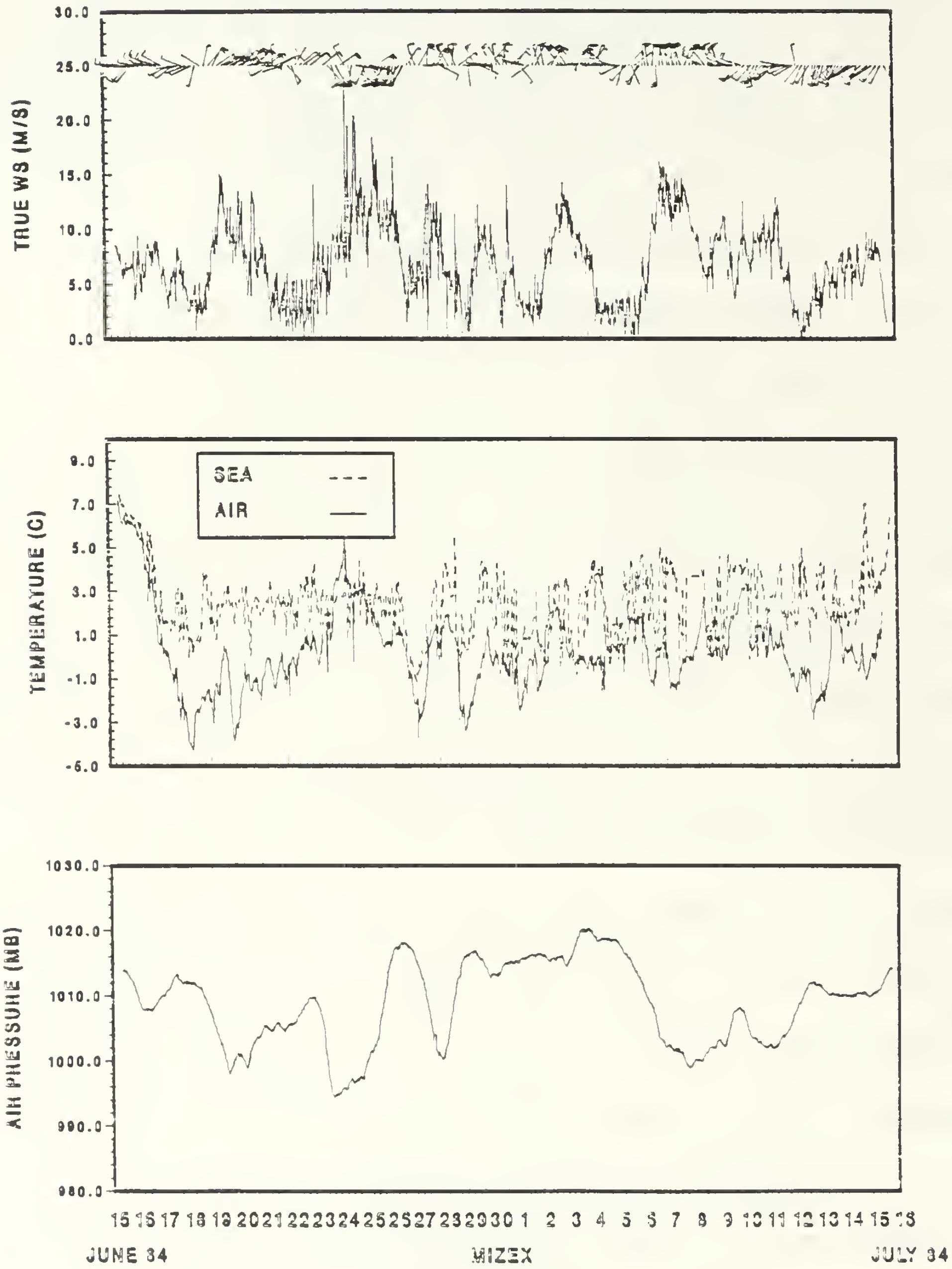

Figure 5. 15 June - 15 July Time Series for True Wind Speed, Temperature, and Surface Pressure

Several synoptic scale systems influenced the East Greenland Sea MIZ from 15 June to 15 July as can be seen from Fig. 5. Approaching storm systems are indicated by a drop in surface pressure and an increase in air temperature due to warm advection from the south. Sea-surface temperatures remained slightly higher than air temperatures throughout the MIZEX. Sea temperatures were normally between 1.0 to 3.0° C. However, air temperatures fluctuated widely ranging from 7.0 °C. to -4.0 ° C., depending upon the synoptic conditions. Five separate high wind periods occurred and were associated with low pressure systems in the region of Svalbard. Four of these were centered east and southeast of Svalbard resulting in north to northeast winds (parallel to the ice edge) over the open water region. (19-21 June, 23-26 June, 3-4 July, 6-7 July). The fifth low was west of Svalbard resulting in south to southeast winds (onto the ice edge) over the open water region (23-26 June). Wind speeds ranged from 25.0 m/s during intense storm activity to 5.0 m/s during periods of light winds.

B. FOUR-DAY PATTERNS

Dividing the time period of the MIZEX into four-day periods enables a closer examination of the effect of the synoptic conditions on the observed surface layer properties and, in particular, the surface stress. Surface stress is expected to increase with increasing geostrophic winds. However, variations of the stress in the marginal ice zone region and its effect on the mesoscale weather pattern and the ice edge, are questions that have yet to be answered.

1. 15 June - 18 June

Figures 6 a-d show the vector true wind, air and sea-surface temperatures, surface pressure, and the surface stress for this period. In addition, Fig. 7 shows the synoptic charts for the four day period. On 15 June, at the beginning of the MIZEX, measurements on the R/V Haakon Mosby indicated a light wind from the northwest at 9.0 m/s. The area was dominated by a high pressure system centered over Greenland. A surface level ridge had developed to the southwest of Spitzbergen. Surface pressure was recorded at 1015 mb. The dissipation stress decreased from 0.16 to 0.08 N/m^2 over the period of the 15th.

On 16 June, the high pressure system moved off Greenland to the north, allowing an old low center to move through the Fram Strait lowering the surface pressure to 1008 mb. Winds were from the west off the ice edge. As the low continued to dissipate and move through the Strait, the surface pressure increased and the wind shifted to the northwest. As the storm system approached the Haakon Mosby on the 16th, the dissipation stress increased steadily. Wind speed gusted to 10.0 m/s and air temperature dropped to 1.0 °C. by midnight. Sea-surface temperature remained above 2.0 ° C. The storm center filled and died on the 17th of June. A pressure decrease on the 17th was due to an upper level low to the north of Spitzbergen. Winds remain less than 10.0 m/s but were now from the southwest.

An interesting increase in stress was recorded between 1200 GMT on the 17th and 0600 GMT on the 18th. (This will be discussed in greater detail in Chapter 4.) Stress values showed

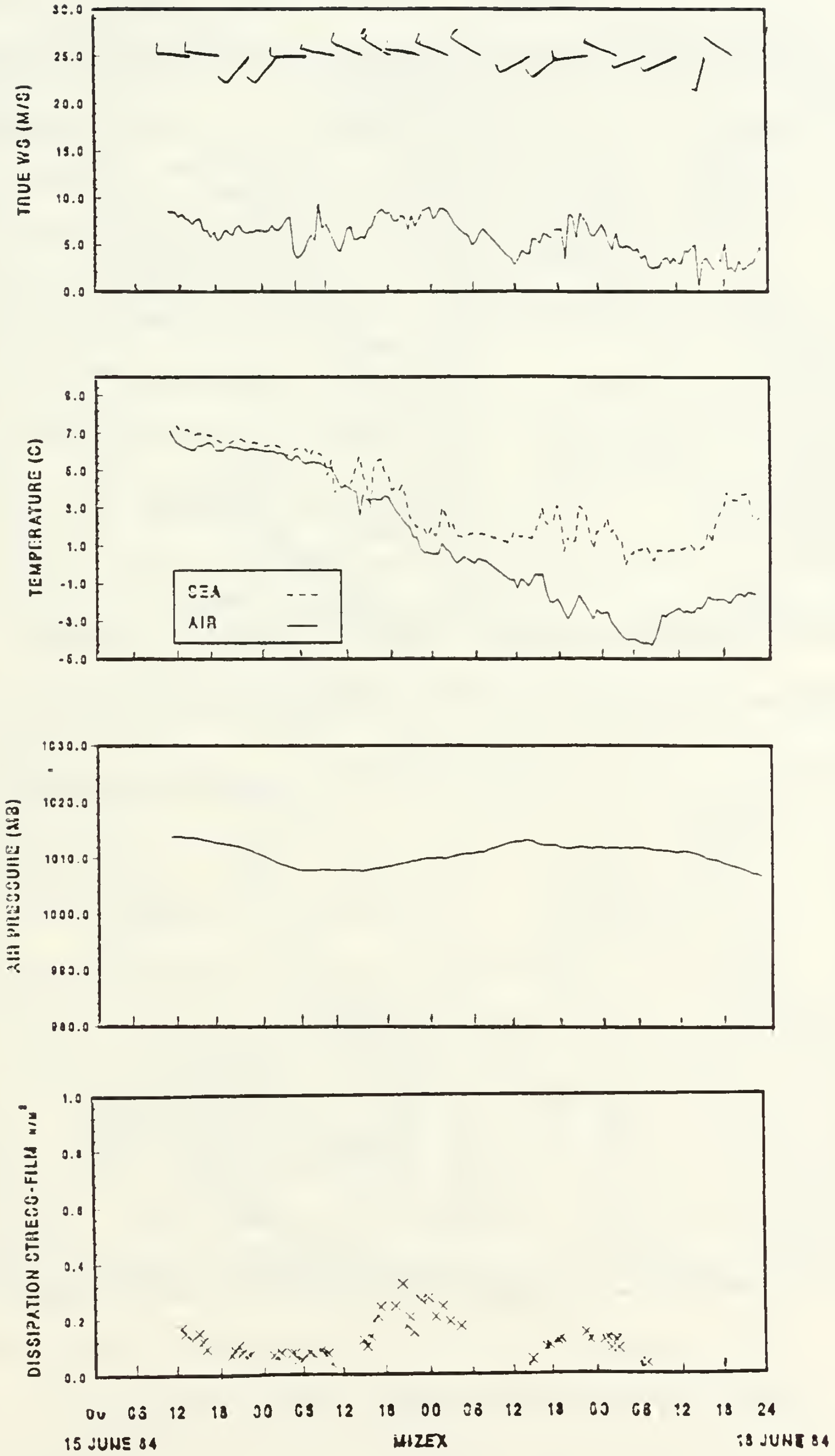

Figure 6. 15 June - 18 June Time Series

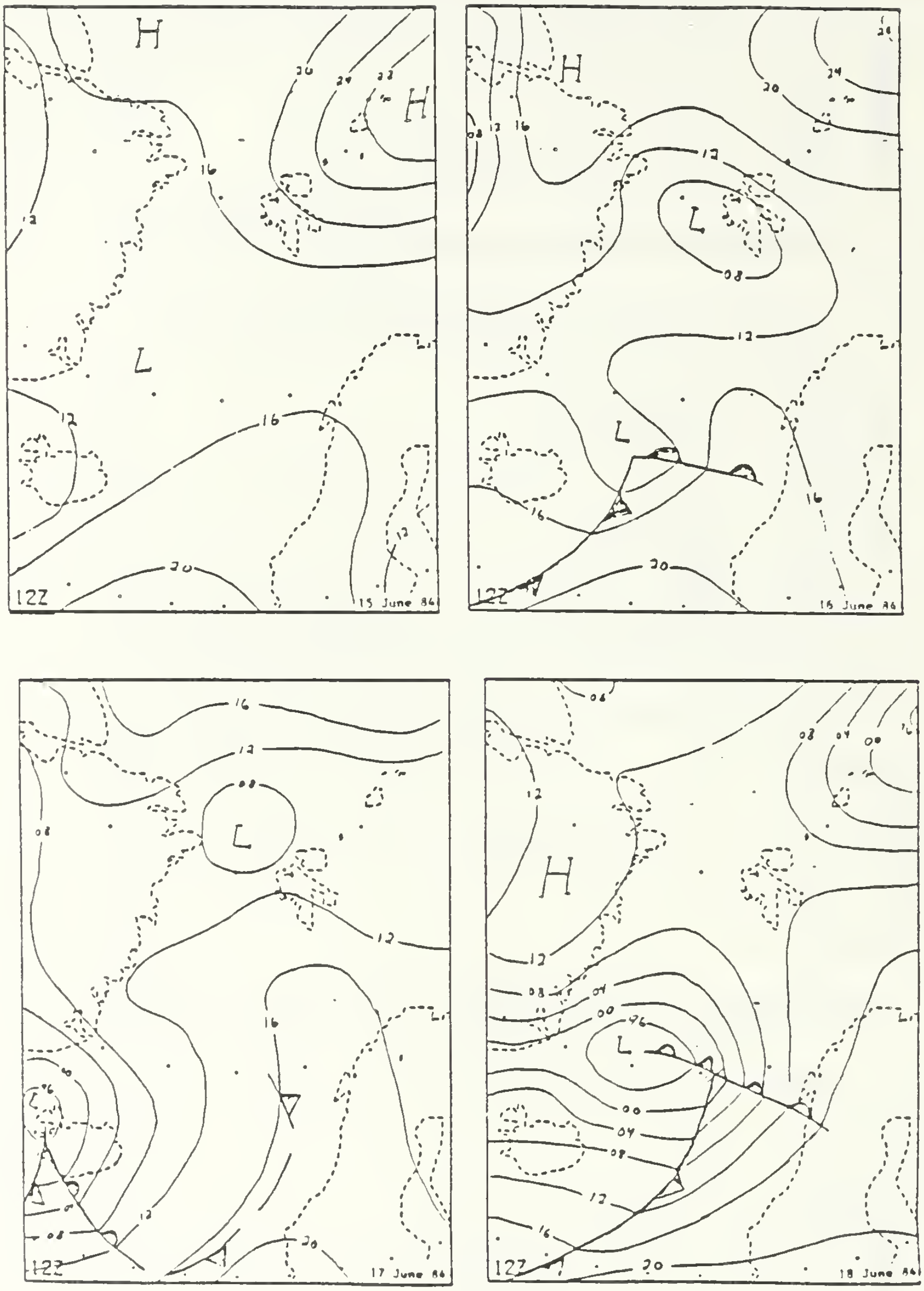

Figure 7. 15 June - 18 June Synoptic Charts

a rapid rise to 0.18 N/m^2 by 0000 GMT on the 18th and then a drop back to 0.12 N/m^2 by 0600 GMT. Wind speeds were only 8.0 m/s and the surface pressure had remained at 1014 mb. Air and sea-surface temperatures, however, varied greatly. The sea temperature during this time was 1.0 °C. with air temperature dropping to -3.0 °C. due to off ice flow. Stress values were less than .2 N/m^2 by the end of the 18th.

During this four-day time period, winds remained light and variable with the exception of 10.0 m/s gusts during the passage of a low pressure system. Air and sea-surface temperature began at 7.0 °C. and rapidly decreased. By the 18th, the layer was unstable with the surface and air temperatures varying by 4 degrees. Surface pressure was fairly high throughout the period and two instances of increased surface stress were recorded.

2. <u>19 June - 22 June</u>

Figure 8 a-d is the time series for this period and Fig. 9 is the synoptic pattern. Pressure dropped to 998 mb and winds increased to 15.0 m/s by 1200 GMT on the 19th. This was due to the presence of a storm system just south of Spitzbergen. The winds were parallel to the ice edge resulting in some ice fog and low-level stratocumulus cloud formation due to the warm water surface (the northward flowing West Spitzbergen current is about 2 degrees warmer than the surrounding waters). Air temperature was recorded at 0.5 °C. Sea-surface temperature was 2.0°C. creating unstable conditions. Surface stress increased to a maximum of 0.94 N/m^2 at 1358 GMT on 19 June as shown by Fig. 8 d.

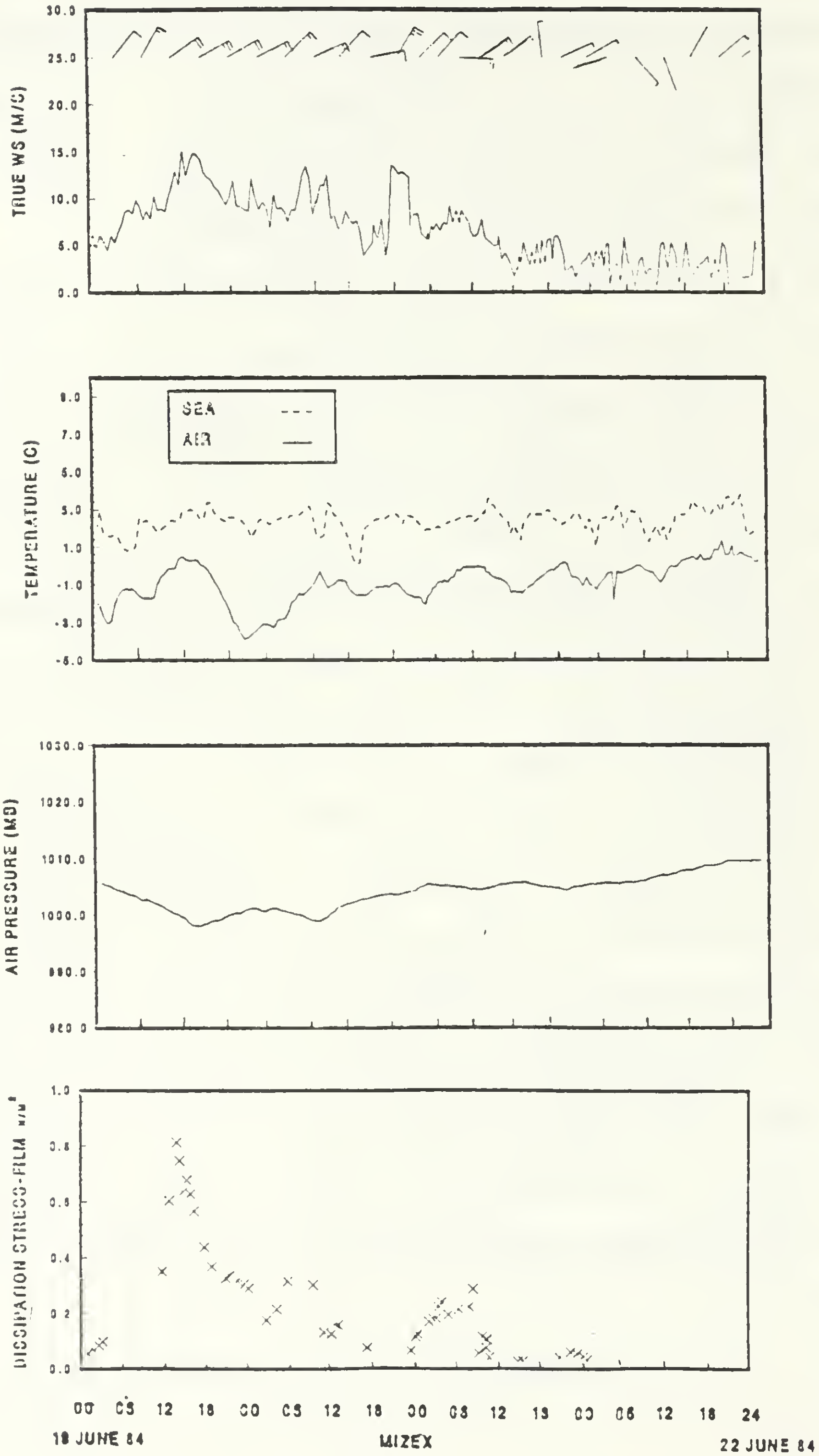

Figure 8. 19 June - 22 June Time Series

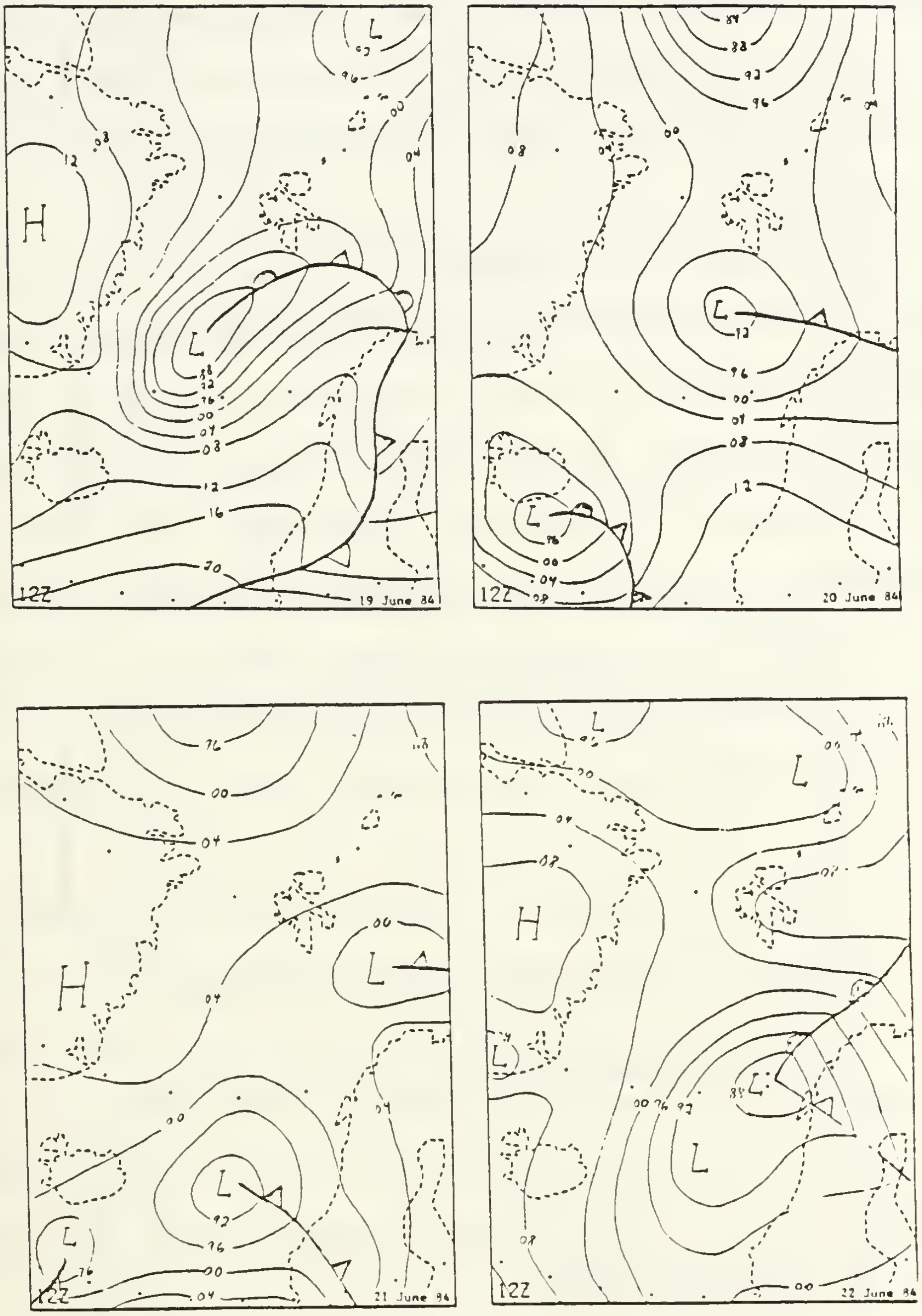

Figure 9. 19 June - 22 June Synoptic Charts

The normal path for a cyclone in the Norwegian Sea during this time of year (June-July) would be to move northward with the Norwegian current. The northward progression of the cyclone did occur and wind speed dropped in the Fram Strait to 5.0 m/s by 1200 GMT on the 21st with a corresponding drop in surface stress to 1.2 N/m^2.

