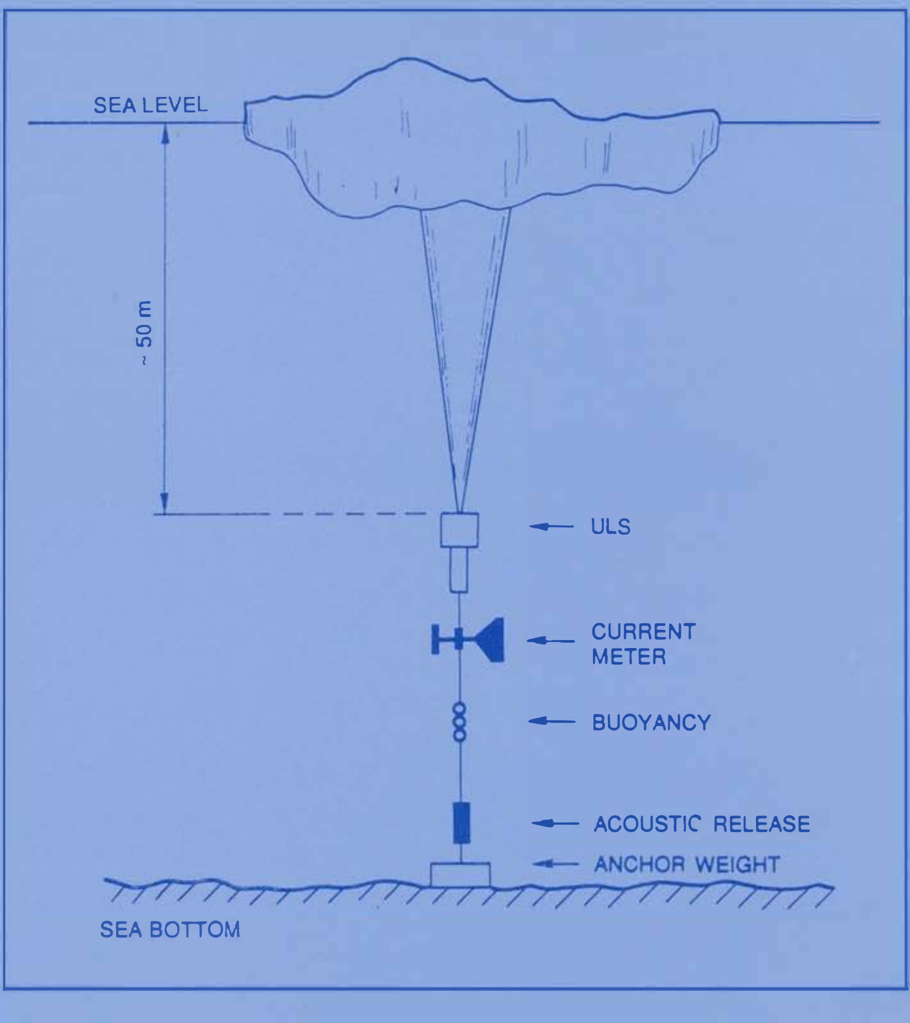
NORSK POLARINSTITUTT

# RAPPORTSERIE

NR. 79 - OSLO 1992

ÅNUND SIGURD KVAMBEKK & TORGNY VINJE

# ICE DRAFT RECORDINGS FROM UPWARD LOOKING SONARS (ULSs) IN THE FRAM STRAIT AND THE BARENTS SEA IN 1987/88 AND 1990/91.



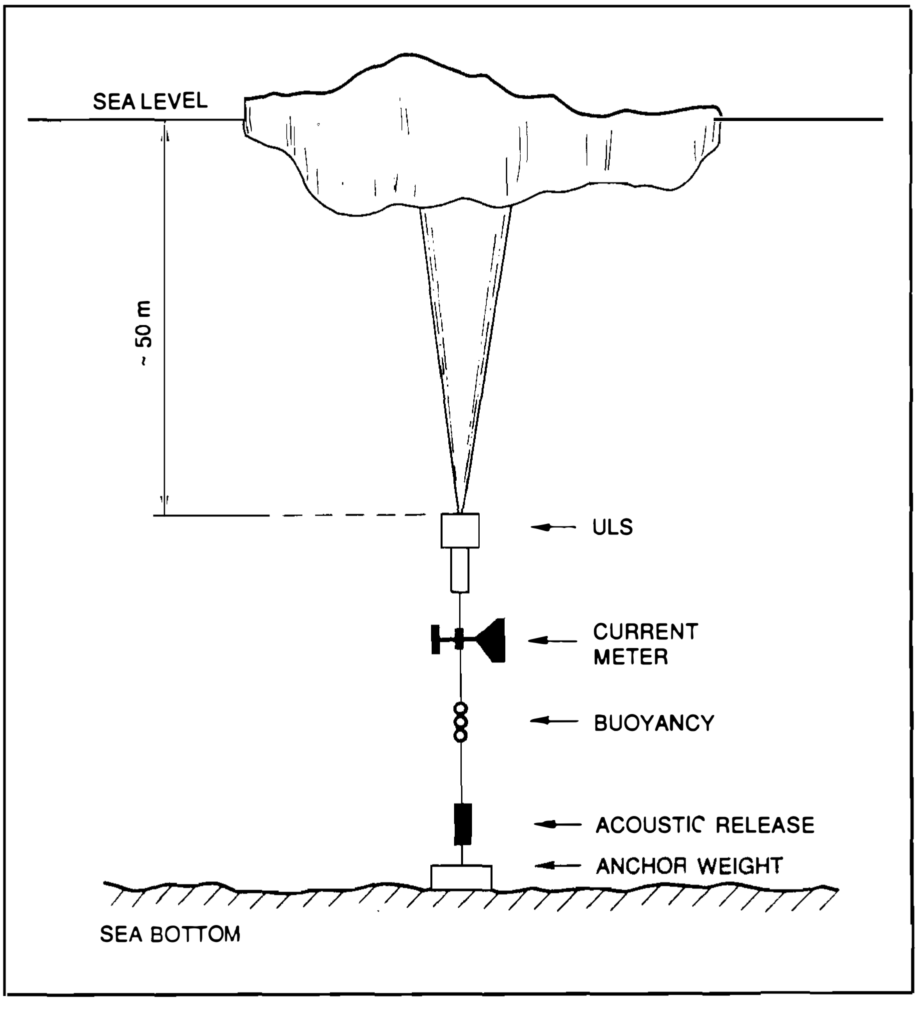
NORSK POLARINSTITUTT

# RAPPORTSERIE

NR. 79 - OSLO 1992

ÅNUND SIGURD KVAMBEKK & TORGNY VINJE

## ICE DRAFT RECORDINGS FROM UPWARD LOOKING SONARS (ULSs) IN THE FRAM STRAIT AND THE BARENTS SEA IN 1987/88 AND 1990/91.



# CONTENTS




ISBN 82-7666-040-1

Printed June 1992



Ånund Sigurd Kvambekk &
Torgny Vinje
Norwegian Polar Research Institute
Postboks 158
N-1330 Oslo Lufthavn
Norway