On 21 June a low pressure system was located to the northeast of Iceland moving across the Norwegian Sea. Along the coast of Norway the system intensified to 988 mb then moved northwest to the Fram Strait. On the 22nd the Haakon Mosby reported a pressure of 1009 mb, light winds from the northeast and air temperature of 0.0° C. Sea-surface temperature remained at 2.0° C. Another low pressure center moving to the east over Greenland, in conjunction with the low to the east of Svalbard, created a calm over the experimental area. The calm was of short duration.

This period contained the highest stress values recorded during the MIZEX. It occurred with 15.0 m/s winds, a 2 degree difference in air-sea temperatures and a surface pressure of 998 mb. Conditions remained unstable throughout the four-day period. As the storm system passed to the east of Svalbard, winds gusted up to 15.0 m/s and surface stress values seemed to reflect the wind increase.

3. <u>23 June - 26 June</u>

The time series for this period are shown in Fig. 10 a-d. The synoptic charts are shown in Fig. 11 for the four-days. By 24 June the storm which was to the east of Svalbard had entered

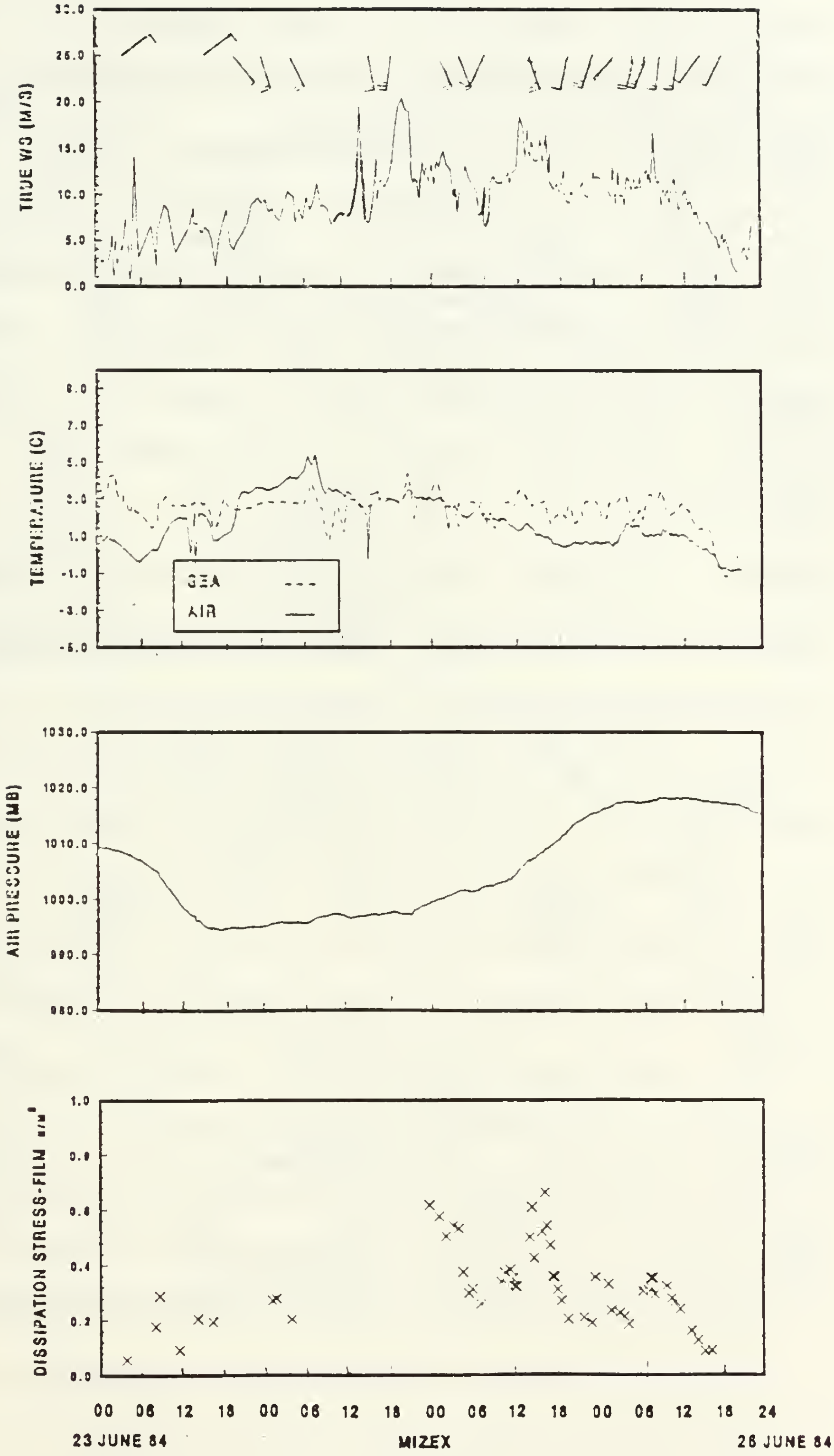

Figure 10. 23 June - 26 June Time Series

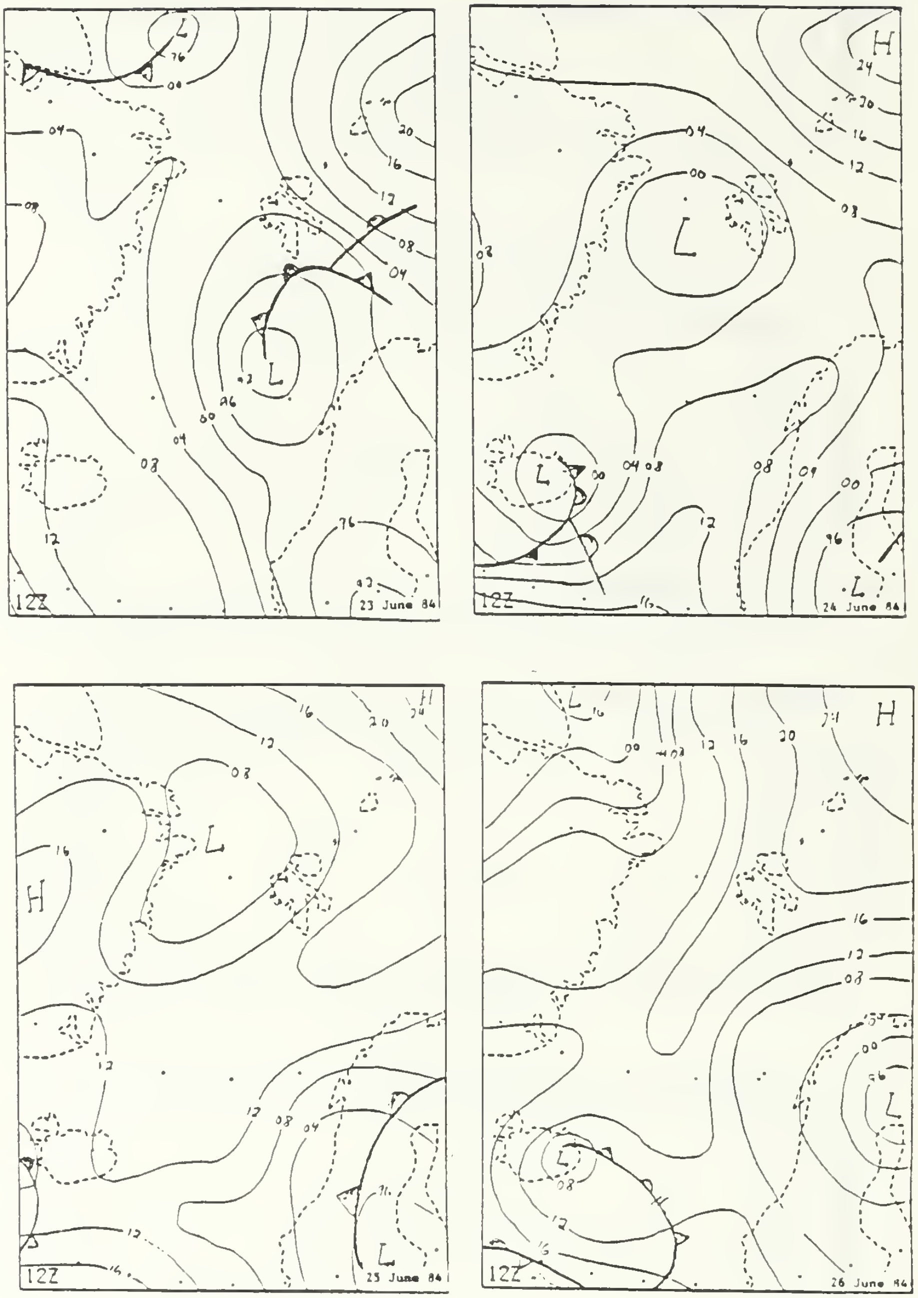

Figure 11. 23 June - 26 June Synoptic Charts

the Fram Strait. The ship was located at 79.8°N, 4.5°E which was within the frontal band of the system. Winds were in excess of 20.0 m/s from the southeast. At 0600 GMT on the 24th the surface pressure was 998 mb with air temperature at 5.0 °C. and sea-surface temperature at 2.5°C. Note that in this instance conditions are stable. This was one of the few times during MIZEX that air temperature rose above the sea-surface temperature. The rise in air temperature was caused by a 10-20 m/s wind from the south bringing warm air into the region. At this time surface stress was calculated at 0.3 N/m^2. This was the only major system to move to the west of Svalbard during the recording period.

The storm continued to the northwest on 25 June. It appeared to slow as it entered the marginal ice zone. At 0000 GMT on the 25th its central pressure was measured at 1002 mb. Winds were 15.0 m/s from the southeast and the air temperature had decreased by 1.0 C. Surface stress at this time had increased to 0.64 N/m^2. By 0600 GMT on the 25th the storm moved away from the ice edge and continued on a northern route out of the Strait. The air temperature dropped below the sea-surface temperature so that conditions once again became unstable and surface pressure began to increase. However, by this time, a strong pressure gradient had developed in a meridional flow pattern and winds increased to 20.0 m/s from the south. Surface stress rose from 0.3 N/m^2 at 0600 GMT to 0.65 N/m^2 at 1200 GMT at which time the winds began to decrease. By 26 June, the MIZEX area was dominted by a high pressure ridge with winds from the southwest.

Wind speeds were still fairly high at 10.0 m/s with gust to 15.0 m/s. The highest stress values recorded were 3.8 N/m^2 which corresponded to 15.0 m/s wind speeds from 0600 GMT to 1200 GMT.

This time period was dominated by strong winds from the south, increasing air temperature considerably. Several instances of high surface stress corresponding to the high wind periods were recorded. A correlation between the roughness of the sea surface and the surface stress values is apparent from the data viewed in this time period.

4. <u>27 June - 30 June</u>

Figure 12 a-d shows the time series for this period and Fig. 13 shows the synoptic pattern. The next major storm system to directly effect the MIZEX developed to the southeast of Spitzbergen on 27 June. Winds were from the northwest (off ice edge) as the storm approached. By 28 June the low had reached the southern end of Spitzbergen. A decrease in surface pressure to 1000 mb and an increase in air temperature was recorded. Winds were 15.0 m/s from the north and conditions were unstable. The surface stress value was a maximum, 0.68 N/m^2, at this time. As can be seen by the 1200 GMT synoptic chart for the 28th, the storm stagnated and filled dropping the winds back to 10.0 m/s. Air temperature also decreased shortly after 1200 GMT to -3.0 $^\circ$C. with the sea temperature remaining close to 1.0° C. Stress values by this time had decreased to 0.16 N/m^2.

On 29 June the circumpolar vortex moved northward and a high pressure system was situated over Greenland and the

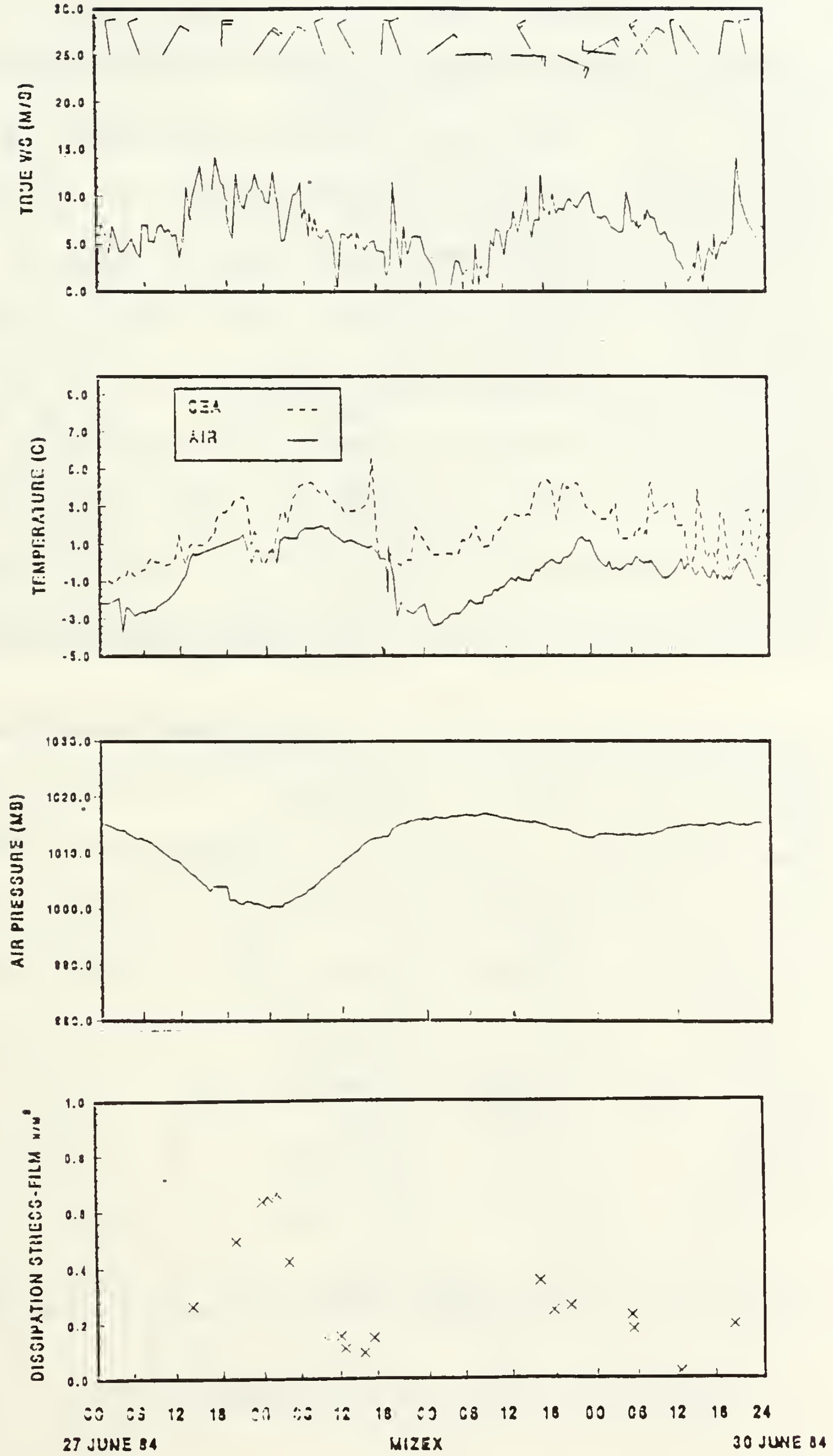

Figure 12. 27 June - 30 June Time Series

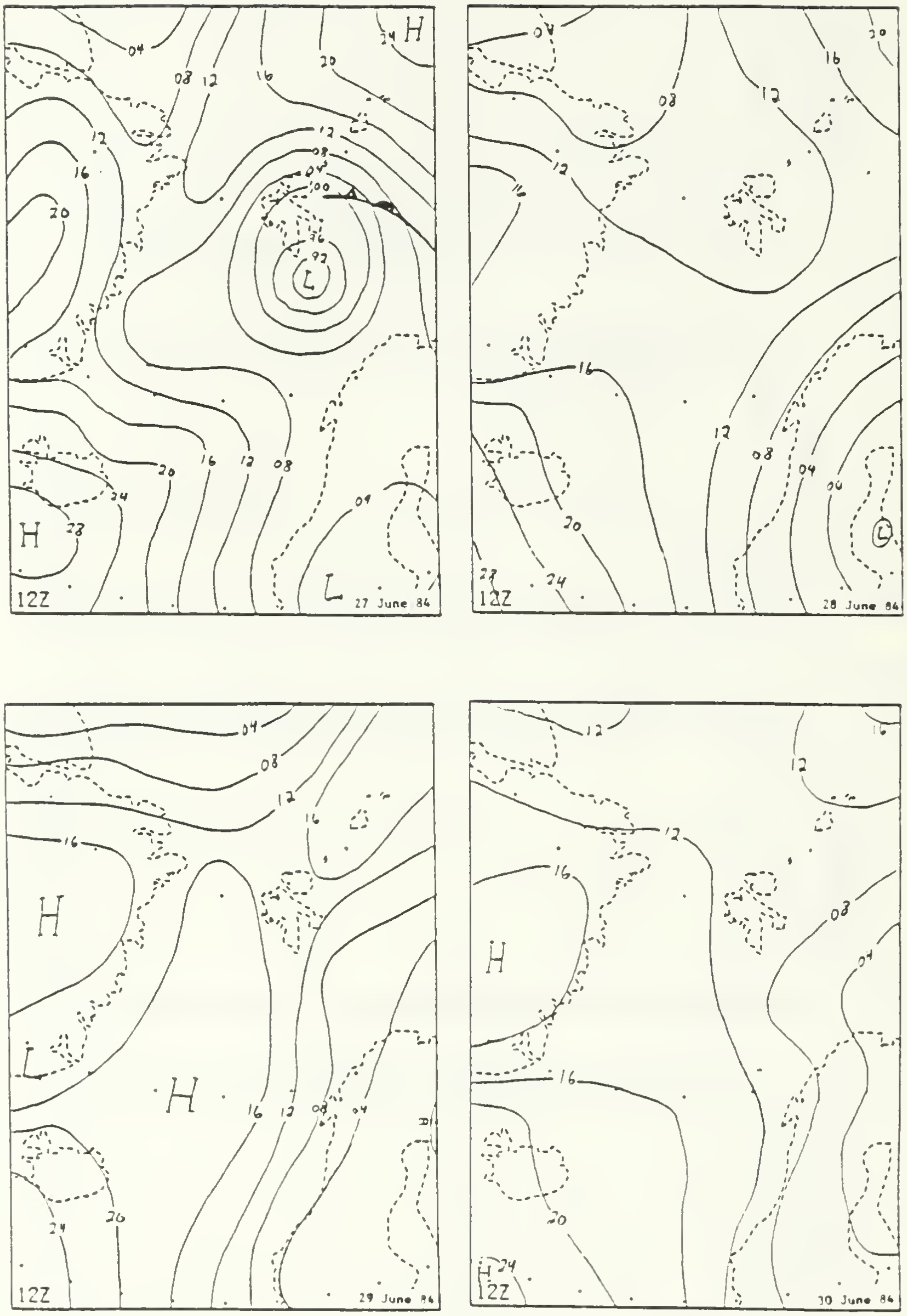

Figure 13. 27 June - 30 June Synoptic Charts

Fram Strait. A weak upper level jet existed over the Fram Strait. Winds were light and from the east. However, by the 30th a meridional flow pattern had again developed and wind speeds picked up to 10.0 m/s. Conditions remained unstable and surface values were remaining close to 0.20 N/m^2.

This time period mainly contained winds from the north with two instances of wind speeds in excess of 10.0 m/s. Unstable conditions existed over the entire four-day period. Only one decrease in surface pressure was recorded with a corresponding increased in surface stress and a decrease in sea-surface temperature. The data supports the existence of a wind-wave effect causing an increase in the surface roughness followed by an increase in surface stress.