# INTRODUCTION

Ice thickness distribution of drift ice in the Fram Strait and in the Barents Sea has been one of the prime research topics at Norwegian Polar Research Institute (NP) for several years. Drillings in the Fram Strait were carried out in 1981-1984 (Vinje & Finnekåsa 1986). Since 1984, moored upward looking sonars (ULS) have been deployed yearly, but instrument failures and complete losses of instruments have significantly delayed the results.

The first successful retrieval of an ULS attached to the top of a mooring was made in the summer of 1988, and Vinje & Berge (1989) made a preliminary report on this one year long ice draft series (P1/87). During the summer of 1991 three more ULSs were retrieved, two covering a full year (P6/90, P8/90) and one covering an eight-day test period (P1/90). Fig. 1 shows the locations of the four retrieved ULSs.

A more careful data analysis has been performed for the four present data sets, resulting in three basic improvements from the first analysis (Vinje & Berge 1989):

-Inclusion of temperature data in sound speed and density calculations.
-Detection of periods with open water (also waves).
-Corrections of ice drafts based on surrounding open water.

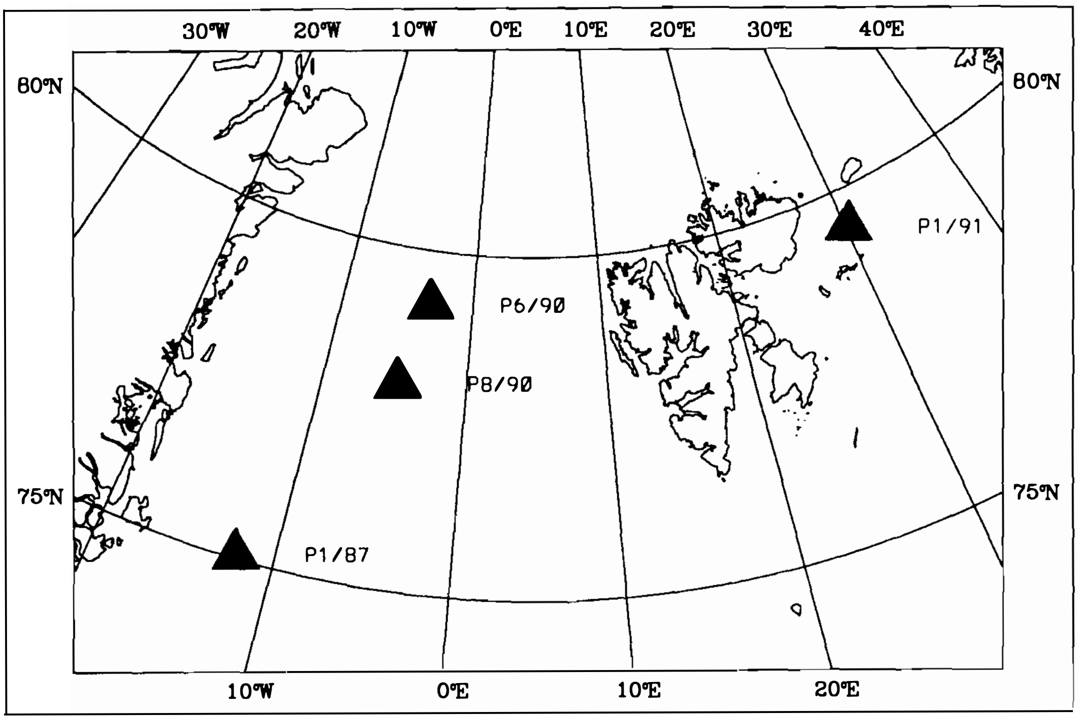



Fig. 1. Positions of the four retrieved ULSs with identification numbers. See Table 2 for more details.

# INSTRUMENTS

## Mooring design

The ULSs were mounted on the very top of a mooring at a nominal depth of 50 m (Fig. 2). At given time intervals, the ULS transmits an acoustic signal concentrated in a vertical conical beam and listens for the return signal from the sea/ice or the sea/air interface. The active reflection area is often referred to as the footprint, and the instrument depth is chosen as a compromise between minimizing the footprint and avoiding collisions with deep ice ridges.

We used kevlar rope on the deep moorings and a 8 mm wire on the shallow moorings (<500m). The anchor weight was connected to the rope with an Oceano acoustic release. Some of the moorings were also equipped with Aanderaa current meters.

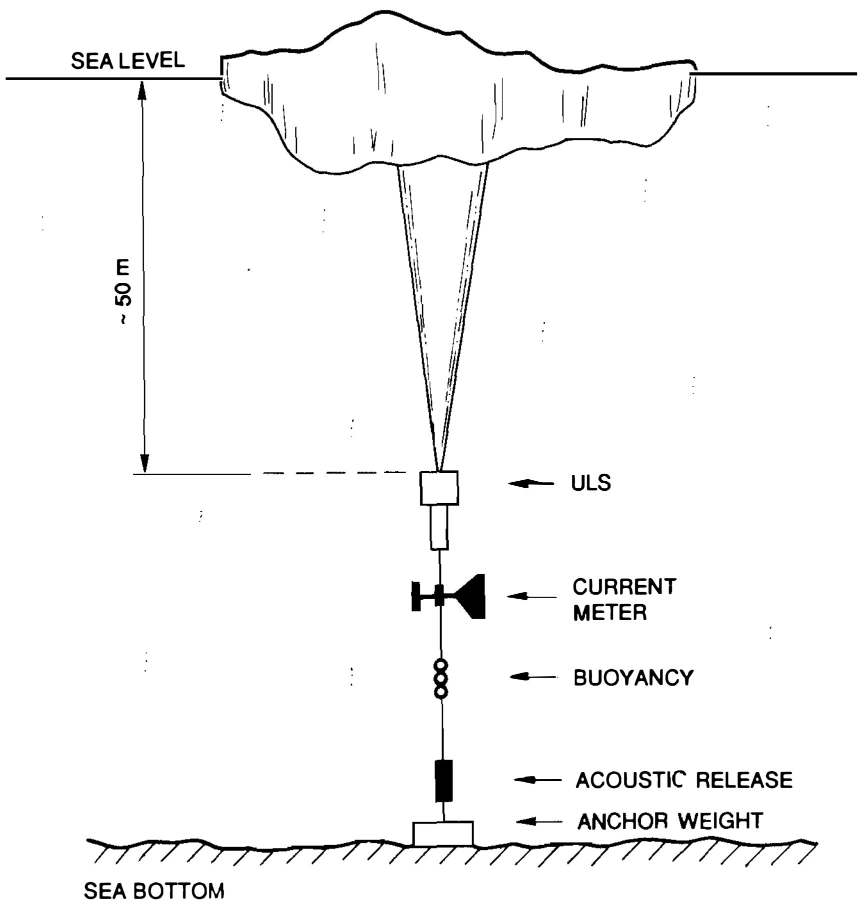



Fig. 2. Sketch of an ULS mooring.

## Instrument specification

Three types of instruments have been used to measure the data presented in this report: ES-300-II and ES-300-IV manufactured by Chr. Michelsens Institute (CMI), Bergen (Norway), and ULS-MARK-2 made by Applied Physics Laboratory (APL), Seattle (USA). Table 1 gives the technical specifications for the instruments.

TABLE 1. Technical specification of the ULS

| | ES-300-II | ES-300-IV | ULS-MARK-2 |
|---|---|---|---|
| | | | |
| **Operational depth** | 20-70 m | 10-140 m | 9-144 m |
| **Pressure resistance** | 400 m | 400 m | 150 m |
| | | | |
| **Sonar beam width** | 5.0° | 2.0° | 2-3° |
| **Acoustic frequency** | 300 kHz | 300 kHz | 300 kHz |
| **Acoustic resolution** | 0.04 m | 0.01 m | 0.002 m |
| | | | |
| **Pressure transducer range** | 20-70 m | 0-140 m | 0-130 m |
| **Pressure resolution** | 0.02 m | 0.04 m | 0.01 m |
| **Temperature sensor** | | | |
| **Temperature resolution** | NA | 0.1°C | 0.1°C |
| | | | |
| **Tilt (XY) resolution** | 1.0° | 1.0° | NA |
| | | | |
| **Data recording interval** | 4 min | 8 min | 5 min / 10 sec |
| **Recording device** | Tape | Solid state | Solid state |
| **Storing capacity** | 550 days | 2 year | 1 year |
| | | | |
| **Physical length** | 1.70 m | 1.16 m | 0.62 m |
| **Physical width** | 0.55 m | 0.60 m | 0.50 m |
| | | | |
| **Weight in air** | 79 kg | 88 kg | 36 kg |
| **Net buoyancy in sea** | 55 kg | 76 kg | 15 kg |

NA = not applicable

For all three instruments, the data recording interval is determined by the user, and Table 1 shows our selections. ULS MARK-2 was set to 5-minute logging intervals, but twice a day there was an intensive period of 25 minutes with 10-second logging intervals.

For ULS MARK-2 the transducer is mounted on a gimbal that keeps the sonar beam vertical. The other two instruments are equipped with tiltmeters, however, it turns out that the stable construction keeps the tilt less than 2° most of the time.

## DEPLOYMENT AND RETRIEVAL

Fig. 1 shows the positions where the four ULSs were deployed, and Table 2 gives the details of the deployments and retrievals of the four ULSs.

TABLE 2. Deployment and retrieval of the ULSs.

| | Lat | Lon | Date | TD | Instr. | ID | WD |
|---|---|---|---|---|---|---|---|
| Deployment (AWI) | 75°03'N | 12°09'W | 22 June 1987 0930 UT | | ES-300-II P1/87 | 45 | 1245 |
| Retrieval (AWI) | | | 20 June 1988 1800 UT | 365 | | | |
| Deployment (NP) | 79°13'N | 3°17'W | 7 Aug 1990 1830 UT | | ES-300-IV P6/90 | 50 | 2203 |
| Retrieval (NP) | | | 20 Aug 1991 2200 UT | 379 | | | |
| Deployment (AWI) | 78°02'N | 4°47'W | 29 July 1990 1030 UT | | ES-300-IV P8/90 | 50 | 1583 |
| Retrieval (NP) | | | 19 Aug 1991 1630 UT | 388 | | | |
| Deployment (NP) | 79°27'N | 30°16'E | 2 Aug 1991 1300 UT | | MARK-2 P1/91 | 65 | 243 |
| Retrieval (NP) | | | 9 Aug 1991 2300 UT | 8 | | | |

Abbreviations:

**Lat** = Latitude
**Lon** = Longitude
**Date** = Date and time
**TD** = Total number of days with measurements
**Instr.** = Type of instrument with serial number
**ID** = Instrument depth
**WD** = Water depth

Institutes involved in deployment or retrieval :

AWI = Alfred Wegener Institute for Polar and Marine Research, Germany.
NP = Norwegian Polar Research Institute, Norway.

## DATA PROCESSING

The ice draft (D) is found as the difference between the depth of the top of the ULS ($d_u$) and the distance from the top of the ULS to the ice bottom ($d_i$):

$$D = d_u - d_i \qquad [m]$$

$d_u$ is found from the pressure observed at the ULS ($p_u$), the air pressure at the surface ($p_a$), the mean water density of the water column above the sonar ($\rho_w$), and the distance between the pressure sensor and the top of the ULS ($d_{pt}$):

$$d_u = \frac{(p_u - p_a)}{\rho_w \cdot g} - d_{pt} \qquad [m]$$

where the gravitational acceleration (g) is given by

$$g = 9.78049 \cdot (1+0.0052884 \cdot \sin^2(\text{latitude})) \qquad [m/s^2]$$

$d_i$ is found from the measured two-way time lapse of the sonar signal (S), the tilt ($\phi$) and the sound velocity ($v_w$):

$$d_i = \frac{S \cdot \cos(\phi) \cdot v_w}{2} \qquad [m]$$

### Acoustic signal return time, pressure and temperature

Although all three instruments measure the ice draft by aid of acoustic pulses and a pressure sensor, technical differences necessitate the individual treatment of the output data which must be converted to

| | |
|---|---|
| -Acoustic signal return time (S) | [µs] |
| -Pressure (P) | [dbar] |
| -Temperature (T) | [dbar] |

To fit into the above formulas for ice draft calculations, these data must be transferred to SI-units .