5. <u>1 July - 4 July</u>

Time series of this period are given in Fig. 14 a-d. The synoptic pattern is shown in Fig. 15. On 1 July the high pressure system over Greenland intensified to 1020 mb. Winds in the MIZEX were from the northeast at 5.0 m/s flowing into a trough over the Fram Strait. The Haakon Mosby was located at 79.3°N,3.5°E. This location went through a series of rapid changes caused by the formation of a cut off low over Greenland. Initially, 0000 GMT, the ship was in the center of a calm resulting in light and variable winds, unstable conditions, and overcast skies. The sea level pressure was recorded at 1015 mb. As the cut off low developed and moved westward a high pressure system developed just to the south of Greenland. By 0000 GMT on 2 July the high pressure system had reached the Fram Strait.

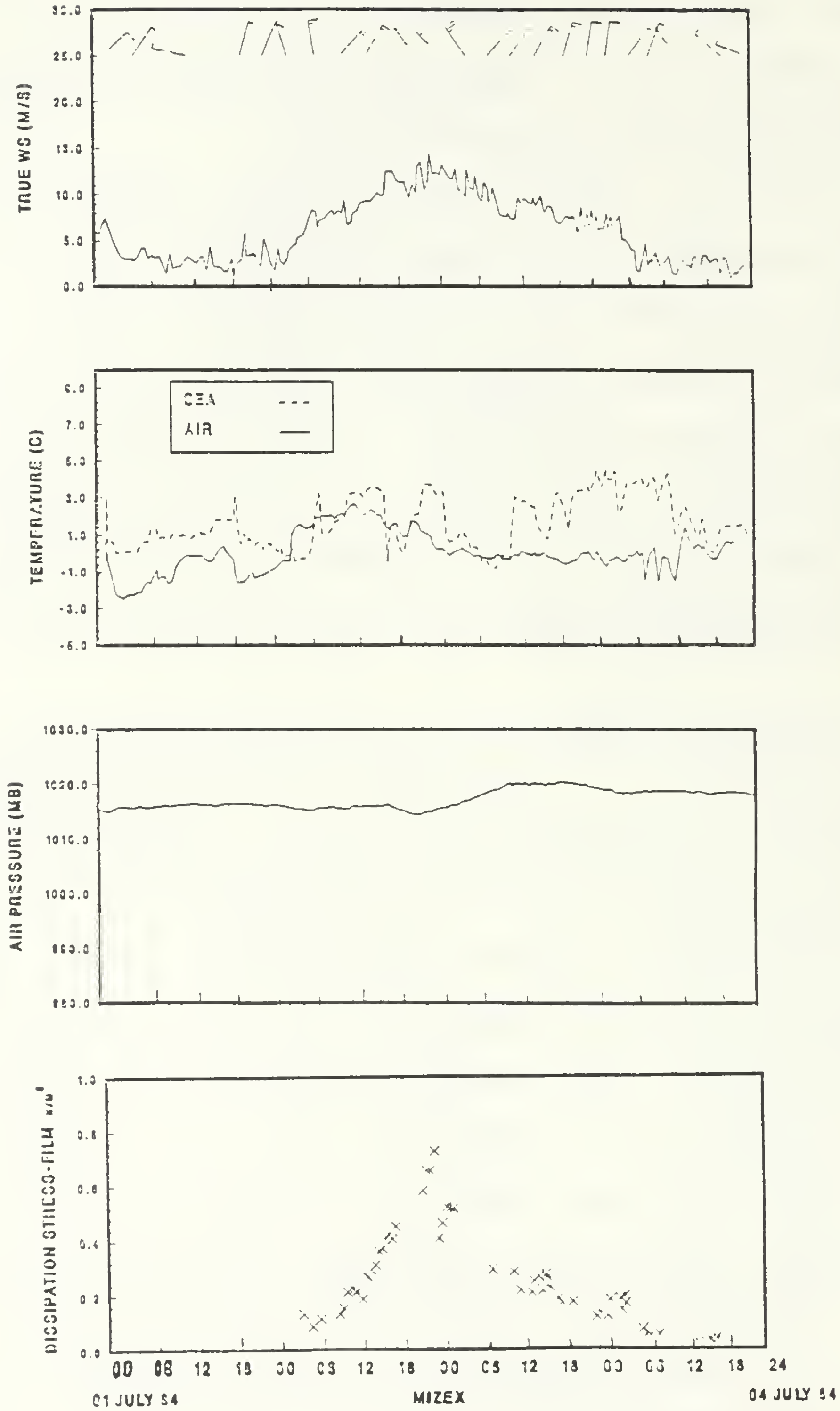

Figure 14. 1 July - 4 July Time Series

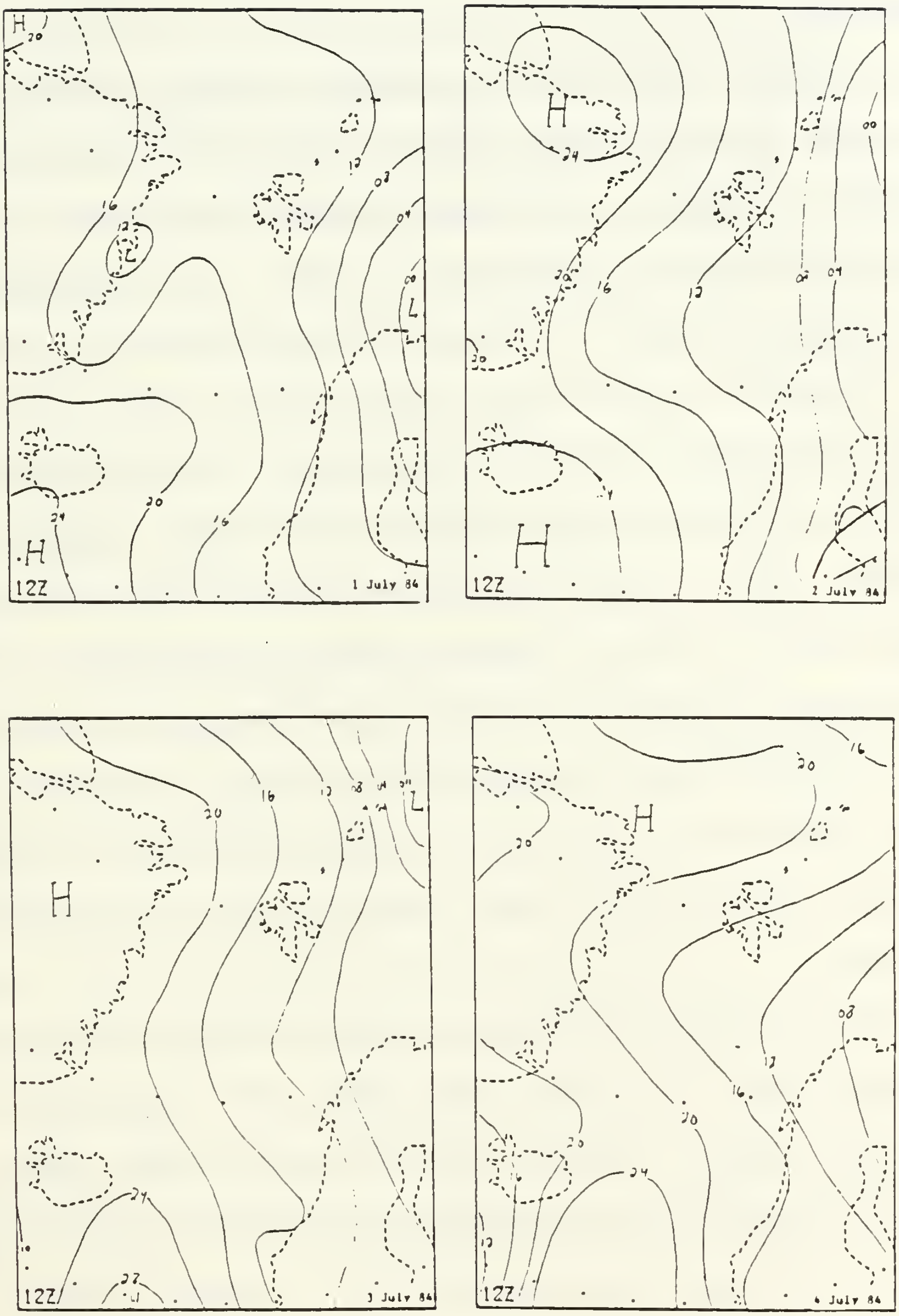

Figure 15. 1 July - 4 July Synoptic Charts

Winds increased to 10.0 m/s from the northeast, parallel to the ice edge. Sea-surface and air temperatures were both near 2.0 °C. Skies were clear with some strands of cirrus and thin altocumulus.

Surface stress values showed a steady increase throughout the day as a north-south pressure gradient developed and winds continued to rise. A maximum dissipation stress value of 0.8 N/m^2 was recorded at 0000 GMT on 3 July. Sea-surface temperature was recorded at 3.0 °C. with air temperature 2 degrees lower.

A strong meridional flow pattern was established with a tight pressure gradient creating a 15.0 m/s wind from the northwest. The pressure gradient weakened somewhat by 4 July accounting for a decrease in wind and surface stress. At 1200 GMT on the 4th, the surface pattern indicated a ridge under the influence of the high pressure system over Greenland, forming over the MIZEX area. By 2100 GMT a zonal flow pattern was established, the winds shifted to the southeast, and the pressure started to drop due to the migration of a low south from the Arctic Sea.

The strong northwest flow pattern in this time period created a period of high winds which corresponded to a maximum in surface stress values. For the most part, the conditions remained unstable and no decrease in surface pressure was noted.

6. July 5 - July 8

Figure 16 a-d shows the time series for this period and Fig. 17 shows the synoptic patterns. On 5 July, the high pressure system over Greenland moved north leaving the area with weak and variable winds. By 1800 GMT, the low pressure system from the Arctic Sea, had moved into the MIZEX area. Winds were from the north at 14.0 m/s causing a decrease in the air temperature to -1.0° C. Sea-surface temperatures remained at 3.0° C. Surface pressure was in a steady decline and by 0000 GMT on the 6th had dropped to 1010 mb. Surface stress values did not show an increase from 0.14 N/m^2 until the winds began increasing again at 1200 GMT due to the location of the low pressure system east of Svalbard. Winds rapidly increased as the low moved towards the MIZEX. Maximum wind speed for the storm was recorded at 0000 GMT on the 7th at 17.0 m/s from the north. Stress values also peaked at this time with a value of 0.6 N/m^2. The high pressure system over Greenland returned on 7 July. An occluded frontal band was covering Spitzbergen at this time and a meridional flow pattern with a tight pressure gradient was in effect. Winds were off the ice edge, from the north at 14.0 m/s. The sawtooth pattern in the true wind on 7 July is unexpected and further analysis is being performed.

By 8 July, the flow pattern was more zonal and the pressure gradient somewhat weaker. The flow pattern remained zonal with light winds over the next several days. Winds were generally from the northwest at less than 10.0 m/s. The surface pressure

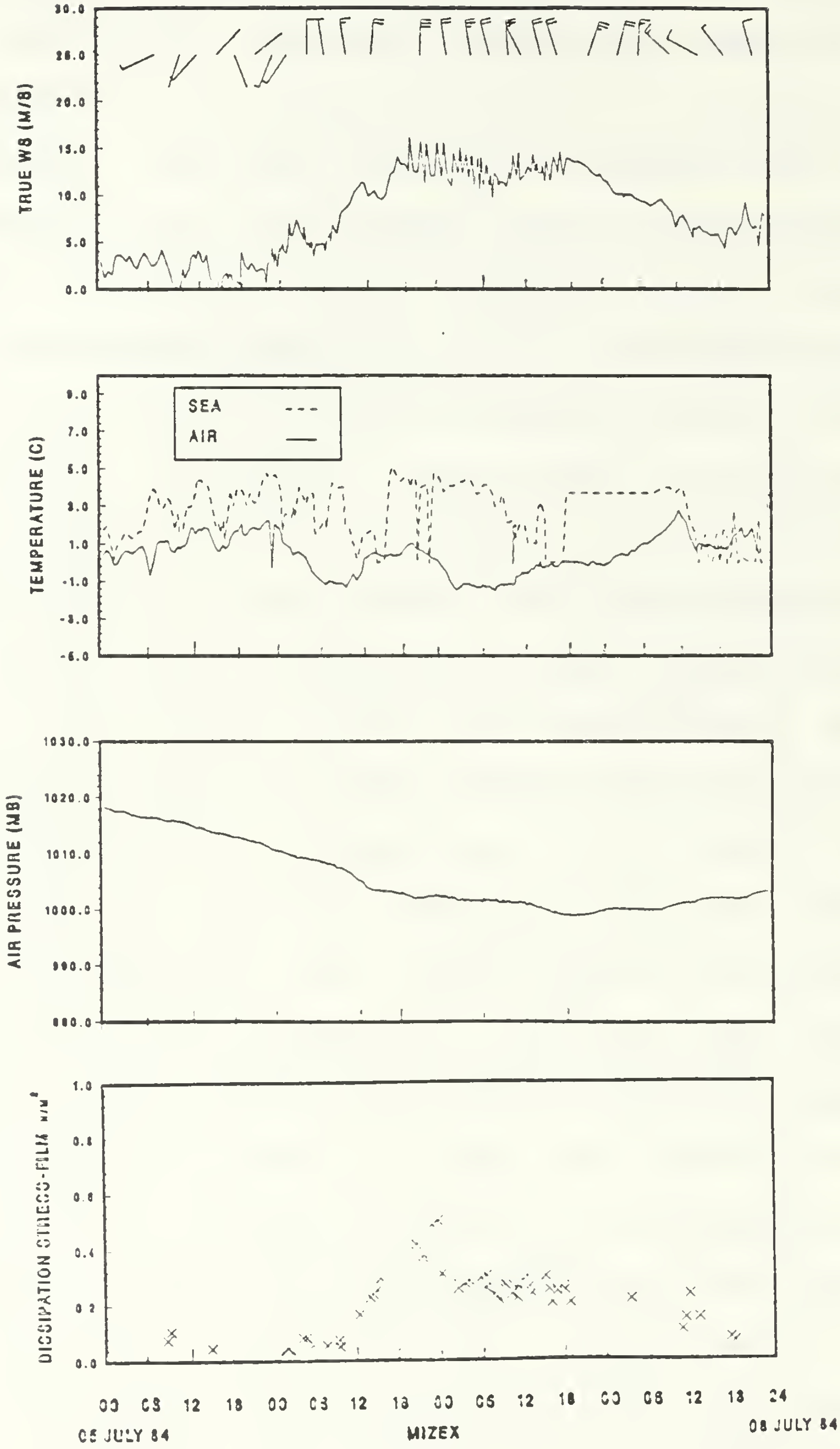

Figure 16. 5 July - 8 July Time Series

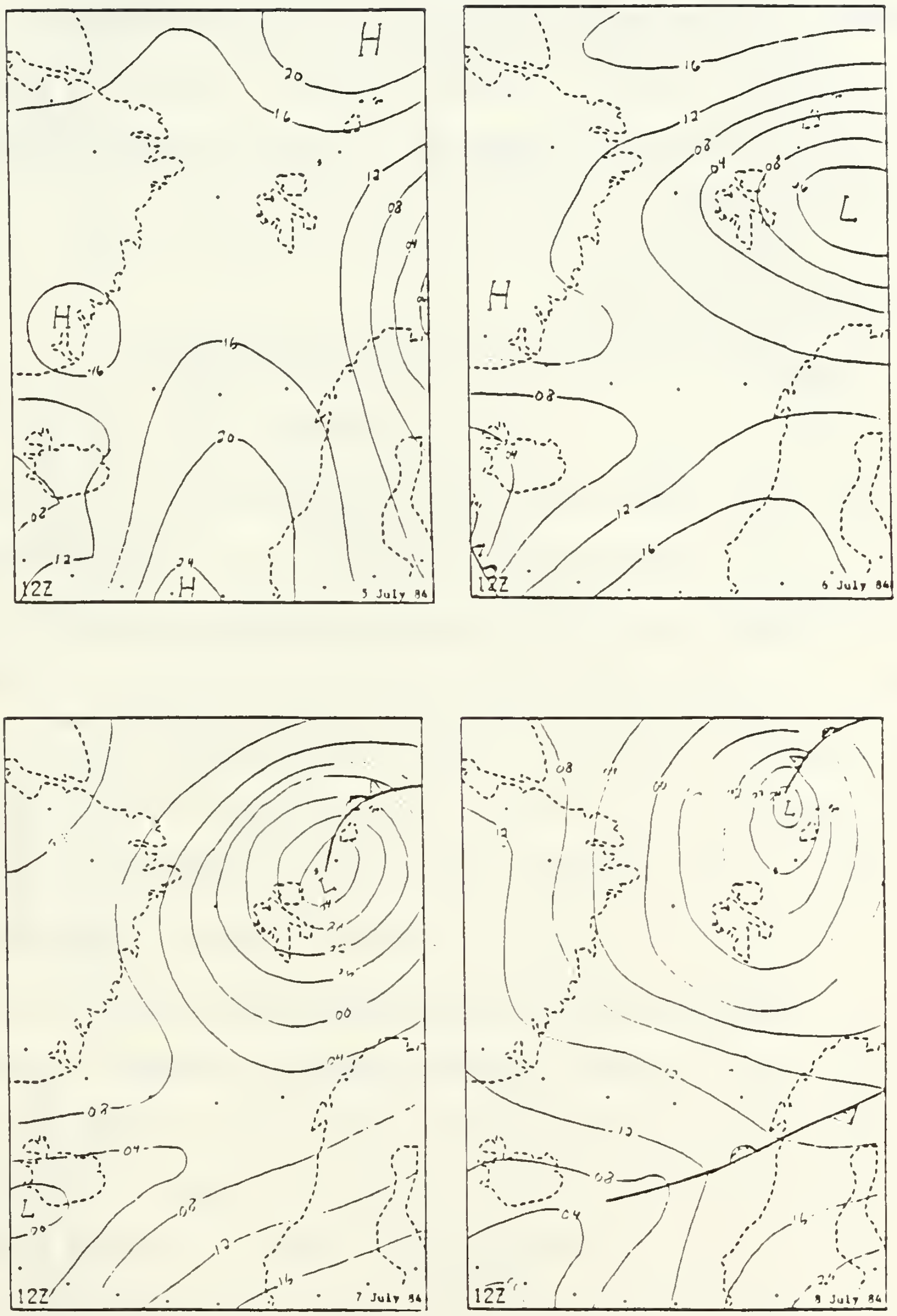

Figure 17. 5 July - 8 July Synoptic Charts

stayed at 1010 mb. During this period of relatively calm conditions, stress values remained close to 0.3 N/m^2.

This time period could be characterized by unstable conditions, a constantly decreasing surface pressure, and strong winds from the north. Surface stress reached a maximum value of 0.4 N/m^2 and decreased steadily as the low moved to the northeast away from the MIZEX.

7. 9 July - 12 July

Figure 18 a-d shows the time series for this period and Fig. 19 shows the synoptic pattern. At 0000 GMT on 9 July winds were from the northwest at 10.0 m/s. Air temperature was 1.0° C. and sea-surface temperature remained near 3.0 C. Surface pressure was 1005 mb and stress values were .15 N/m^2. By 1200 GMT the winds had shifted indicating the approach of a high pressure system. This corresponded to an increase in surface pressure of 4 mb and a slight upward trend in air temperature. The low was situated just north of Svalbard and was dissipating. By noon on 10 July winds became steady at 10.0 m/s from the southwest and did not change until 0600 GMT on 11 July The dissipation stress values showed a steady increase to 0.4 N/m^2. When the winds became light and variable on 11 July, the dissipation stress values dropped to below 0.1 N/m^2.

By 12 July a weak north south pressure gradient had been established over the MIZEX area. Dissipation stress values remained low as a high pressure system moved into the area from Greenland.