Four shots are made from the ULSs and only the two most equal shots ($S_{1out}$ and $S_{2out}$) are stored in the data memory. A pair of measurements is later rejected if the measurements differ by more than 700 µs (50 cm in draft).

A detailed description of the conversion from ULS output data (measured data) is given in the following sections. Variables that are not explained are either calibration factors provided by the manufacturer or temporary variables constructed to ease the readability.

### ULS ES-300-II

The two-way time lapse (S) is calculated from the two measurements $S_{1out}$ and $S_{2out}$ :

$$S = \frac{S_{1out} + S_{2out}}{2} \cdot 51.2 - 45 \qquad [\mu s]$$

where 51.2 µs is the time step of the internal clock and 45 µs is the mean delay time inside the instrument.

The pressure (P) is obtained from the measured value $P_{out}$ :

$$P = P_{out} \cdot 0.0195494 - 0.43696 \qquad [dbar]$$

The temperature (T) was not observed in the sonar but taken from a current meter attached to the same mooring at a depth of 70 m.

The pressure sensor is located 13 cm below the transducer (top of the ULS).

### ULS ES-300-IV

The two-way time lapse (S) is calculated from the two measurements $S_{1out}$ and $S_{2out}$ :

$$S = \frac{S_{1out} + S_{2out}}{2} \cdot 13.2 - 22 \qquad [\mu s]$$

where 13.2 µs is the time step of the internal clock and 22 µs is the mean delay time inside the instrument.

The pressure (P) is obtained from the measured value $P_{out}$ :

$$P = P_{out} \cdot 0.04862058 - 0.14688399 \qquad [dbar] \qquad P6/90$$

$$P = P_{out} \cdot 0.03649410 - 0.17980825 \qquad [dbar] \qquad P8/90$$

The temperature (T) measured in the instrument is converted from the output value $T_{out}$ :

$$T = -T_{out} \cdot 0.0061728 + 15.259 \qquad [°C] \qquad P6/90,\ P8/90$$

The pressure sensor is located 15 cm below the transducer (top of the ULS).

## ULS MARK-2

The sound signal from the transducer penetrates through a 12.7 cm liquid-filled focusing lens with a sound velocity that differs from the seawater. We have to subtract this time from the measured time to obtain the two-way time lapse from the top of the ULS.

The temperature (T) is found from the output value $T_{out}$ :

$$T = u\cdot(-3931.895 + u\cdot(-9479.874 + u\cdot 58377.99)) \qquad [°C]$$

where the temporary variable u is obtained from

$$u = \frac{10^6 \cdot 12 \cdot (T_{out} + 327680)}{12004500 \cdot 65536} - 5.812415$$

The time needed for the sonar signal to pass twice through the focal lens ($S_f$) is temperature-dependent and found from

$$S_f = 2 \cdot \frac{0.127}{v_f} \cdot 10^6 \qquad [\mu s]$$

$$v_f = 642 - 3.05\cdot T \qquad [m/s]$$

where $v_f$ is the sound speed in the focal lens.

The two-way time lapse from the top of the ULS is calculated from the two measurements $S_{1out}$ and $S_{2out}$ subtracting the time used inside the instrument (electronics and focal lens):

$$S = \frac{(S_{1out} + S_{2out}) \cdot 40 \cdot 10^6}{2 \cdot 12004500} - 96 - S_f \qquad [\mu s]$$

The pressure (P) is obtained from the observed value $P_{out}$ :

$$P = cc\cdot q\cdot(1 - 0.0089870\cdot q) \cdot 0.6894757 \qquad [dbar]$$

where the temporary variables cc and q are found from the variable u calculated above and the output value $P_{out}$ from the pressure sensor:

$$cc = 1030.189 + u\cdot(24.75692 - u\cdot 1894.634)$$

$$q = 1 - (t0 / pp)^2$$

$$pp = \frac{10^6 \cdot 12 \cdot (P_{out} + 131072)}{12004500 \cdot 6000}$$

$$t0 = 24.98628 + u\cdot(0.1443408 + u\cdot 14.82197)$$

where pp and t0 also are temporary variables. The pressure sensor is located 42 cm below the transducer, i.e. 54.7 cm below the top of the ULS (the focal lens surface).

## Ice draft calculations

The ice draft is calculated from

| | |
|---|---|
| -Distance in time from signal leaving the ULS to the return | [µs] |
| -Pressure (instrument depth) | [dbar] |
| -Temperature | [°C] |
| -Tilt of the instrument | [deg] |
| -Air pressure at the surface | [dbar] |

The speed of sound is the least controlled parameter in the ice draft calculations. In principle it is known from the temperature and salinity profiles, but the temperature at the ULS is the only sea parameter that is actually measured. The temperature and the salinity in the water column above the ULS are parametrized from the observed ULS temperature based on in situ measurements from numerous expeditions, e.g. Østerhus 1989, Foldvik et al. 1990 and unpublished data at NP from 1984 to 1988. Table 3 gives the ice draft errors corresponding to temperature and salinity deviations.

TABLE 3. Calculated ice draft errors due to deviations in temperature and salinity in the water column between the ULS and the ice. Values are relative to water with practical salinity of 33 and temperature of -1°C with the ULS deployed at 50 m depth.

| | 0 m draft | 10 m draft | 20 m draft |
|---|---|---|---|
| **Error of 1 in practical salinity** | 0.05 m | 0.04 m | 0.03 m |
| **Error of 1°C in temperature** | 0.16 m | 0.13 m | 0.10 m |

The three ULSs in the Fram Strait were located in the main ice current at the edge of the continental slope. They experience great variations in the water column above the sonar where warm, saline Atlantic Water meets the cold, less saline Arctic Water. The most common situation in this position is that Arctic Water prevails at the surface while Atlantic Water prevails at the depth of the ULS (50 m). However, situations where one of the two water types dominates the upper 50 m have also been observed.

The upper 50 m between Kvitøya and Nordaustlandet in the Barents Sea are mainly dominated by Arctic Water intermixed by Atlantic Water. The water is not so strongly stratified as in the Fram Strait, and different climatic estimates of the temperature and the salinity have to be used in the ice draft calculations.

As there are very few observations of temperature and salinity in the ice covered areas during the winter season, climatic estimates for this season are mainly based on assumptions. The assumed temperature and salinity estimates made for the surface conditions and for the salinity at the depth of the ULS (50 m) are shown in Tables 4 and 5. The deviations from the assumed values are probably less than 2°C and 1 in practical salinity. This indicates that the temperature is the most critical parameter (Table 3).

TABLE 4. The assumed temperature [°C] and practical salinity at the surface in the Fram Strait and in the Barents Sea for each month.

| Surface Fram Strait | | Jan | Feb | Mar | Apr | May | June |
|---|---|---|---|---|---|---|---|
| | Temperature | -1.75 | -1.75 | -1.75 | -1.75 | -1.35 | -1.00 |
| | Salinity | 32.0 | 32.0 | 32.0 | 32.0 | 31.7 | 31.2 |
| | | July | Aug | Sep | Oct | Nov | Dec |
| | Temperature | -0.60 | -0.60 | -1.20 | -1.75 | -1.75 | -1.75 |
| | Salinity | 30.5 | 30.5 | 31.7 | 32.0 | 32.0 | 32.0 |

| Surface Barents Sea | | Jan | Feb | Mar | Apr | May | June |
|---|---|---|---|---|---|---|---|
| | Temperature | -1.75 | -1.75 | -1.75 | -1.75 | -1.35 | -1.00 |
| | Salinity | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 |
| | | July | Aug | Sep | Oct | Nov | Dec |
| | Temperature | -0.60 | -0.60 | -1.20 | -1.75 | -1.75 | -1.75 |
| | Salinity | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 |

TABLE 5. The assumed practical salinity at the depth of the ULS (50 m) in the Fram Strait and in the Barents Sea as a function of the sea temperature.

| ULS depth Fram Strait | Temperature | < -1.7°C | -1.0°C | 0.0°C | 2.0°C | > 4.0°C |
|---|---|---|---|---|---|---|
| | Salinity | 34.0 | 34.5 | 34.8 | 34.9 | 35.0 |
| | | | | | | |
| ULS depth Barents Sea | Temperature | < -1.0°C | 0.0°C | 1.0°C | 2.0°C | > 2.5°C |
| | Salinity | 34.1 | 34.3 | 34.5 | 34.7 | 34.8 |

The density $\rho_w$ [kg/m$^3$] and sound velocity $v_w$ [m/s] are calculated from standard formulas using pressure, salinity and temperature. The ice draft calculations include mean water density and mean sound velocity for the water column above the ULS, here taken as the mean of the values at the surface and at the ULS:

$$\rho_w = \frac{(\rho_{ws}+\rho_{wULS})}{2}$$

$$v_w = \frac{(v_{ws}+v_{wULS})}{2}$$

where the subscripts s and ULS refer to the values at the surface and at the depth of the ULS respectively.

## Open water detection and adjustment of draft observations

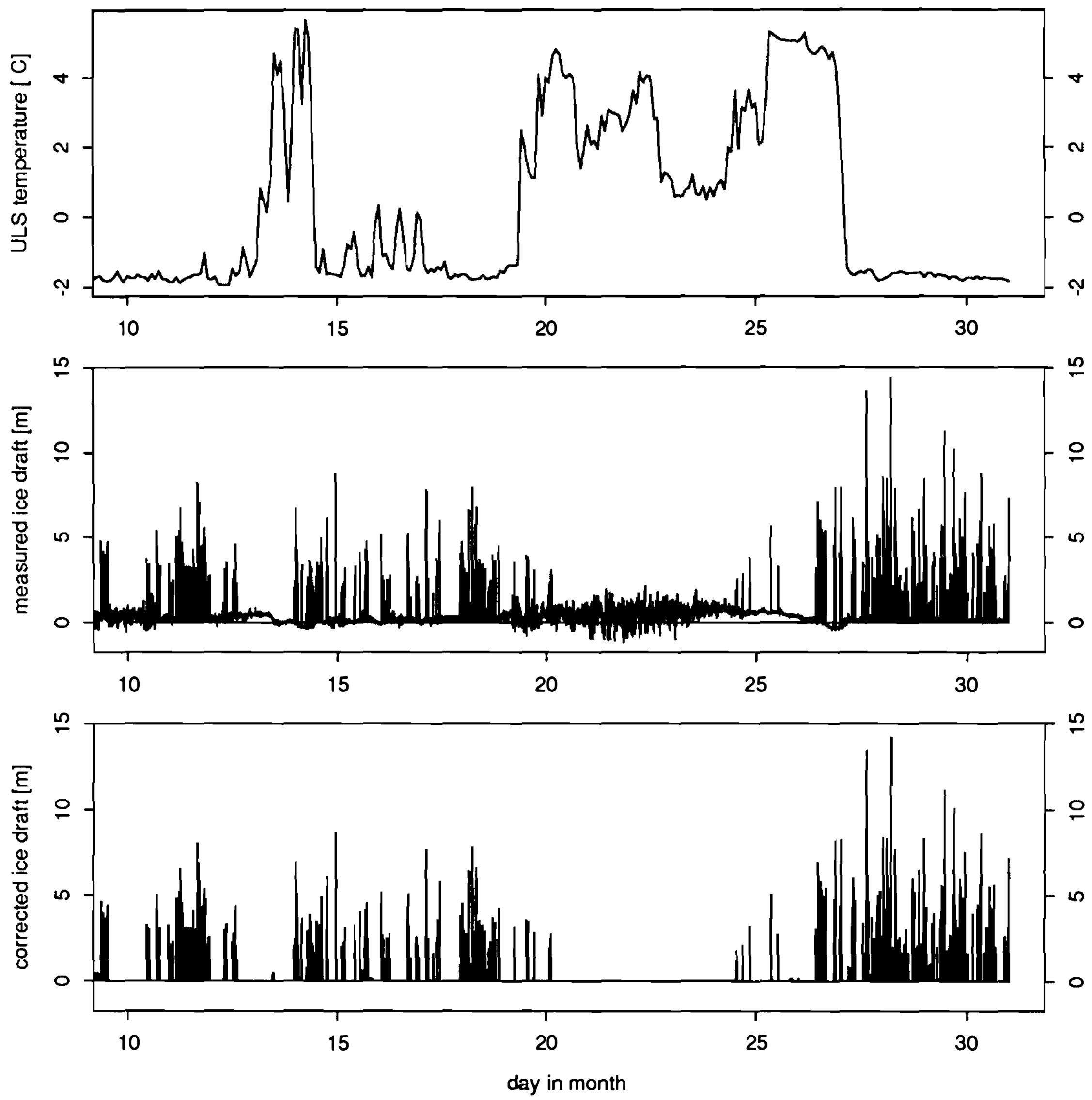



Fig. 3. Data for September 1990 for ULS P8/90 at 78°02'N and 4°47'W. The upper plot shows the temperature observed at the ULS, the middle shows the recorded ice draft, and the lower shows the corrected ice draft after adjustment to the mean sea level. Note the waves during the period 20-24 September.