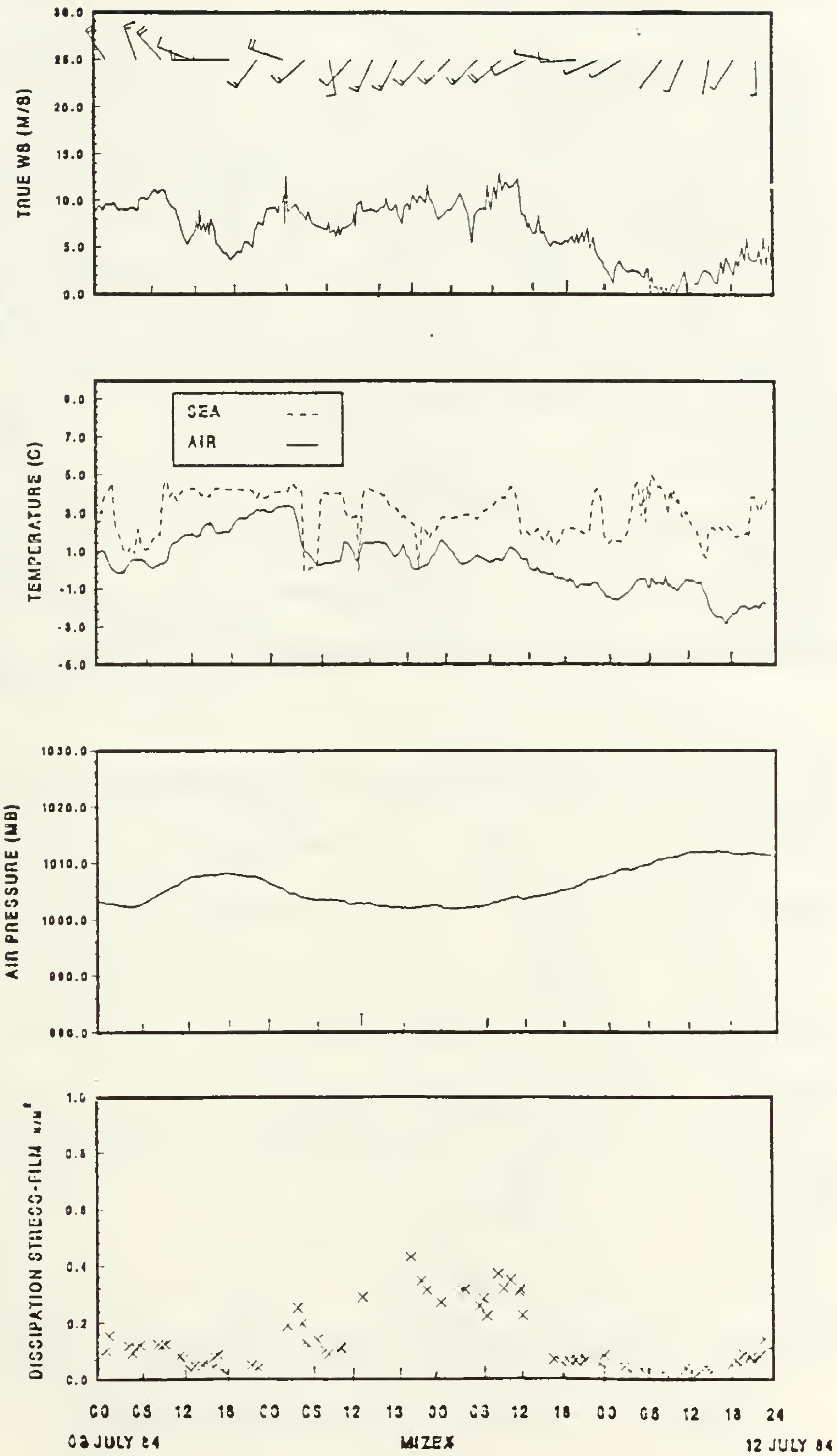

Figure 18. 9 July - 12 July Time Series

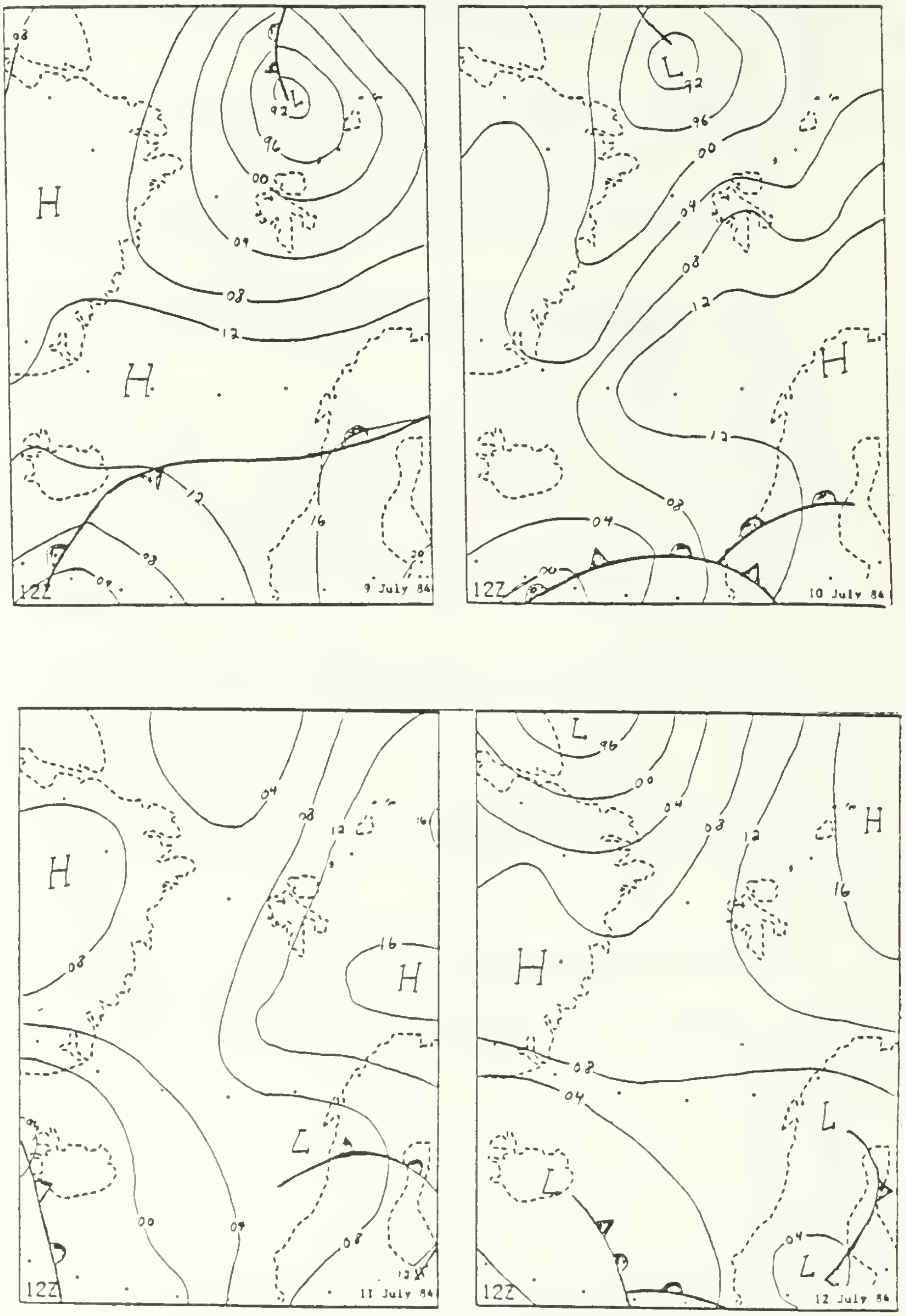

Figure 19. 9 July - 12 July Synoptic Charts

This time frame was dominated by the low center creating fairly strong winds from the south. Conditions remained unstable over the entire four-day period and surface pressure did not drop below 1000 mb.

8. <u>13 July - 15 July</u>

The final set of time series in this chapter are shown in Fig. 20 a-d and the synoptic chart is given in Fig. 21. As can be seen from the true wind time series, winds remained light and from the southwest through to the 15th. Surface pressure remained fairly constant at 1012 mb. Unstable conditions existed with sea-surface temperatures at 3.0 °C. and air temperatures 1-4 degrees lower. At the beginning of this time series a high existed over Svalbard creating a southwest to northeast flow pattern. This caused the increase in air temperature noted at 1200 GMT. However, the pattern rapidly changed as a low pressure system approached the area from the northwest with another low located over Norway. A high pressure system was over Greenland. Winds remained light and from the southwest, but air temperature was dropping. On 15 July, the meridional flow pattern was beginning to develop again and a slight increase in winds was noted. Stress values remained less than 0.2 N/m^2 from 13-15 July.

This period can be characterized by light winds from the southwest, low dissipation stress values, a fairly constant surface pressure and unstable conditions.

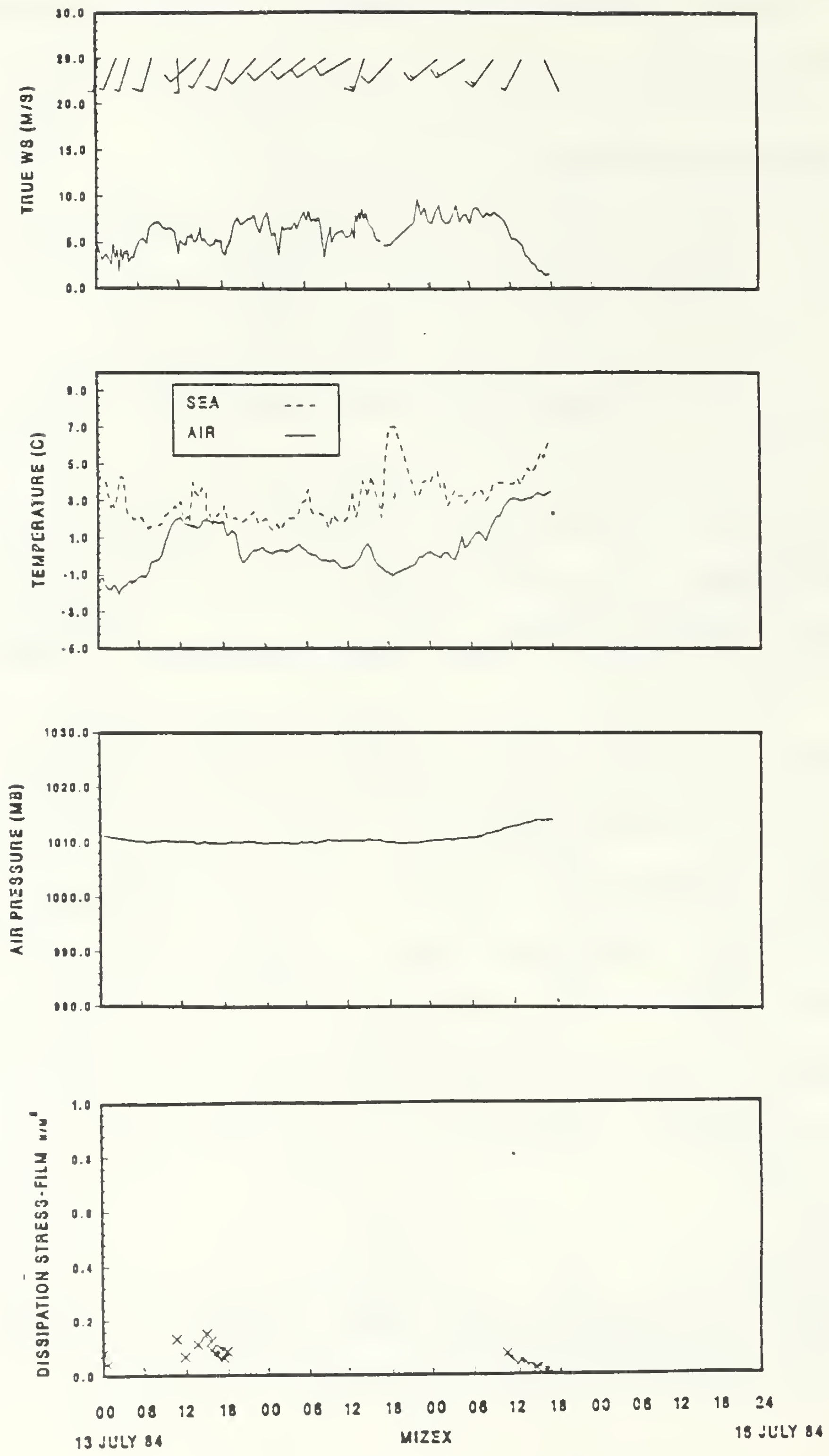

Figure 20. 13 July - 15 July Time Series

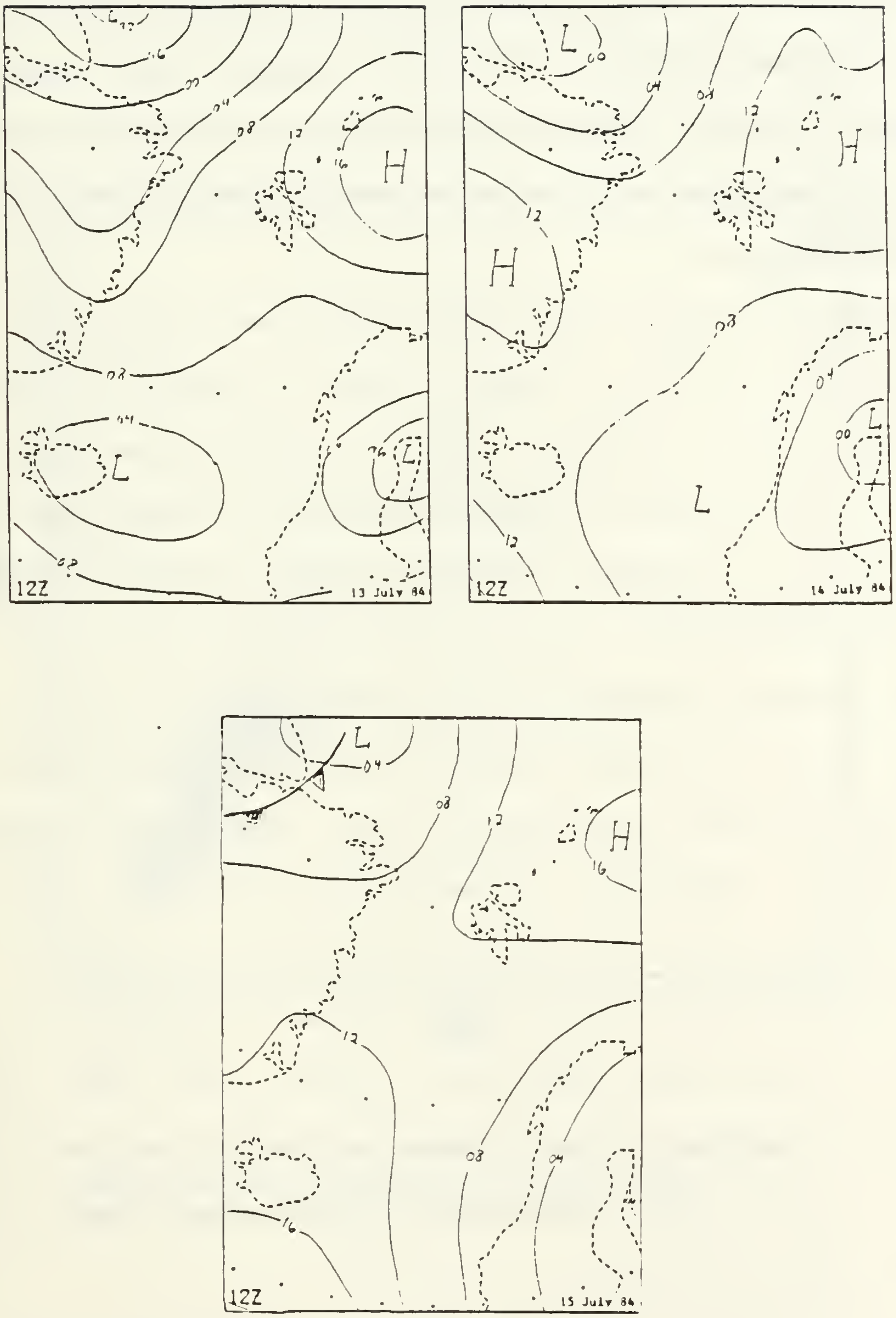

Figure 21. 13 July - 15 July Synoptic Charts

IV. VARIATION OF THE DRAG COEFFICIENT WITH THE ADVENT OF MAJOR STORM SYSTEMS DURING THE MIZEX

Atmospheric forcing of the MIZ is increased in the presence of storm systems. During such times the changes in the marginal ice zone are the greatest. For that reason this chapter deals with specific storm events and the associated changes in the air and sea temperature, wind speeds, dissipation stress, and the drag coefficient.

Variations in the drag coefficient were observed when the ship moved away from or towards the ice edge, therefore the ship movement and location relative to the ice edge will be emphasized. In addition to these changes due to the ships location, stability and wind speed and direction have a marked effect on the drag coefficient.

In this chapter the observed drag coefficients will be compared with those based on a bulk formulation of Large and Pond (1981). The drag coefficients obtained by Large and Pond are open ocean values, whereas the data collected during MIZEX was for the ice edge region.

As indicated by Fig. 22, the stress calculated from the dissipation method was generally higher than that calculated from the bulk method. The largest value for U^* from the bulk formulation was 0.5 m/s while the highest using the dissipation measurements was 0.78 m/s.

Fig. 23 examines the wind speed influence in terms of the drag coefficient. The Large and Pond neutral drag coefficient increases from 1.2 at 5.0 m/s to 1.46 at 15.0 m/s. The neutral

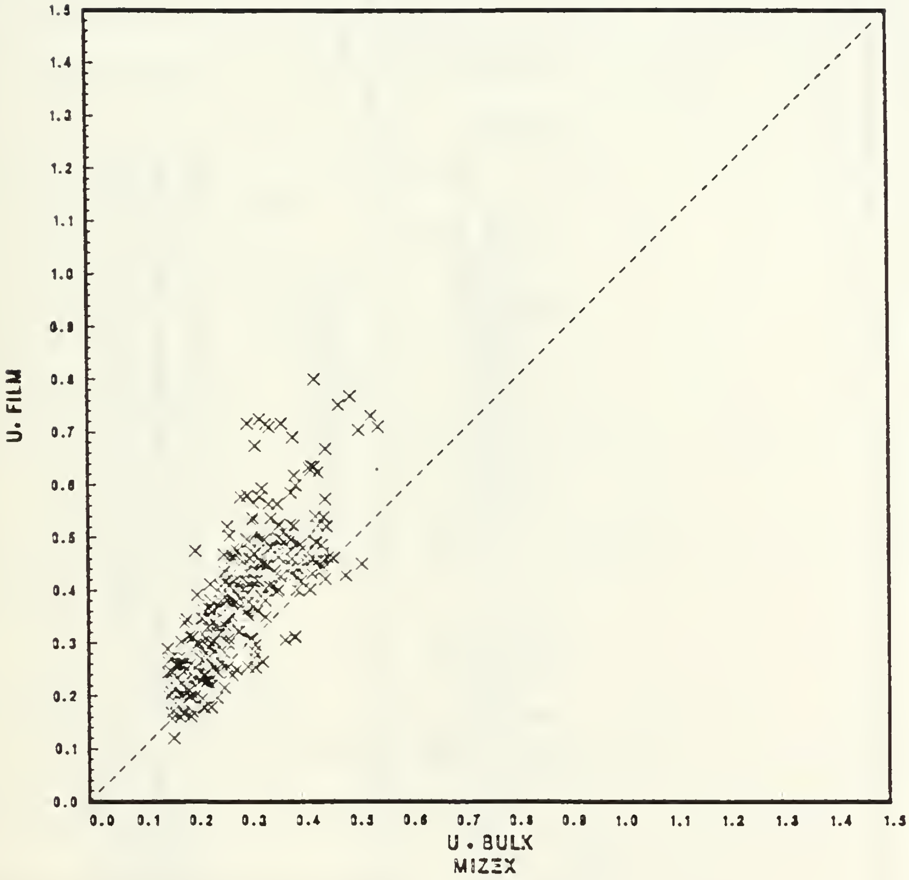

Figure 22. Friction Surface Velocity Calculated using the Film Dissipation Method versus the Bulk Formulation of Large and Pond (1981)

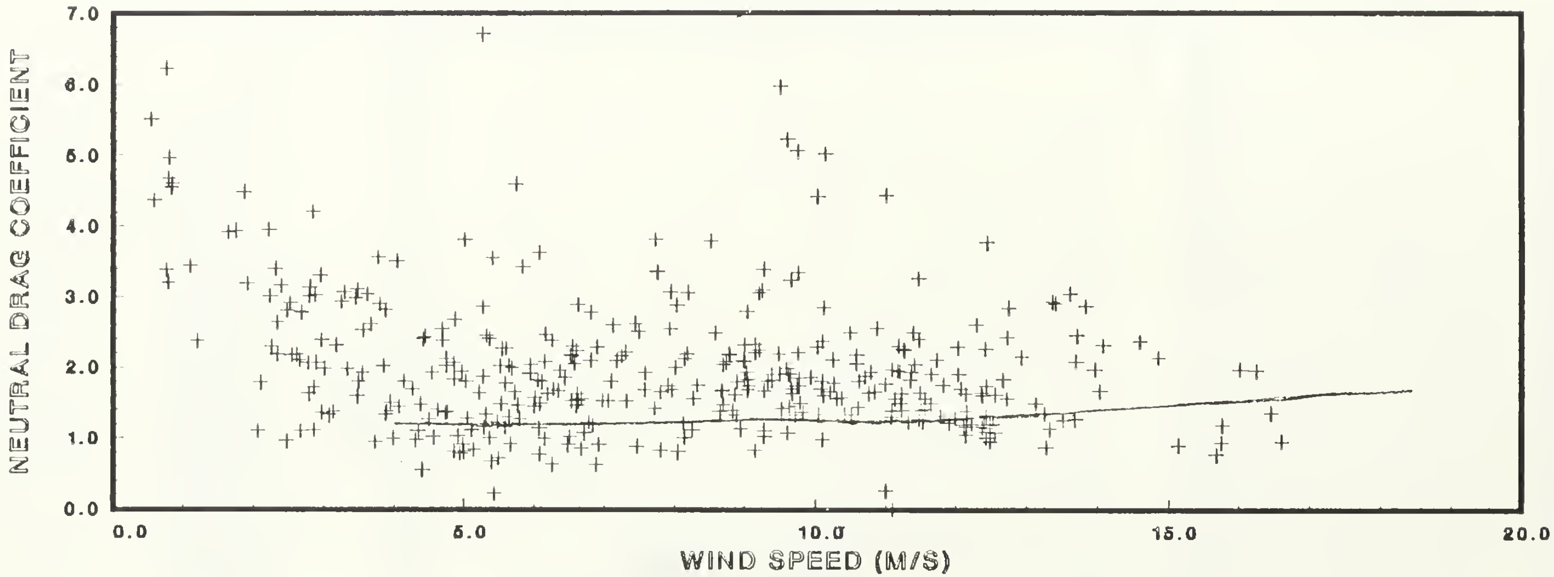

Figure 23. MIZEX Neutral Drag Coefficient versus Wind Speed. The solid line indicates the Large and Pond (1981) Neurtal Drag Coefficient versus Wind Speed.

drag coefficient calculated from dissipation measurements are consistently higher, showing that winds speed is not the sole factor in determining the drag coefficient. By investigating periods when the largest variation in wind speed occurred, a better understanding of the difference between bulk neutral drag coefficients and those measured by the dissipation method may be obtained. Five separate instances of high winds corresponding to the movement of low pressure systems near the MIZEX area were recorded from 15 June - 15 July. These were as follows:

1) 19 June - 21 June
2) 23 June - 26 June
3) 27 June - 28 June
4) 2 July - 3 July
5) 6 July - 7 July

Synoptic conditions occurring in these storms were described in Chapter 3.