Deviations from the assumed two-layer structure may in extreme situations lead to errors in the ice draft close to 1 m. In addition, waves and swells affect the surface without affecting the pressure sensor at 50 m depth. The largest errors occur in windy, open-water situations were they may be close to 3 m.

Fig. 3 reveals an open water period (20-27 September 1990) associated with a recirculation of warmer Atlantic Water across the Fram Strait from the Vest-Spitsbergen Current. Open water is detected as a smooth line close to zero (the middle plot), and waves are observed as noise on this line (20-24 September). At the beginning of the 26 September, the measured ice draft is close to 80 cm, even though it obviously should have been zero (open water). The complete water column was probably filled with warm, saline water with a sound velocity greater than the assumed one. The measured ice draft was then reduced during the whole day without any change in the sea temperature at the ULS. This can be explained by a steadily increasing surface layer of cold, less saline water with a lower sound velocity. It is obvious that a single temperature measurement at the ULS is insufficient to take such changes into account. However, from a statistical evaluation of the ice draft time series, it is possible to correct for these errors if the ice cover is less than 80%. A two-step automatic method has been developed to remove the errors in the present data set by detecting open water and adjusting the drafts to correct sea level. The basic elements of the method is described in keywords below :

*Step 1. Remove long periods with open water (waves).*

Analyse 12 hours at a time.

**Restriction:** Median ice draft less than 1 m.

Find *minimum*.

Open water with waves will vary around the *median* value down to *minimum* and up to *upper* = (*median*+(*median-minimum*)).

**Restriction:** At least 80% of the measurements must be less than *upper*. (Less than 20% ice cover).

Define standard deviation (*sd*) as (*median-minimum*) / 3.

Check that we have normal distribution among those less than *upper*.

Check that there is random variation in time around the *median* .

Corrections if the tests are OK :

Data less than 5 ·*sd* is assumed to be open water (= 0.0 m).

The remaining measurements are assumed to be real ice drafts and are reduced by the *median* value.

Move one hour and analyse next period. 11 hours are overlapped. All tests use the uncorrected data as input.

*Step 2. Are the minimum values open water ?*

The data already corrected will not be used in this test.

Analyse 24 hours at a time.

Remove ice drafts above 0.8 m.

**Restriction:** At least 30% of the measurements left. (< 70% ice cover)

Find the first peak in the distribution that satisfies these conditions:

Intervals equal 10 cm.

At least 6 elements occur in the selected peak.

The peak must be less or equal to the *median*.

Corrections if the tests are OK :

Data less than (*median* + 0.10 m) are assumed to be open water (= 0.0 m).

The remaining measurements are assumed to be real ice drafts and are reduced by the *median* value.

Move one hour and analyse next period. 23 hours are overlapped. All tests use uncorrected data.

# THE ICE DRAFT SERIES

*Effective ice draft* is defined as the mean ice draft including open water. *Mean ice draft*, on the other hand, gives the mean ice draft of the ice floes (excluding open water). From the effective ice draft we directly obtain the ice volume by multiplying with the area. To extend the point measurement to other regions, however, it is important to take the ice concentration into account. The mean ice draft multiplied by the regional ice concentration and the area gives the regional ice volume if the same mean ice draft is applicable to the complete region. At least it gives a better estimate than extending the effective ice draft to larger regions. Furthermore, the ice volume transport can be deduced from the mean ice draft and the locally observed ice concentrations and drift velocities.

## Monthly overview

The corrected ice draft series have been analysed for each month and the results are given in Appendix A, Figs. A1-A7 for the 1987/88 data, Figs. A8-A21 for the two one-year series of 1990/91, and Fig. A22 for the 8-day 1991 data. The figures give effective ice draft, mean ice draft, standard deviation (of mean ice draft), maximum ice draft, percentage of open water (ice draft=0), and percentage of missing values compared to a whole month with the same sampling interval.

The ice drafts and daily mean ice draft are plotted in a time series diagram as negative values (to simulate the view from beneath). Missing values are indicated by positive values (2 m) and may be seen in the figures as a thick black line in periods with many missing values. It must be emphasized that the measurements are only point measurements, and the line drawn between points is for the intention of increasing the readability only and must not be confused with the actual ice draft. The continuous line was broken when more than one hour passed between the observations.

The frequency of occurrence is plotted for ice drafts greater than 0 m and less than or equal to 8 m, and for ice drafts larger than 8 m.

## Annual overview

Open water (ice concentrations) can also be found from the weekly ice maps of DNMI (Norwegian Meteorological Institute). Each map comprises an average of the ice conditions for the last 3-6 days, depending on the cloud cover. The monthly average is therefore based on 4 weekly ice maps which actually cover about half the month.

The DNMI ice map ice concentrations are on average in good accordance with the objective open water detection method applied on the ULS series. In fact, the yearly averaged ice concentrations obtained from the ice maps and from the ULS series differ only by 0.1%, 1.4% and 4.5% for P1/87, P6/80 and P8/90, respectively (Table 6).

Table 6 gives yearly mean values of effective ice draft, mean ice draft, maximum ice draft, ice concentration from the ULS data, ice concentration from the DNMI ice maps and data coverage in time. The months with observations from more than one year (i.e. June 1987/88, July 1990/91 and August 1990/91) were first averaged weighted against the number of observation days.

Monthly mean ice drafts, monthly effective ice drafts, monthly maximum ice drafts and monthly percentage of open water from the ULS observations and from the DNMI ice maps are plotted in Fig. 4 for P1/87 and in Figs. 5A and 5B for P6/90 (station A) and P8/90 (station B).

The average annual ice draft was 2.97 m for P1/87, 2.78 m for P6/90 and 2.49 m for P8/90. The difference between P6/90 at 79°N and P8/90 at 78°N may be explained by systematic local divergence of the ice field as observed from several buoy drifts (Vinje & Finnekåsa 1986) with creation of new (thin) ice in the expanding leads in the freezing season. Fig. 5A (middle) confirms this seasonal change in the ice draft discrepancy between P6/90 and P8/90 with a maximum difference in the winter season and almost no difference in the summer season when there is no freezing. The buoy drifts indicate 30-40% increase of an ice area from 79°N to 78°N, so a considerable new ice formation can take place. A more careful study of the ULS series may quantify the freezing rate, but this will not be considered here. From these observations P6/90 is regarded more representative for the regional mean ice draft than P8/90.

TABLE 6. Yearly mean values for ULS P1/87, P6/90 and P8/90.

| | | | | |
|---|---|---|---|---|
| **Eff ID** | = | Effective ice draft | (including open water) | [m] |
| **Mean ID** | = | Mean ice draft | (excluding open water) | [m] |
| **Max ID** | = | Maximum ice draft | | [m] |
| **IC ULS** | = | Ice concentration obtained from ULS data | | [%] |
| **IC IM** | = | Ice concentration obtained from DNMI ice maps | | [%] |
| **DC** | = | Data coverage in time, percentage of possible | | [%] |

| | Eff ID | Mean ID | Max ID | IC ULS | IC IM | DC |
|---|---|---|---|---|---|---|
| **P1/87** | 2.24 | 2.97 | 26.80 | 75.3 | 75.2 | 84.9 |
| **P6/90** | 1.97 | 2.78 | 27.68 | 71.4 | 72.8 | 99.7 |
| **P8/90** | 1.39 | 2.49 | 29.47 | 57.0 | 61.5 | 98.3 |

## Footprint corrections and ice thickness

Reflections from the deepest drafts give a systematic overestimation of the mean ice draft. The error increases with the opening angle of the sonar beam due to the enlarged reflection area. P1/87 had a sonar beam with a 5° opening angle while P6/90 was equipped with a narrow sonar beam of 2°. Observations from individual ice floes with a high resolution scanning sonar (1.7°) only 20 m below sea level will be used to quantify the long-term overestimation. Preliminary results suggest these errors to be 0.15 m and 0.30 m for P6/90 and P1/87 respectively. By making adjustments for these errors and converting from ice draft to ice thickness from the observed relationship 1:1.136 (Vinje & Finnekåsa 1986), we obtain a yearly mean ice thickness of 3.0 m both for P6/90 at 79°N and for P1/87 at 75°N. Wadhams (1992) measurements from a submarine transect indicates that a melting of approximately 1 m of ice takes place between 79°N and 75°N in the East Greenland Ice Drift. The above exact accordance therefore rather indicates that interannual variations take place in the out flow from the Arctic Ocean, as also should be expected.

The ULS recordings from 79°N (P6/90) can be compared with submarine ice draft recordings from the periods April-May 1979 and May 1987 by Wadhams (1983, 1992) and ice drillings in July-August 1981-84 by Vinje & Finnekåsa (1986).

Wadhams (1983) found a rapid decrease in the mean effective ice draft as the ice edge was approached. The mean effective ice draft ranged from 1.5 m to 3.5 m in the marginal ice zone. Wadhams (1992) observed a mean effective ice draft of 2.0 m around 79°N, but most of the submarine track lay close to the ice edge. P6/90 was also close to the ice edge in April-May 1991 and our mean effective ice draft of 2.2 m corresponds with Wadhams measurements.

Vinje & Finnekåsa obtained a mean ice thickness of 4.4 m (July-August) from drillings and calculated ice ridge effects on the ice thickness. Our mean ice draft observations converted to ice thickness yield 3.9 m for the same season. Considering annual differences and the uncertain ridge effect correction of 0.7 m, the results must be regarded as similar.

Finally we will point out the marked seasonal change observed in the ice draft during the 1990-1991 season. The ice draft at 78°N and 79°N had a minimum in October and a maximum in June-July. The 1987-1988 season at 75°N, however, had two ice draft maximums (May-July and December-January) but showed no significant seasonal change. It remains to be seen whether interannual variations or different thermal regimes can account for latitudinal differences.