A. 19 JUNE - 21 JUNE

On 19 June, as described in Chapter 3, a low pressure system was approaching the MIZEX area from the south as indicated by a drop in surface pressure from 1012 mb on 18 June to a minimum of 998 mb on 19 June. Winds shifted to the northeast as the frontal system approached and increased from 5.0 m/s to 18.0 m/s by 19 June (Fig. 6, Chapter 3). Air temperature was recorded at -4.0° C. on the 18th and increased to 0.5° C. within a 36 hour period due to warm air advection caused by the low pressure system to the south (Fig. 9, Chapter 3). Sea-surface temperature remained close to 3.0° C. Air temperature did not exceed 0.0° C. during this time period.

The Haakon Mosby track during the storm period, 19 June - 21 June, is shown in Fig. 24 - 26. Time series of the storm period showing true and relative wind speed and direction, air and sea-surface temperature, and the ratio of the dissipation neutral drag coefficient to the Large and Pond (1981) open water neutral drag coefficient (C_D10N/C_D10N bulk) is provided in Fig. 27 a-d.

Relative winds that were not within the range 300-090 degrees were rejected due to the distortion in the wind field caused by the ship's structure. Note that the closer the drag coefficient ratio is to 1.0, the better the correlation between the Large and Pond (1981) values and the dissipation derived drag coefficient values.

The Haakon Mosby was positioned at 79.5°N,6.0°E at 0000 GMT 19 June (Position 1 Fig. 24) and moving away from the storm system. As the ship continued to move closer to the ice edge, the drag coefficient ratio increased. By 0300 GMT the ratio was 2.4. At 0559 GMT the Haakon Mosby turned into the wind and moved away from the ice edge (Position 7 Fig. 23). No dissipation measurements were recorded until 1200 GMT at which time the ship was moving to the southeast with a relative wind direction of 030° (Position 16 Fig. 24). The ship was moving towards the low pressure system. Wind speeds were 15.0 m/s. At this point the drag coefficient ratio was 2.0, and it was continuing to increase as the ship moved towards the storm system.

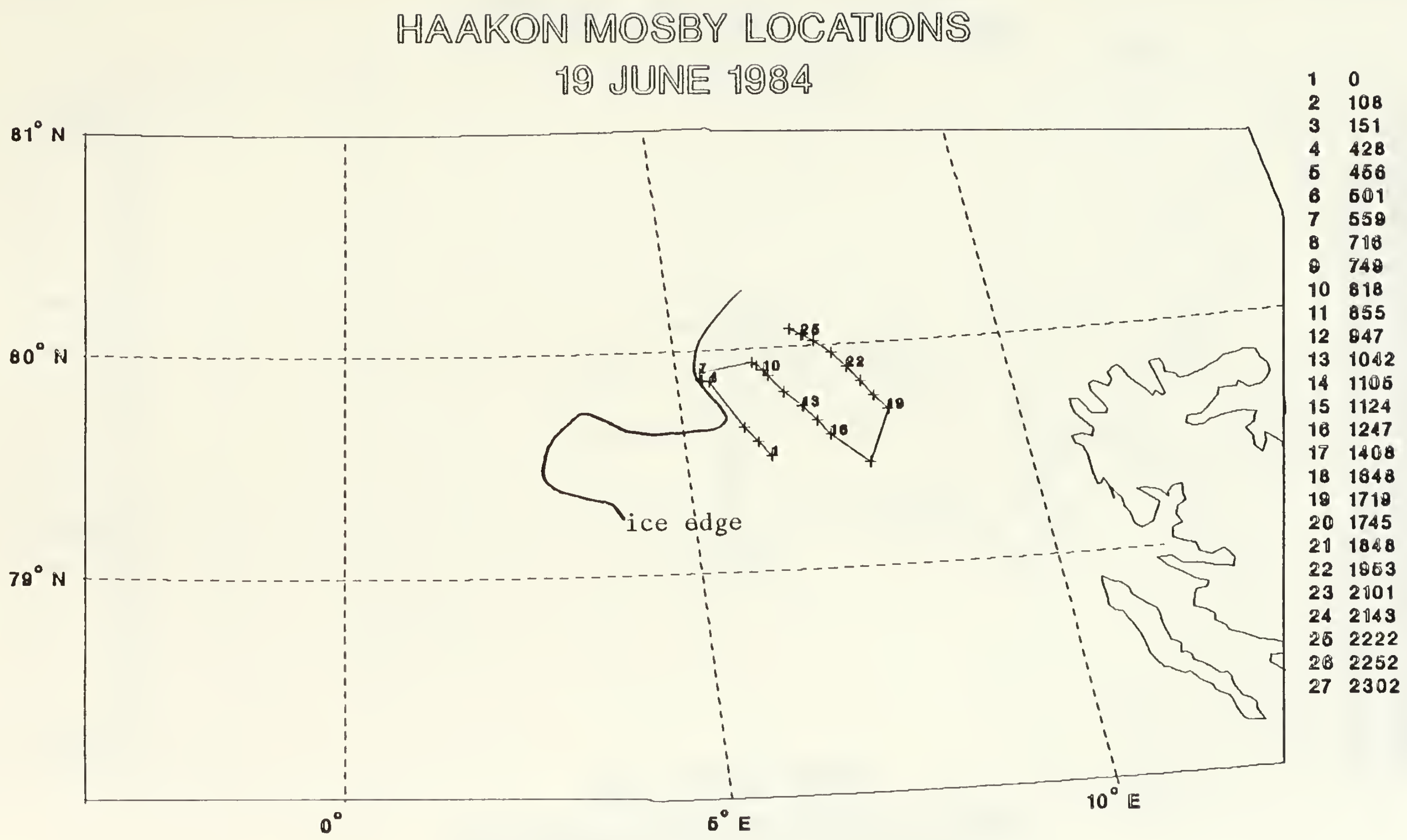

Figure 24. Ships track for 19 June

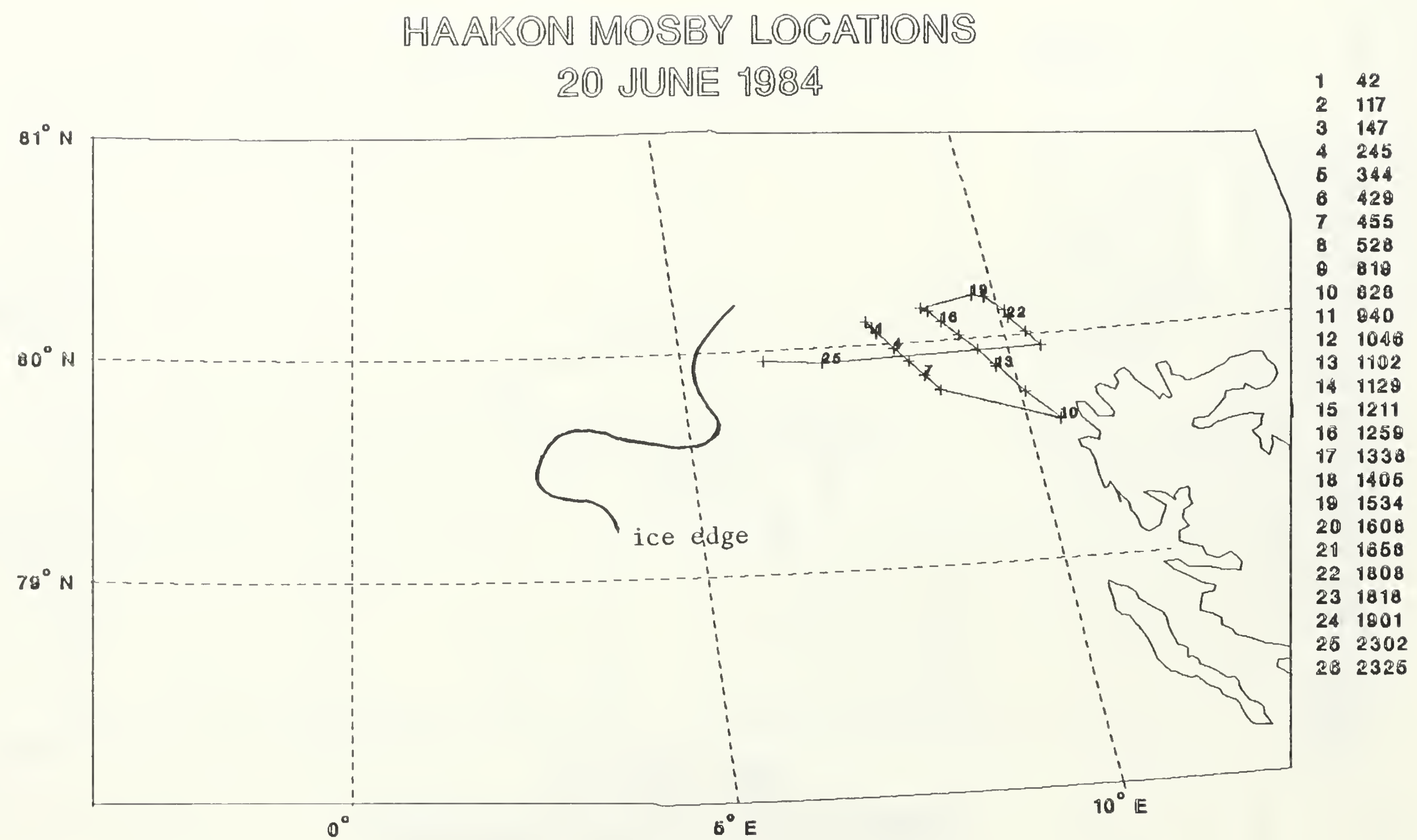

Figure 25. Ships track for 20 June

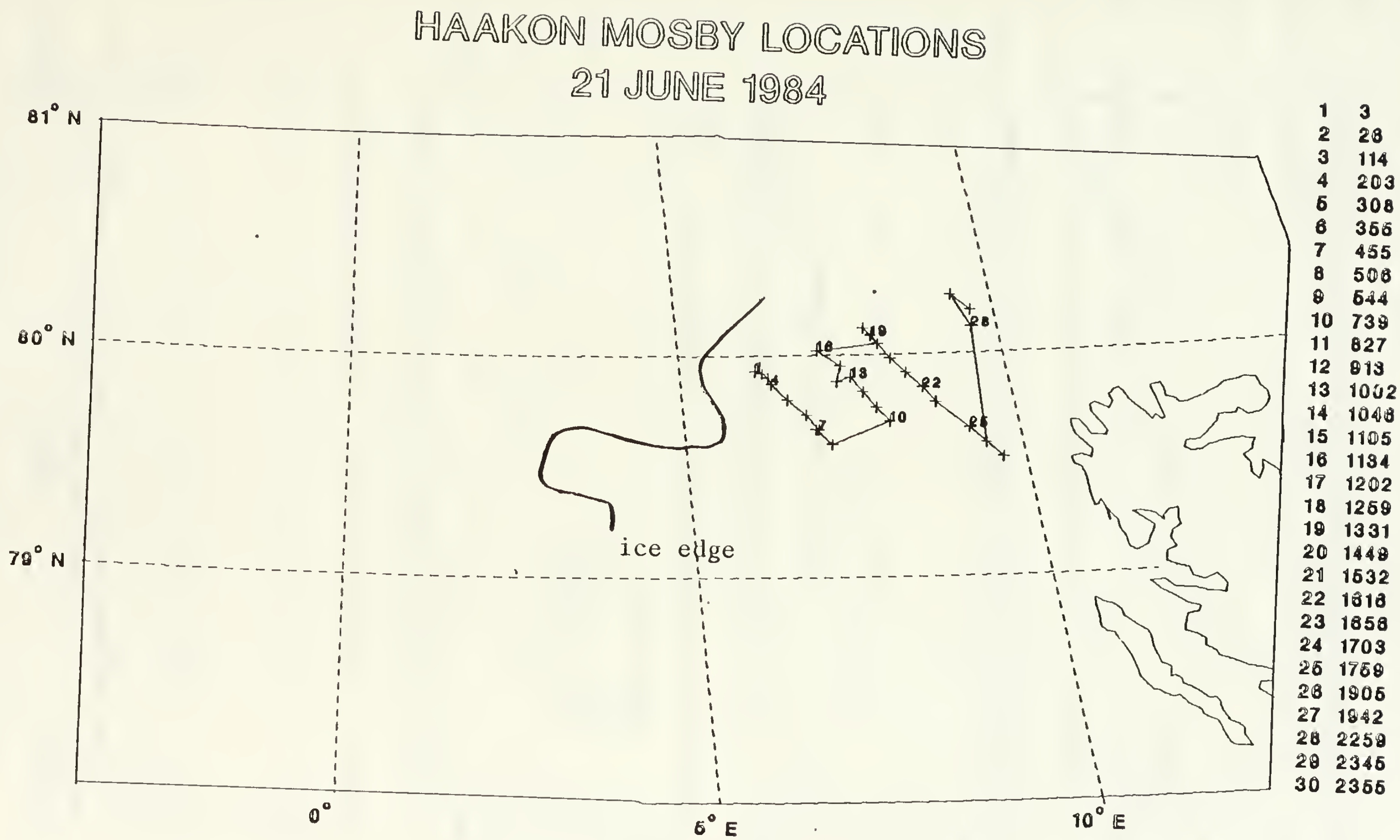

Figure 26. Ships track for 21 June

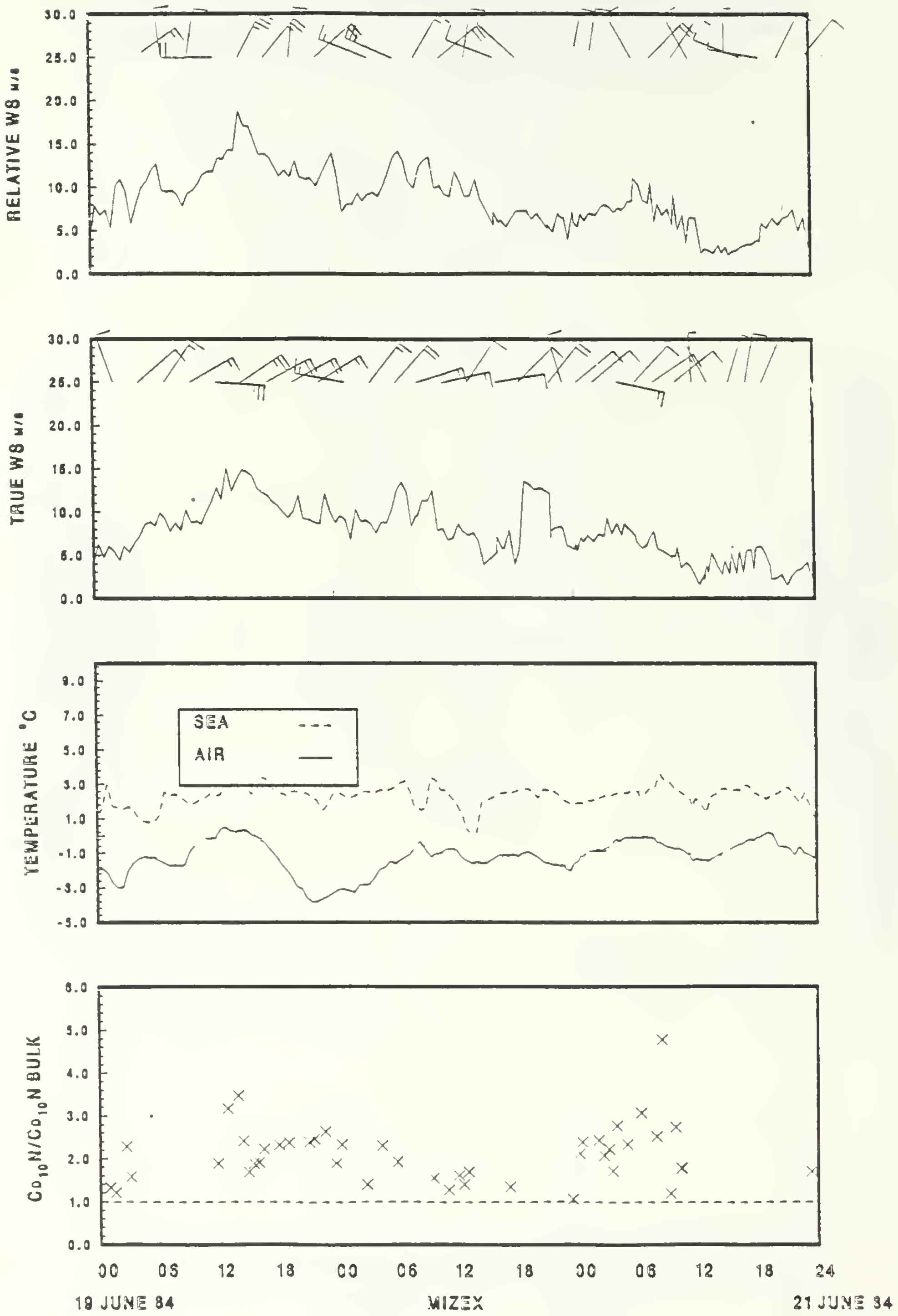

Figure 27. 19 June - 21 June Time Series

The drag coefficient ratio peaked at 1400 GMT on 19 June with a value of 3.6. Note, at this point, air temperature had increased to 0.8 ° C. due to warm air advection caused by the low pressure system to the south of Spitzbergen and sea-surface temperature remained at 3.0 ° C. (unstable). Winds were 16.0 m/s with a relative wind direction of 030 ° . Although the ship continued towards the storm until 1648 GMT, the drag coefficient ratio decreased to 2.2 after 1400 GMT possibly due to a decrease in wind speed to 13.0 m/s as the storm system started to dissipate. At 1648 GMT the ship turned into the wind (Position 18 Fig. 24) and the drag coefficient ratio remained at 2.2. The wind speed and the air temperature was steadily decreasing. Surface pressure was increasing from 998 mb at 1400 GMT indicating the system was headed away from the MIZEX area. The ship remained on its northeast heading until 1719 GMT. At that time the Haakon Mosby turned to the northwest, towards the ice edge (Position 19 Fig. 24). Winds had dropped to 12.0 m/s with a relative wind direction of 030°. The ratio of the drag coefficients remained fairly constant at 2.5 through the remainder of the day as the ship continued to the northwest, towards the ice edge. At 2300 GMT the ship was positioned at 80.2°N,6.5°E (Position 27 Fig. 24).

On 19 June, the drag coefficient ratio was the highest when the ship was moving towards the storm system, parallel to the ice edge. This also corresponded to the period of highest wind speeds and air temperature.

By 20 June the low pressure system was moving to the northeast in the Norwegian Sea, away from the MIZEX area. However, air temperature was increasing and surface pressure was decreasing due to the presence of another low pressure system northeast of Iceland (Fig. 9, Chapter 3). Winds were 12.0 m/s with a relative wind direction of 290°. The drag coefficient ratio was declining from a value of 2.4 measured at 0000 GMT. The Haakon Mosby was headed southeast towards Spitzbergen. At 0528 GMT when the Haakon Mosby turned to the southeast, (Position 8 Fig. 25) the drag coefficient ratio had decreased to 1.8. Instability was decreasing due to an increase in the air temperature, and wind speeds had increased to 14.0 m/s at this time. The relative wind direction was 030°. At 0828 GMT the ship turned to the northwest, again moving parallel to the ice edge (Position 10 Fig. 25). The ship was traveling away from the low pressure system and surface winds decreased to 10.0 m/s. Relative wind direction remained the same. At 1400 GMT the Haakon Mosby turned to the northeast (Position 18 Fig. 25), away from the ice edge. Winds were light and variable and the drag coefficient continued to decline. The only increase in the drag coefficient ratio on 20 June occurred when the ship turned due west and moved towards the ice edge. Note position 26 on Fig. 25 and the corresponding increase in the drag coefficient ratio shown in Fig. 27 d at 0000 GMT on the 21st. The drag coefficient ratio increased from a value of 1.0, as the ship moved over the open water area, to a value of 2.4 as the ship moved into the ice edge area.

By 0000 GMT on 21 June the Haakon Mosby was positioned at 79.9°N,6.0°E. This was the same position recorded at 0700 GMT on the 19th. This time however, winds were at 8.0 m/s rather than the 13.0 m/s as on the 19th. At 0300 GMT on the 21st, the ship turned to the southeast (Position 1 Fig. 27), just as on the 19th. The relative wind direction was 010° compared to 020° on the 21st. The drag coefficient ratio increased to 3.0 by 0600 GMT on the 21st. It is interesting to note that when the wind speed was doubled on 19 June, and the ship on the same course, the drag coefficient ratio increased to 3.4 over a 7 hour period. The drag coefficient ratios do not appear to be solely wind dependent or a much larger variation between the drag coefficient ratios would have occurred.

At 0544 GMT the ship turned to the northeast, away from the ice edge (position 9 Fig. 26). Winds began to decrease but were still from the northeast. The drag coefficient ratio dropped to 2.8. Only when the ship turned to the northwest at 0739 GMT (Position 10 Fig. 26), moving parallel to the ice edge with a relative wind direction of 035°, did the ratio of the drag coefficients increase to 4.8. By 1200 GMT on the 21st winds had become light and variable and remained low as the ship turned to the southeast at 1259 GMT (Position 18 Fig. 20), moving parallel to the ice edge towards Spitzbergen.

In summary, from 19 June to 21 June winds were mainly from the northeast between 5.0 m/s - 15.0 m/s. Unstable conditions existed during this time period. Two significant increases in the drag coefficient ratio occurred. The first occurred at 1200 GMT on 19 June when the ship encountered 20.0 m/s and a temperature difference of 2.0° C. The relative wind direction was 030°. The ship was moving towards a low pressure system, away from the ice edge. The drag coefficient ratio was 3.4. The second occurred at 0700 GMT on 21 June with a lower wind speed, 8.0 m/s. A 2.0° C. temperature difference still existed. The relative wind direction was 035 . The ship was again moving away from the ice edge. In this instance the drag coefficient ratio was 3.0.

B. 23 JUNE - 26 JUNE

The next low pressure system passed through the MIZEX area on 23 June (Fig. 11, Chapter 3). This was the only major storm to enter the Fram Strait. Time series of the relative and true wind speed and direction, temperature and the drag coefficient ratio are shown in Fig. 32.

On the 23rd at 1800 GMT the surface pressure decreased to 995 mb from 1010 mb at 0000 GMT. Relative wind direction at 1800 GMT was 270° and wind speed was 7.0 m/s. Air temperature was recorded at 3° C. indicating warm air advection. The ice edge had receded. The track of the Haakon Mosby during the storm period (23 June - 26 June) and the position of the ice edge is shown in Fig. 28 - 31.

At 0000 GMT on 23 June the Haakon Mosby, located at 79.6° N,5.1° E (Position 1 Fig. 28), was moving to the northeast, paralleling the ice edge and headed into a wind of 5.0 m/s. The incoming low pressure system was still to the south of Spitzbergen. The drag coefficient ratio was 2.5 at 0600 GMT on the

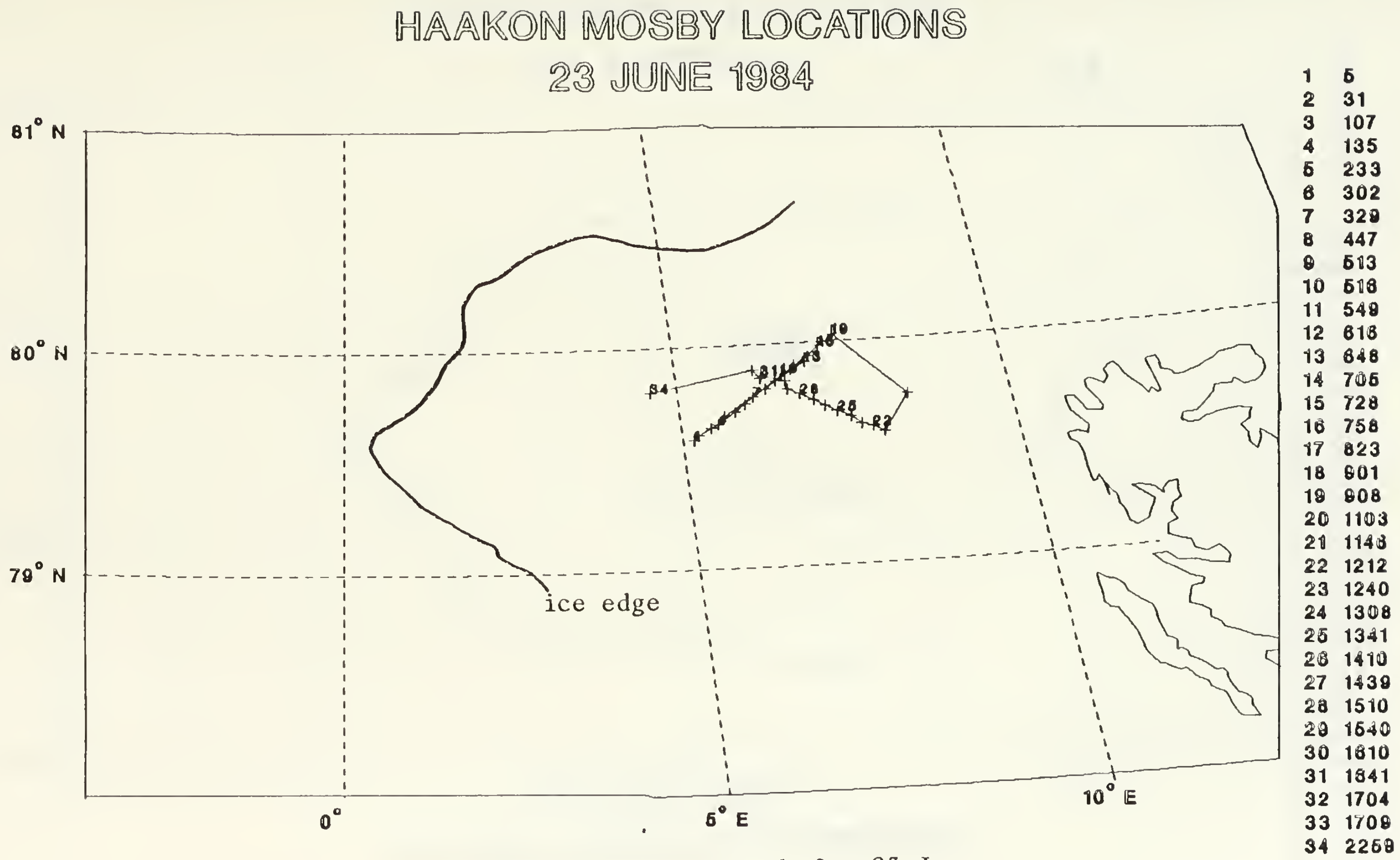

Figure 28. Ships track for 23 June

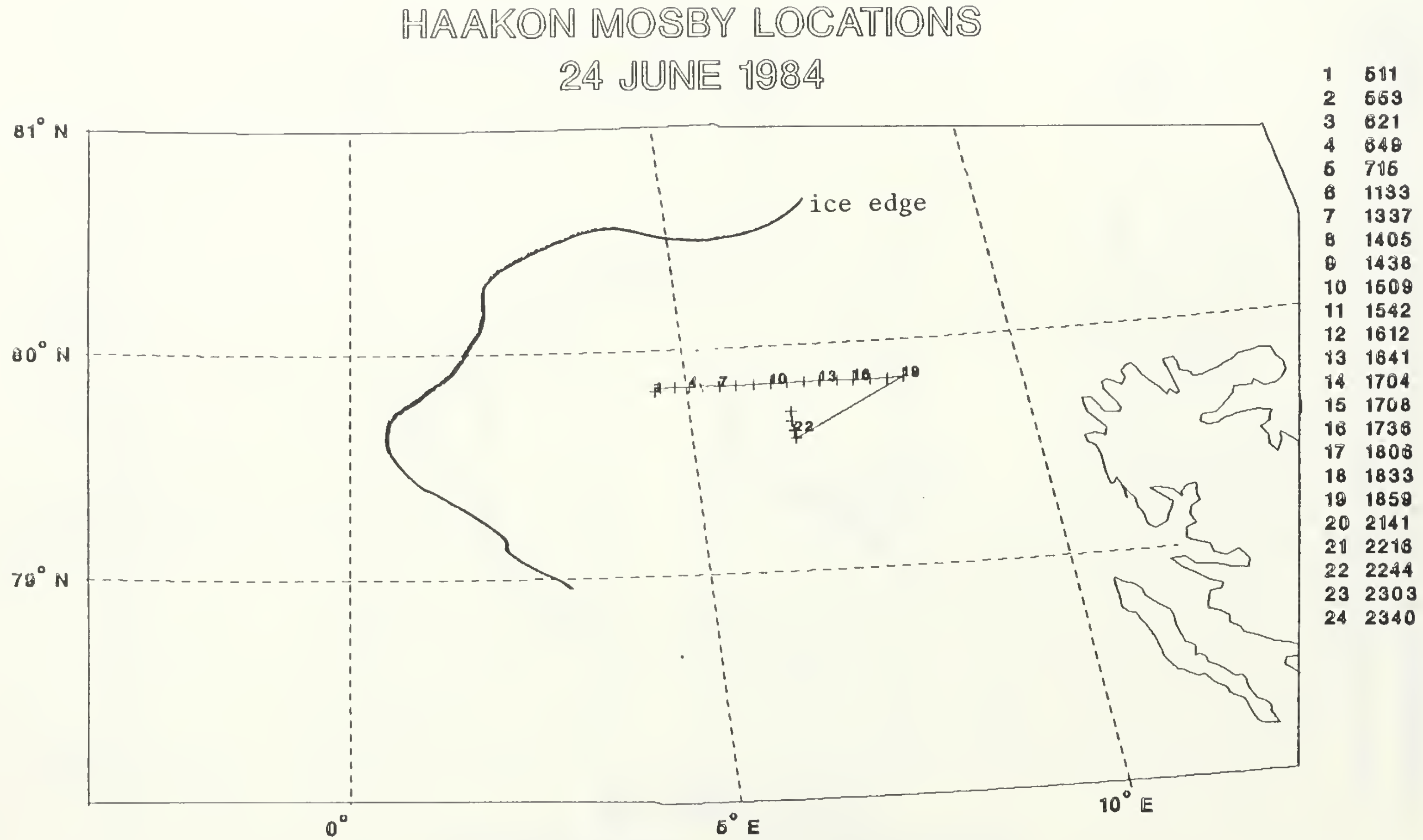

Figure 29. Ships track for 24 June

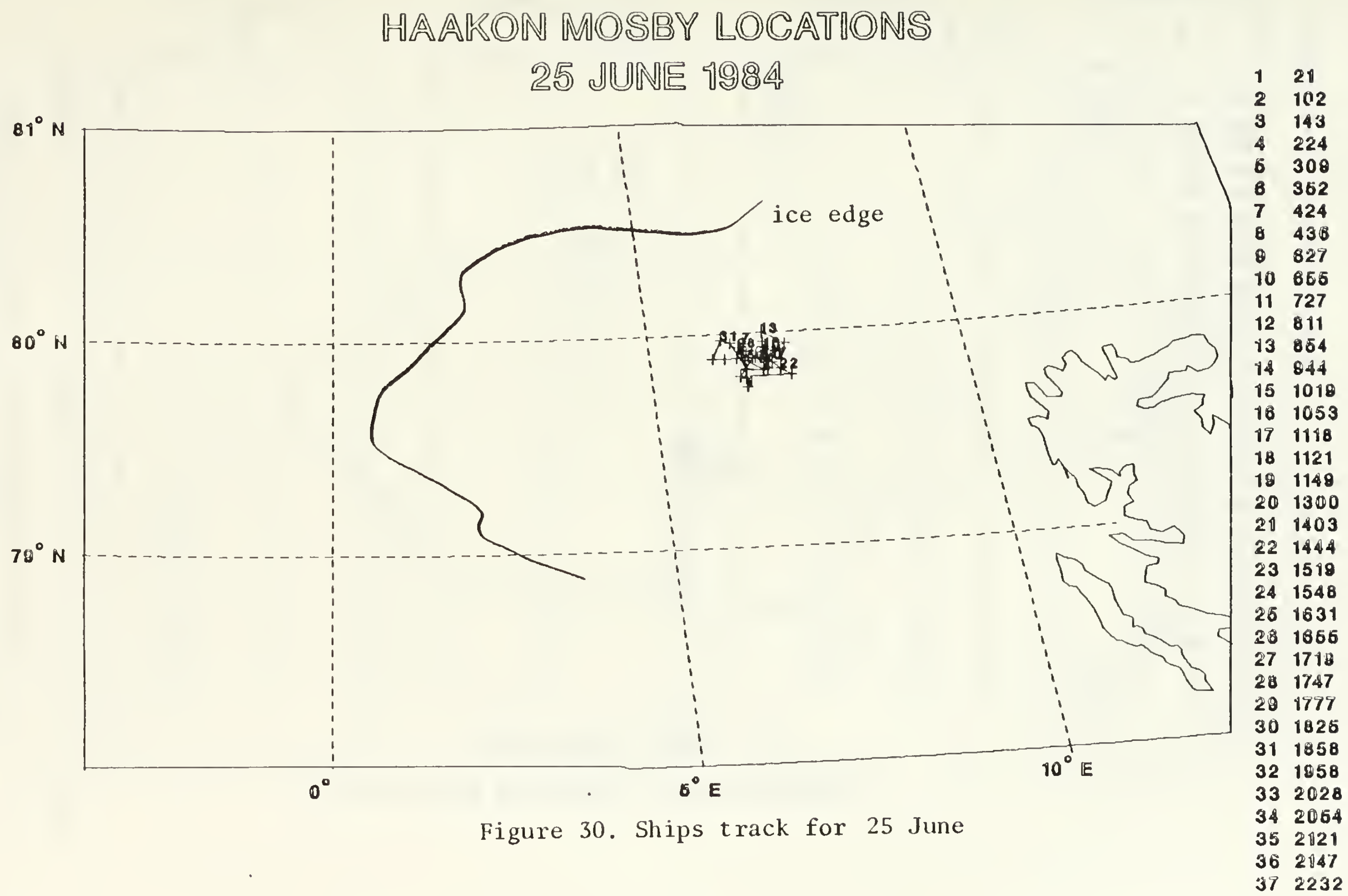

Figure 30. Ships track for 25 June

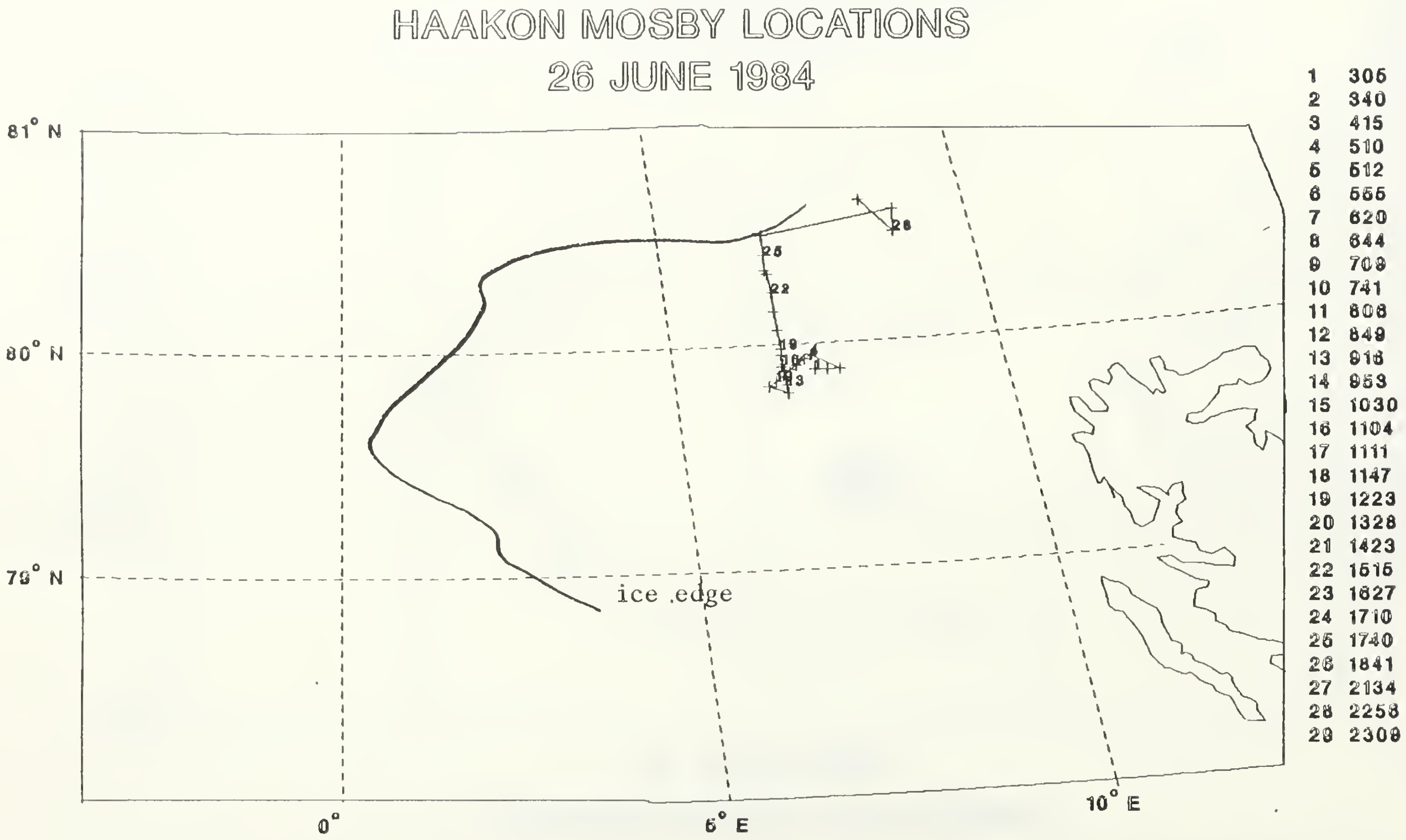

Figure 31. Ships track for 26 June

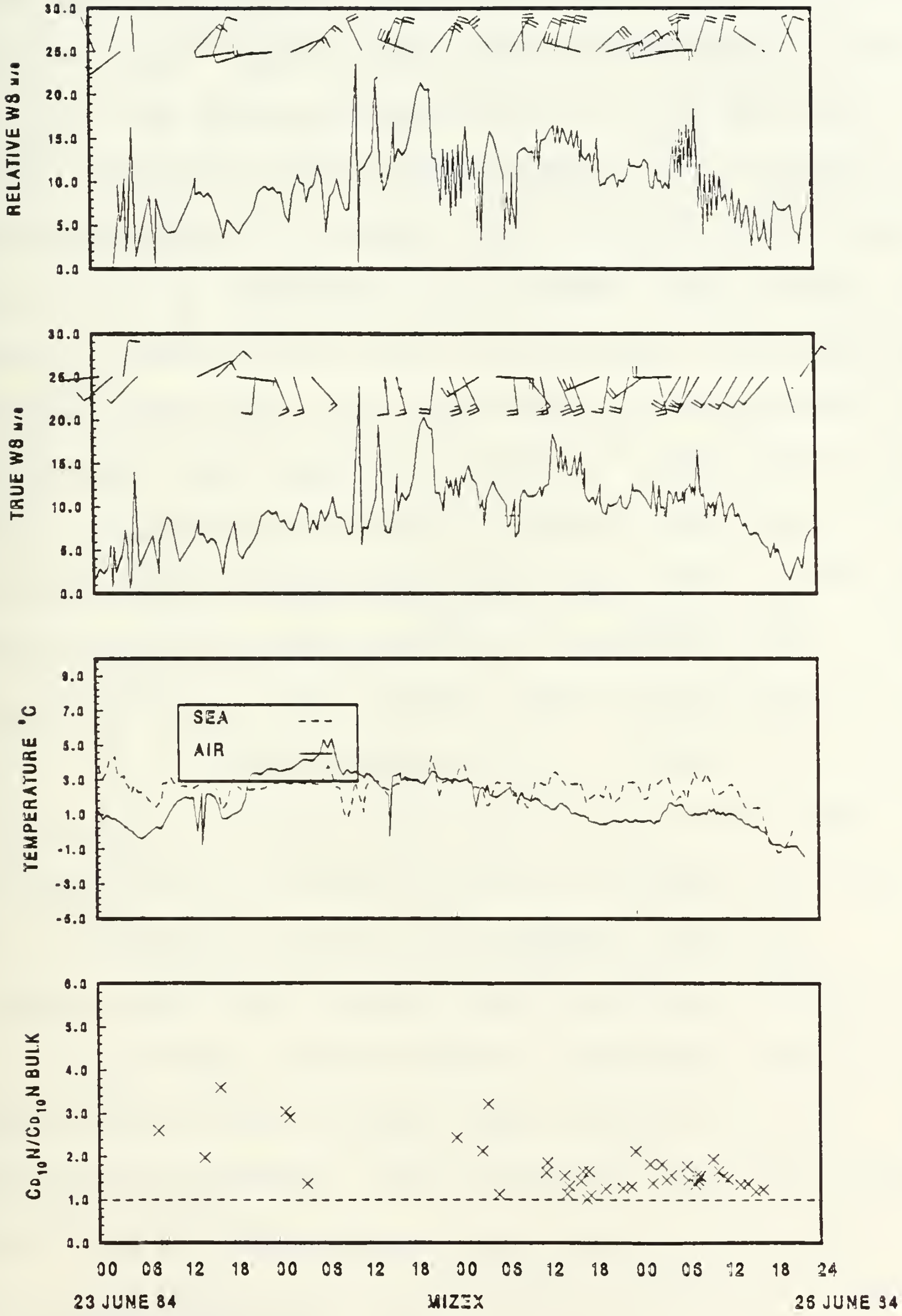

Figure 32. 23 June - 26 June Time Series

23rd as the ship continued northeast away from the low pressure system. At 0908 GMT the ship turned to the southeast (Position 19 Fig. 28). The ship was now moving towards the low pressure system with a relative wind direction of 045° and a wind speed of less than 5.0 m/s. At 1146 GMT (Position 21 Fig. 28) the ship was moving with the wind towards the southwest. The drag coefficient ratio was 2.0. At 1212 GMT (Position 22 Fig. 19) the ship turned back towards the ice edge, to the northwest. Air temperature was beginning to rise due to warm air advection from the low pressure system, while the sea-surface temperature remained fairly constant at 3.0° C. At 1600 GMT a frontal system entered the area and surface pressure decreased to 996 mb. The ratio of the drag coefficients increased to 3.6 as the ship continued to the northwest. At 1704 GMT (Positions 32-34 Fig. 28) the ship turned to the southwest and moved in towards to ice edge with a relative wind direction of 060°.

On 24 June the frontal band was directly over the MIZEX area. Warm air advection had increased the air temperature to 4.0° C. while sea-surface temperature remained at 3.0° C. In this instance conditions were stable. The ship headed away from the ice edge, due east, at 0000 GMT (Position 1-19 Fig. 29). The drag coefficient ratio should be close to 3.0 from observing similar instances of wind speed and ship direction. However, the values for the drag coefficient are not available for 24 June. The ship turned towards the southwest at 1359 GMT (Position 19 Fig. 29) and then headed due north at 2216 GMT (Position 21 Fig. 29).

As can be seen from Fig. 30, the Haakon Mosby remained primarily in one location on the 25th. The drag coefficient ratio was 2.5 at 0000 GMT on the 25th as a strong meridional flow pattern developed over the MIZEX area with the passage of the low pressure system to the north and out of the Fram Strait. However, by 0600 GMT the wind speed had decreased to 12.0 m/s with a relative wind direction of 020 as the low continued to move to the northwest. This corresponded to a decrease in the drag coefficient ratio to 1.2 by 0600 GMT. A high pressure system was approaching the MIZEX area from the southeast creating a tight pressure gradient and increased wind speeds as the front finally moved out of the MIZEX area at 1200 GMT on the 25th. The ratio of the drag coefficients remained less than 2.0 once the front passed the MIZEX area at 1200 GMT. By 26 June air temperature had decreased to 1.0° C. while sea-surface temperature remained at 3.0° C. (Unstable conditions). Winds were decreasing to 5.0 m/s from 10.0 m/s at 0000 GMT. Relative wind direction was 045° shifting to 005° by 0600 GMT. Again, the drag coefficient ratio remained less than 2.0 throughout the 26th.

This storm period is characterized by warm air advection from the south, causing stable conditions for about a 24 hour period. When the air temperature decreased, the drag coefficient ratio also decreased. This was in a time frame when the winds were also decreasing.

C. 27 JUNE - 28 JUNE

The next major increase in the drag coefficient occurred on 28 June. A low pressure system was located off the coast of Norway on 27 June (Fig. 13, Chapter 3). Winds were light and from the north with a surface pressure of 1015 mb. Air temperature was measured at -2.0° C. As the frontal band moved towards Spitzbergen air temperature began a steady increase to 2.0° C. by 0000 GMT on the 28th. Winds had increased to 13.0 m/s. The pressure had decreased to 1000 mb. The Haakon Mosby's track in relation to the ice edge is shown in Fig. 33 and 34. Time series of the storm period are shown in Fig. 35 a-d.

At 0000 GMT on the 27th the ship was moving parallel to the ice edge with a 7.0 m/s true wind. Relative wind direction was 065 . At 1200 GMT, as the ship turned to the southeast (Position 9 Fig. 33) in the direction of the approaching storm system, the drag coefficient ratio was 1.8. At 1800 GMT on the 27th the low pressure system was situated off the southern tip of Spitzbergen. Winds had increased to 15.0 m/s. Relative wind direction was 355 and air temperature was 1.0°C. as the low advected warm air into the MIZEX area. By 0000 GMT on the 28th the drag coefficient ratio was 5.8. Note at this point that the sea-surface temperature decreased to -1.0° C. with air temperature slightly above that at -0.8° C. (stable conditions). Winds were 12.0 m/s with a relative wind direction of 005 . At this point, the low had crossed over the southern tip of Svalbard and was moving towards the MIZEX area (Fig. 13, Chapter 3). The Haakon Mosby turned due east at 0000 GMT (Position 7 Fig. 34) to intersect the low as it moved through the Fram Strait. However, in passing over the land mass, the cyclone

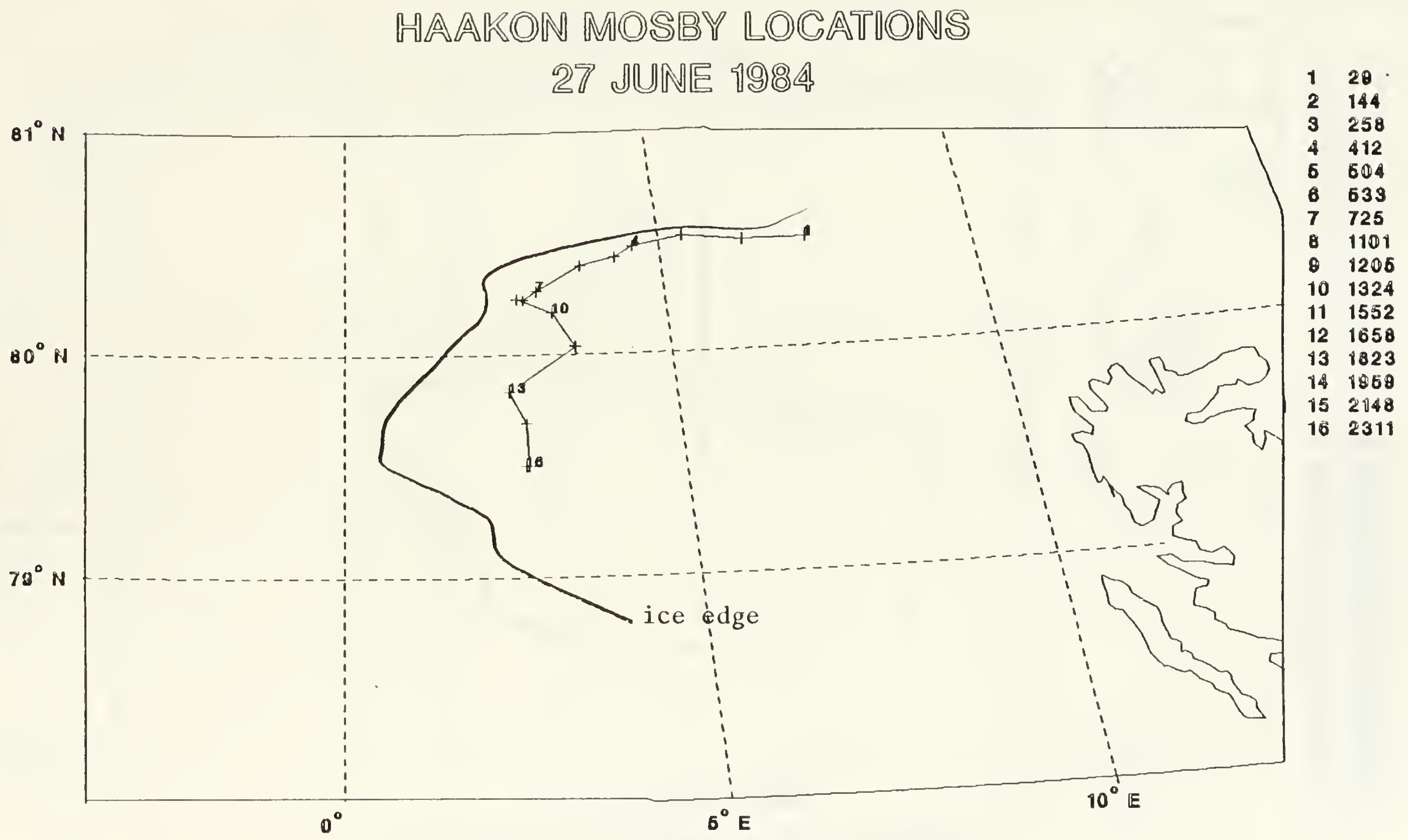

Figure 33. Ships track for 27 June

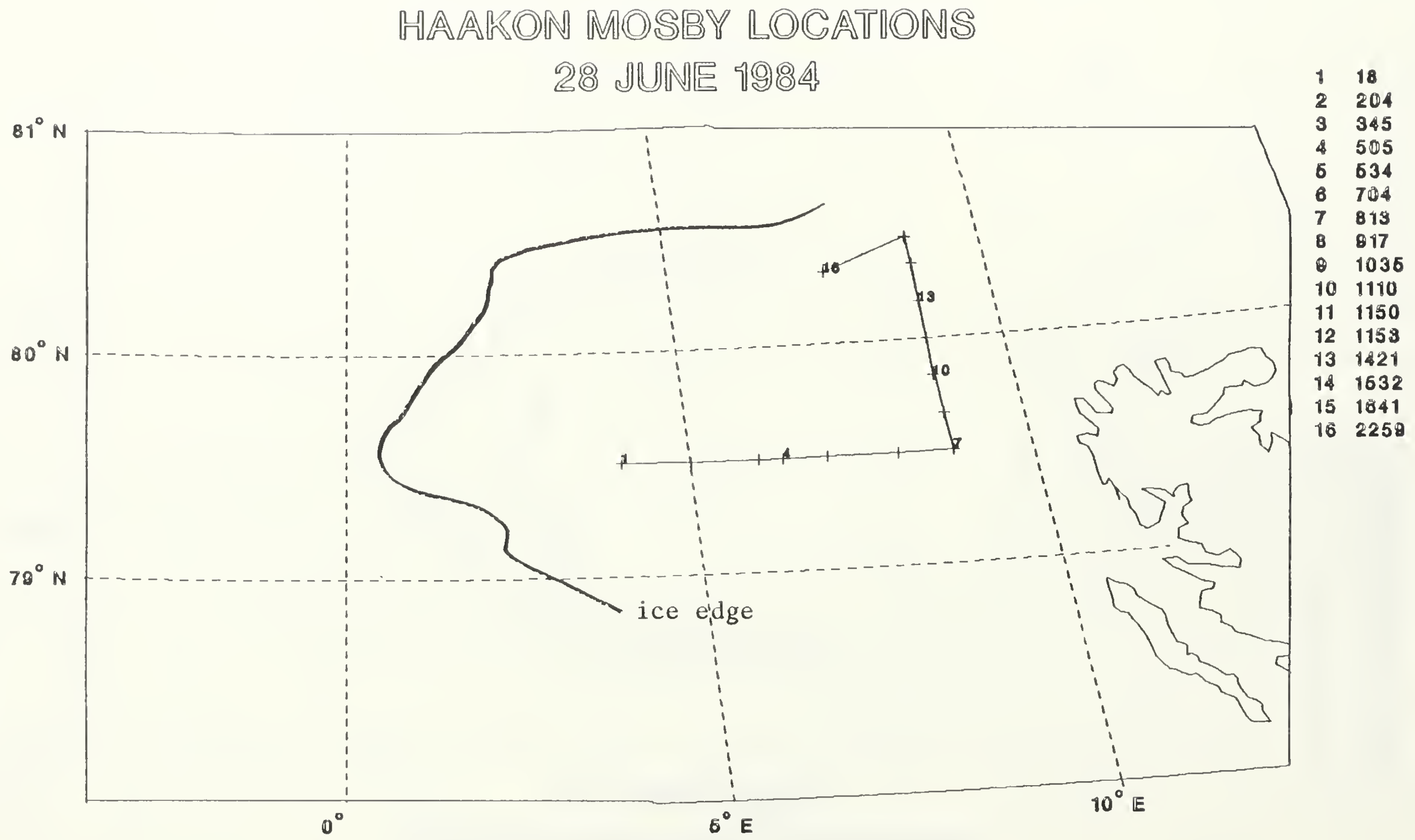

Figure 34. Ships track for 28 June

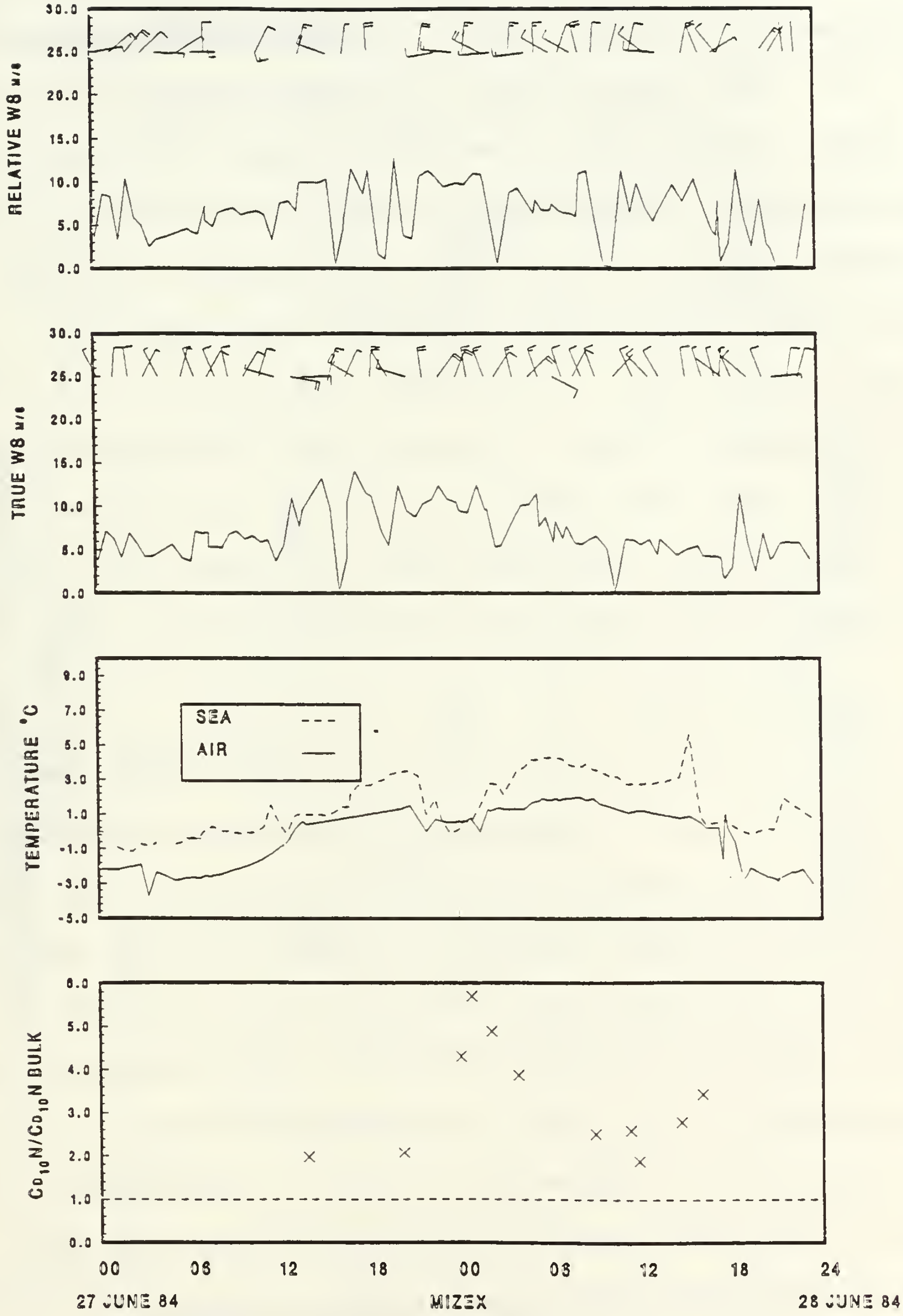

Figure 35.. 27 June - 28 June Time Series

lost intensity and by 1200 GMT on the 28th had dissipated. As the Haakon Mosby turned to the east the winds had already decreased to 10.0 m/s and air temperature had fallen back to 0.0° C. The Haakon Mosby continued east until 0917 GMT on 28 June. During this time winds became light and variable as the low pressure system began to decay off the coast of Spitzbergen. A steady decrease in the drag coefficient was noted. By 1200 GMT the ratio of the drag coefficients was only 1.8.

One of the most interesting features of this storm period was the sudden increase in the drag coefficient ratio corresponding to stable conditions and 12.0 m/s winds from the north. A strong flow pattern was developed and continued over several hours but note that the winds were not exceptionally high.

D. 2 JULY - 3 JULY

Late on 2 July a strong lee trough formed along the coast of Greenland (Fig. 15, Chapter 3). This feature persisted throughout the next day creating winds up to 15.0 m/s. The Haakon Mosby was moving northward along the ice edge at 0000 GMT on 2 July. The ships position with respect to the ice edge is shown for the two day period in Fig. 36 and 37. Time series of this period are presented in Fig. 38. Air temperature was -1.1° C. initially with sea-surface temperature at 0.9° C. (unstable). Winds were only 2.0 m/s and relative wind direction was 100°. By 0600 GMT stable conditions were present caused by an increase in the air temperature to 2.0° C. due to warm air advection from a low pressure system considerably to the south of Spitzbergen.

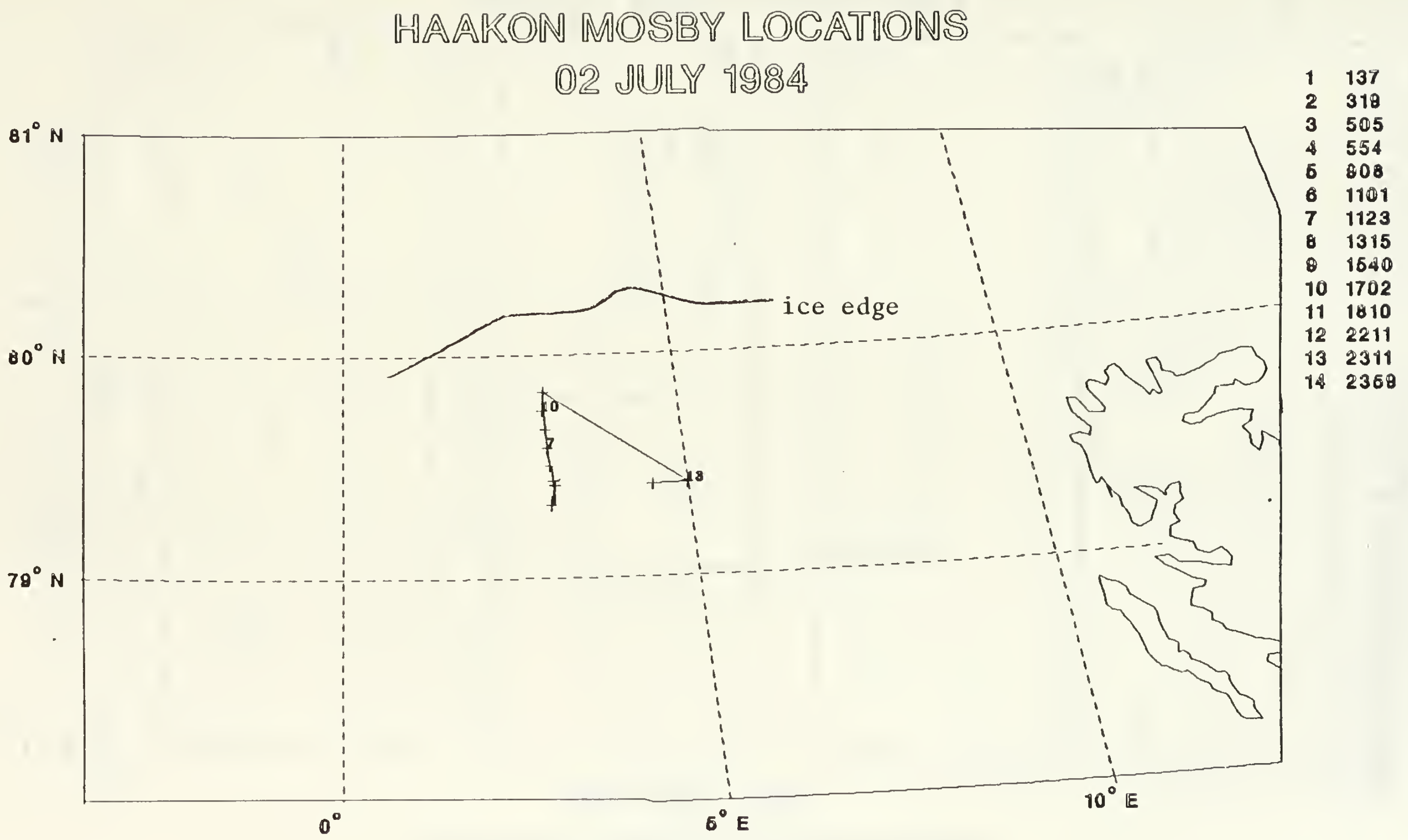

Figure 36. Ships track for 2 July

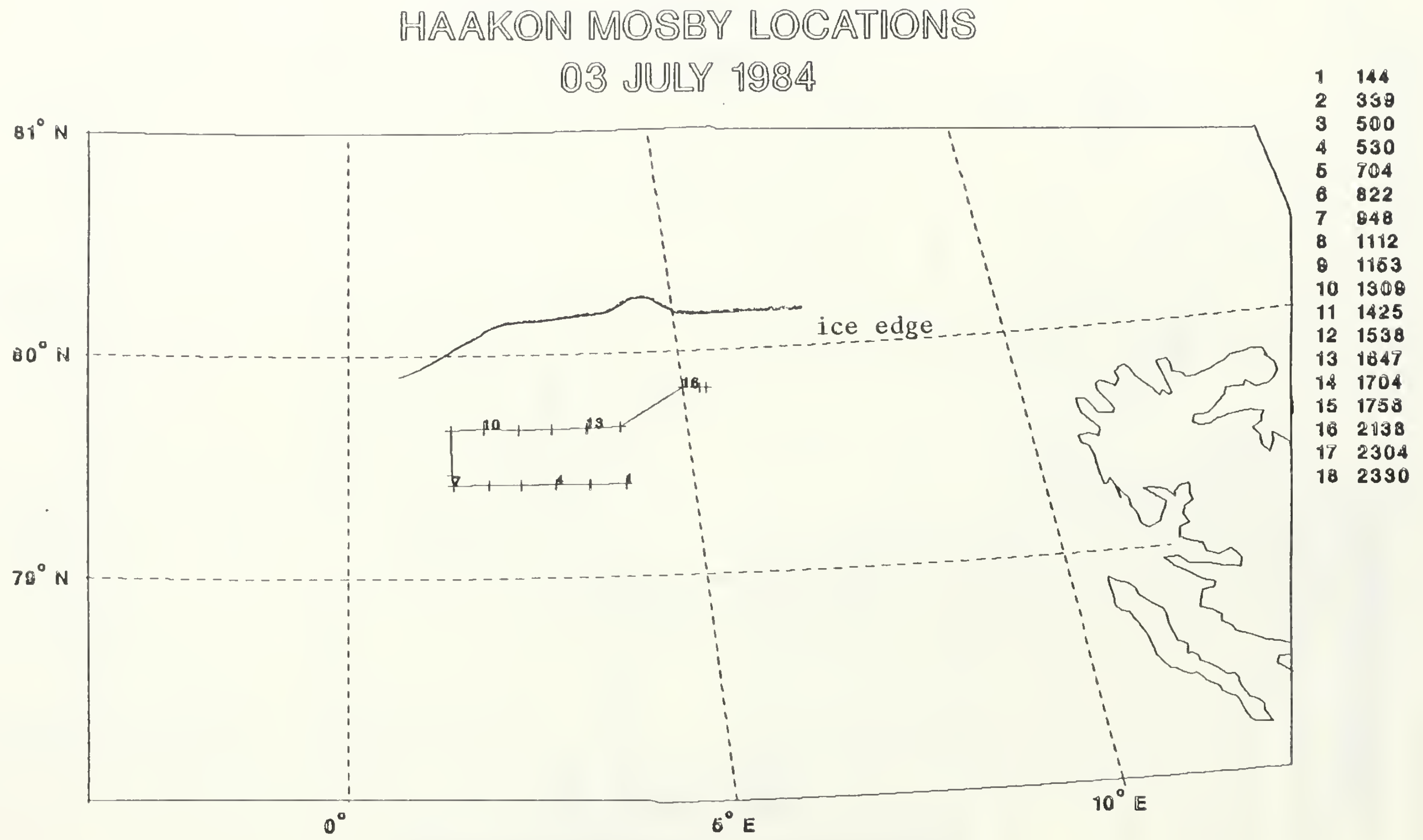

Figure 37. Ships track for 3 July

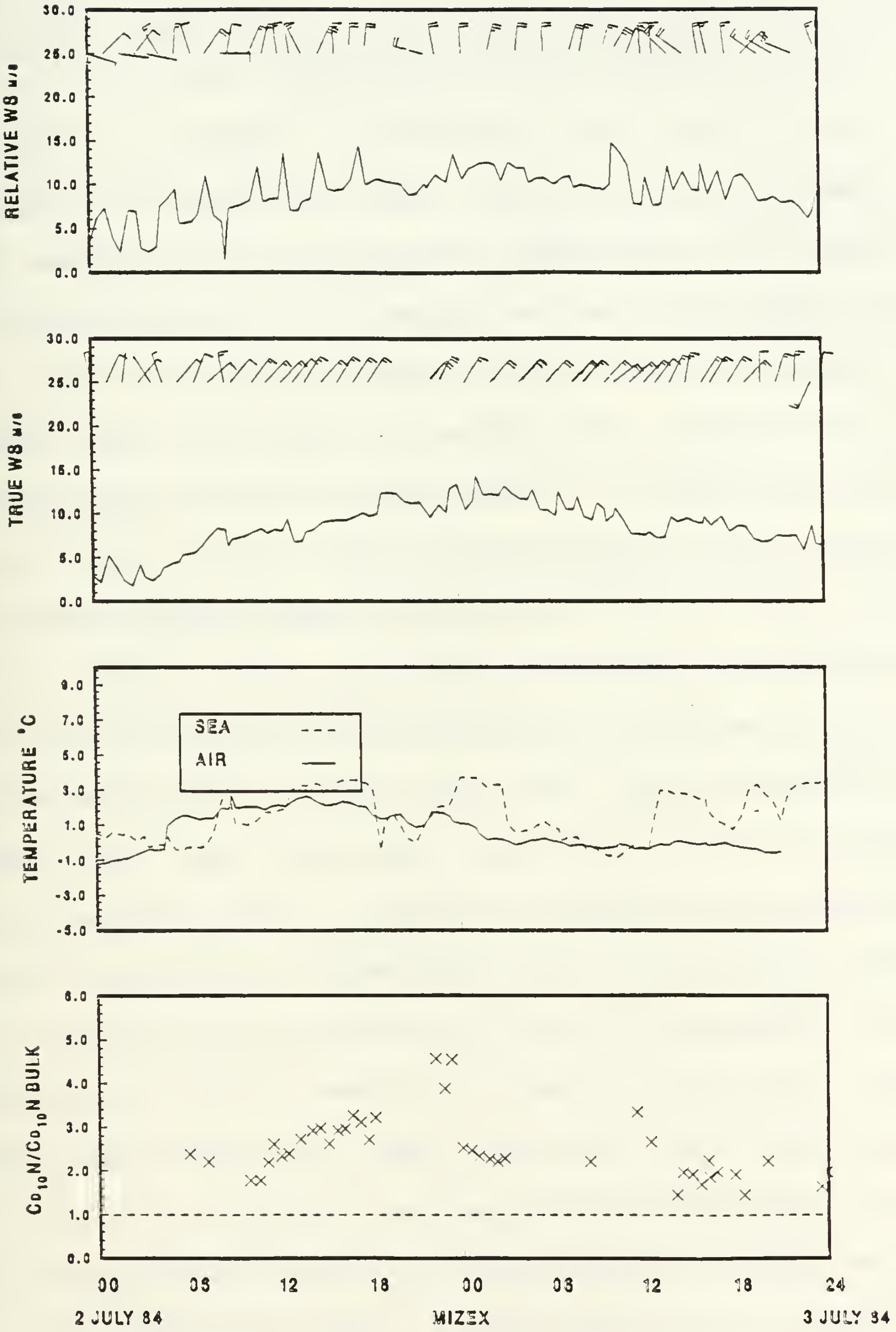

Figure 38. 2 July - 3 July Time Series

The drag coefficient ratio was 2.4 at 0600 GMT and wind speeds had increased to 5.0 m/s with a relative wind direction of 355°.

As the ship continued northward on the 2nd, towards the ice edge, winds shifted to the northeast (onto the ice edge) and the ratio of the drag coefficients began to increase with increasing wind speeds. By this time a meridional flow pattern had developed. At 1800 GMT the Haakon Mosby changed course and headed southeast with an increase in the drag coefficient ratio to 3.6. Relative wind direction was 000 at 13.0 m/s. The drag coefficient ratio peaked at 2200 GMT with a value of 4.6. This corresponded to a high wind period and unstable conditions. At 2300 GMT the Haakon Mosby again turned west (Position 13 Fig. 36), towards the ice edge and continued on that course until 0948 GMT on the 3rd (Position 7 Fig. 37).

At this time the low to the south of Spitzbergen was dissipating and winds were decreasing. The ratio of drag coefficients showed an increase as the ship approached the ice edge. At 1000 GMT, the drag coefficient ratio increased to 3.5. Note that the sea temperature decreased and conditions were stable. The drag coefficient remained high as the Haakon Mosby turned to the north. When the ship turned away from the ice edge at 1200 GMT the drag coefficient decreased to 2.0. Relative wind direction was 340 and wind speed had dropped to 8.0 m/s.

This time period was dominated by winds from north at about 10.0 m/s, causing low sea-surface and air temperatures. The layer remained very close to stable throughout the 2nd. A steady increase in the drag coefficient ratio was noted as winds began to increase and a peak value was obtained when winds reached their highest speed of 15.0 m/s. The drag coefficient also increased when the Haakon Mosby approached the ice edge.

E. 6 JULY - 7 JULY

The final time period of interest in this chapter occurred on 6 and 7 July. The surface pressure at 0000 GMT on the 6th was 1014 mb and was decreasing due to the presence of an upper level low. A strong surface level trough dominated the weather pattern over the MIZEX area (Fig. 17, Chapter 3). The Haakon Mosby's course and the location of the ice edge are shown in Fig. 39 and 40 for 6 and 7 July respectively. The time series for the period is shown in Fig. 41.

The Haakon Mosby's location at the beginning the the 6th was within the broken ice off the Greenland coast. The drag coefficient ratio was low over the first ten hours of the 6th. Winds during that time were light and variable. As the upper-level low dissipated, a strong meridional flow pattern developed increasing the wind speed to 10.0 m/s by 0900 GMT. At this time the Haakon Mosby was moving to the northeast. The drag coefficient ratio remained low at 1.2. As the ship moved out of the ice, into open water, the wind speed continued to rise. The Haakon Mosby was traveling parallel to the ice edge until 1600 GMT. Winds were still from the north at 13.0 m/s. Relative wind direction was 330°. At 1600 GMT the ratio of the drag coefficients increased to 1.8. Wind speed continued to increase as the Haakon Mosby turned to the southwest (Position 20 Fig. 39). The ship turned back towards the ice edge at 2045 GMT

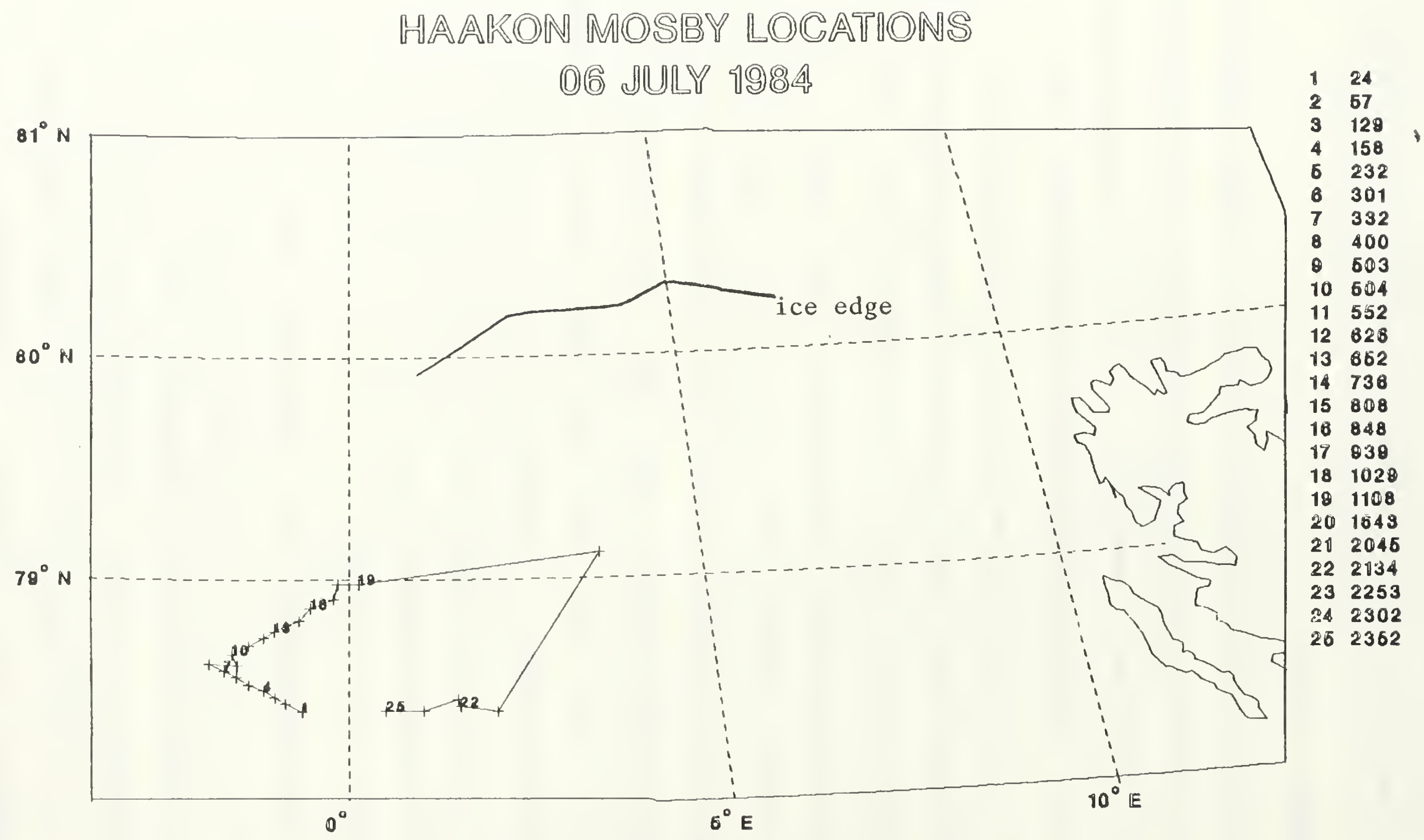

Figure 39. Ships track for 6 July

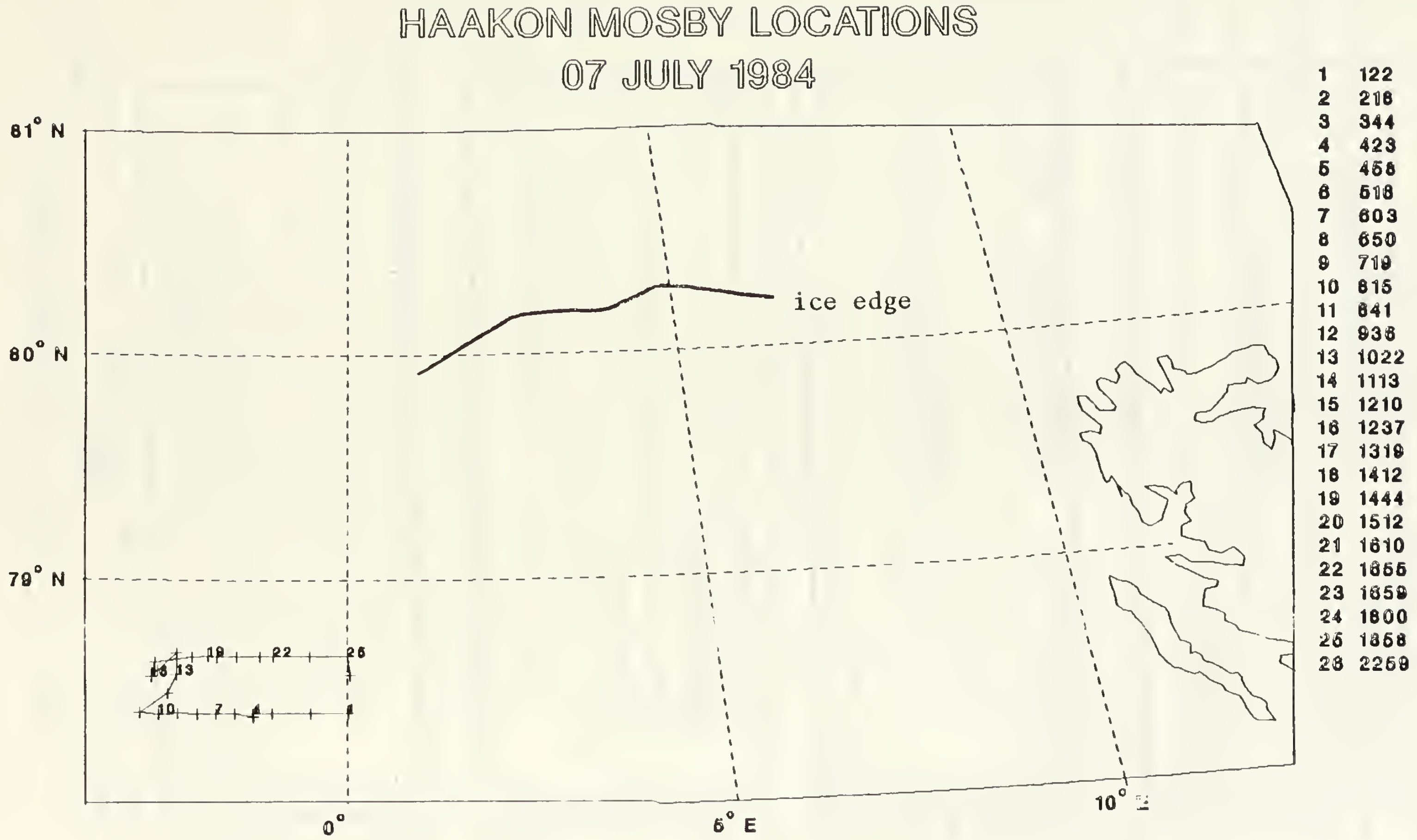

Figure 40. Ships track for 7 July

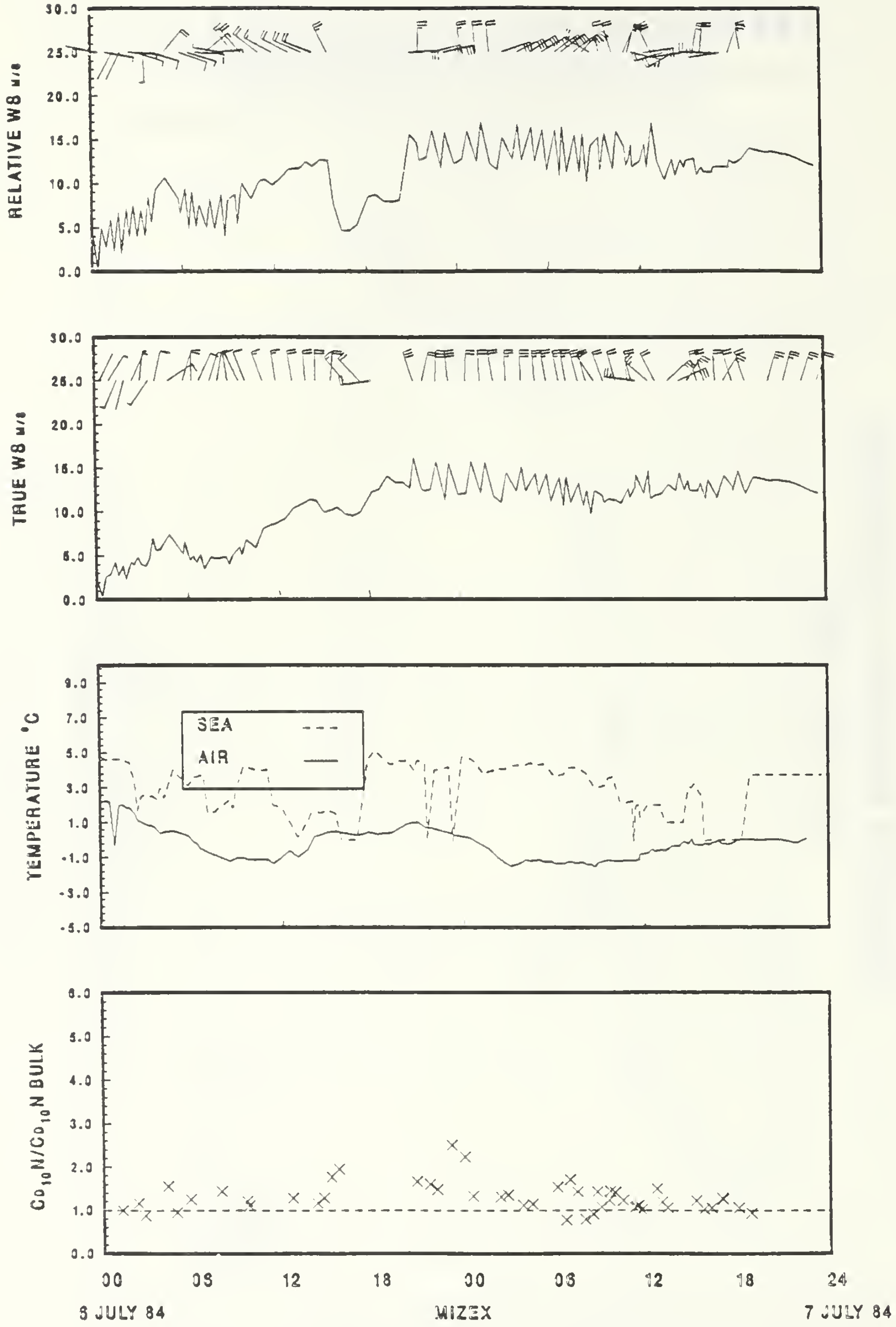

Figure 41. 6 July - 7 July Time Series

(Position 21 Fig. 39). The maximum winds were recorded at 0000 GMT on the 7th. A tight pressure gradient, orientated north to south, existed over the MIZEX area. A frontal band was centered over Spitzbergen. Air temperature dropped to -1.0°C. and surface pressure was 1004 mb. Wind speed increased to 15.0 m/s.

The ship continued westward and at 0000 GMT on the 7th was located at 78.4°N,0.0°E (Position 1 Fig. 31). The drag coefficient ratio also reached its peak value for this time period of 2.4. Wind speeds began to decrease as a low to the east of Spitzbergen began to move towards the MIZEX area and disrupt the meridional flow pattern. The drag coefficient ratio also decreased after 0000 GMT on the 7th and remained close to 1.0. This is somewhat unusual since the Haakon Mosby was within the ice edge of the MIZ and a value of 1.0 for the drag coefficient ratio would indicate a good correlation with the Large and Pond (1981) open water values.

This time period, 6 June - 7 June, can be summarized by low drag coefficient values, unstable conditions, wind speeds of 15.0 m/s and a fluctuating wind direction. The drag coefficient reached its peak value of 2.4 when winds were from the north at 15.0 m/s and the ship was within the ice edge. This was an area of high surface roughness due to the proximity of the ice edge and the increased wind speeds. As previously indicated, the higher the surface roughness, due to winds or ice flows, the larger the surface stress.

V. SUMMARY

The compilations of numerous types of data taken onboard the Haakon Mosby have presented a description of the variation of surface stress for different synoptic conditions and ship's locations with respect to the marginal ice zone. There is a definite correlation between wind speed and the drag coefficient. As wind speeds increase, the drag coefficient correspondingly increases. The drag coefficient also increased when the ship approaches the ice edge, possibly suggesting a wind-wave coupling effect. The larger waves, giving rise to increased surface roughness, cause an increase in the drag coefficient. Several instances were noted where stable conditions corresponded to high neutral drag coefficient ratios. These usually corresponded to high winds from the south bringing warm air into the area.

Of particular importance is that the drag coefficient values measured in the MIZ, using the dissipation method, were much higher than the Large and Pond (1981) open ocean values. By using more accurate surface stress values, a more realistic view of the forcing mechanisms in the marginal ice zone has been obtained.

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