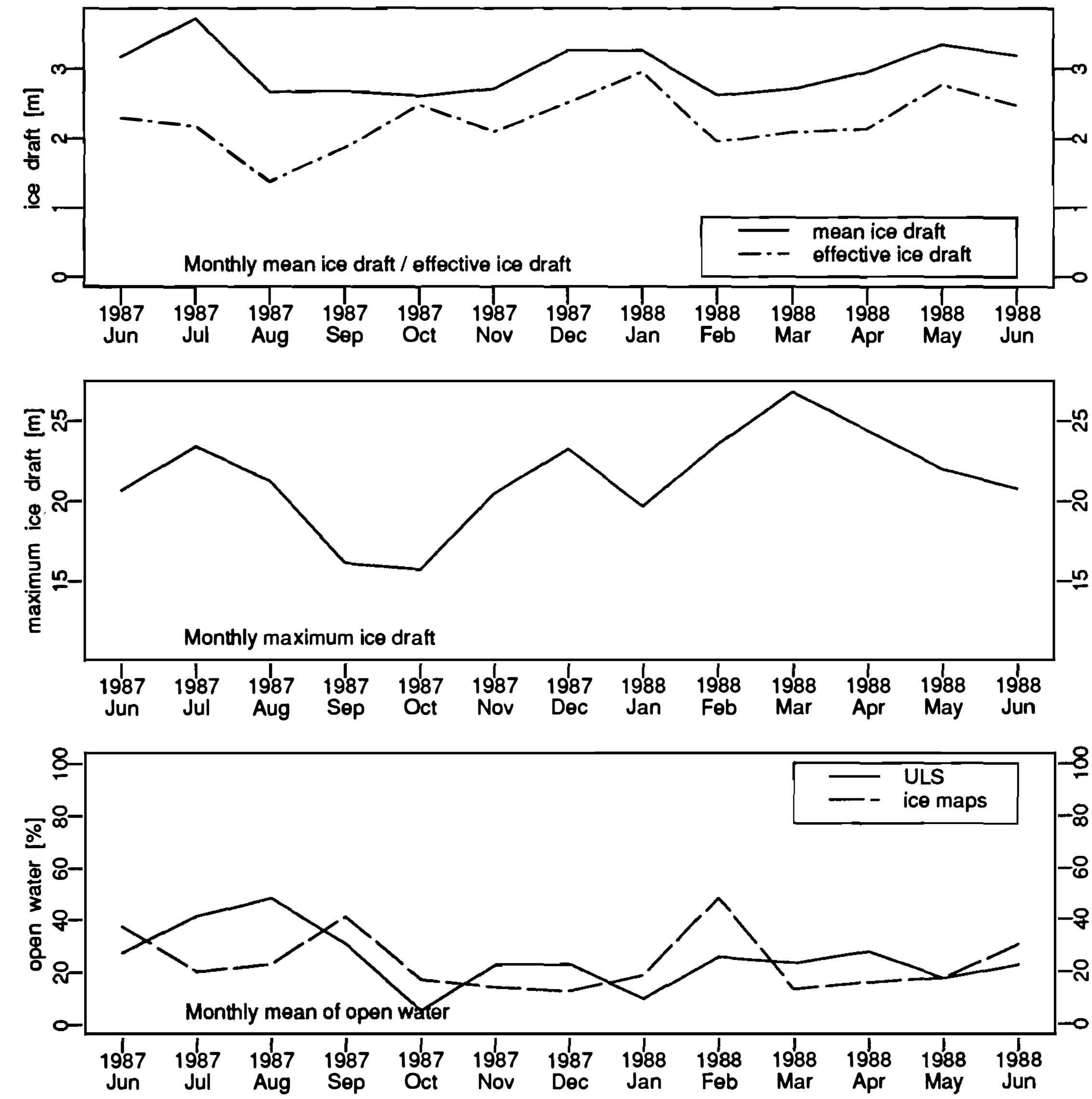



Fig. 4. Monthly mean ice draft, monthly effective ice draft, monthly maximum ice draft and monthly percentage of open water from the ULS observations and from the DNMI ice maps for the period June 1987 - June 1988 at N75°03' W12°09' in the Fram Strait.

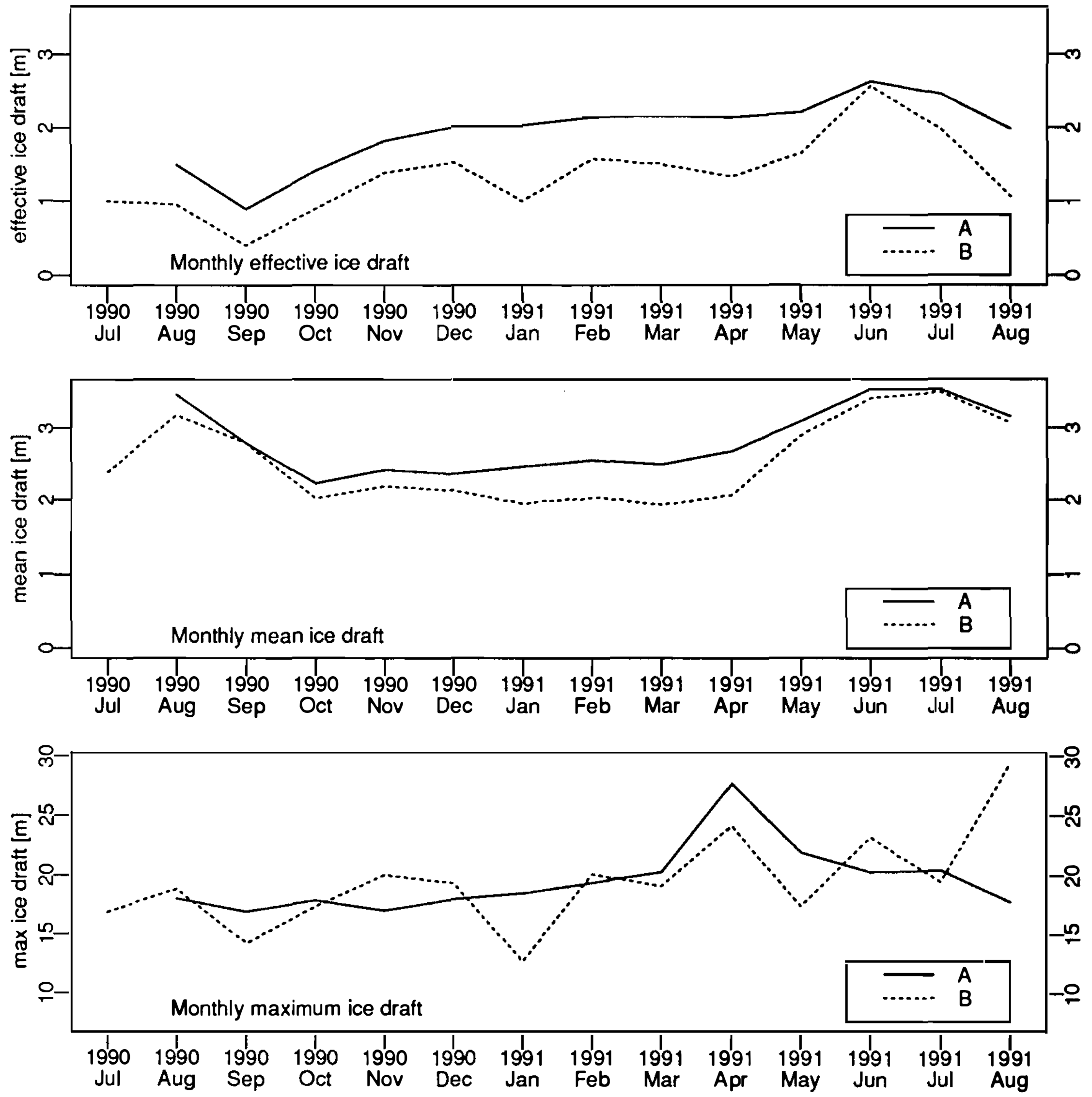



Fig. 5A. Monthly effective ice draft, monthly mean ice draft and monthly maximum ice drafts from the ULS observations for the period July 1990 - August 1991 at N79°13' W3°17' (A) and N78°02' W4°47' (B) in the Fram Strait.

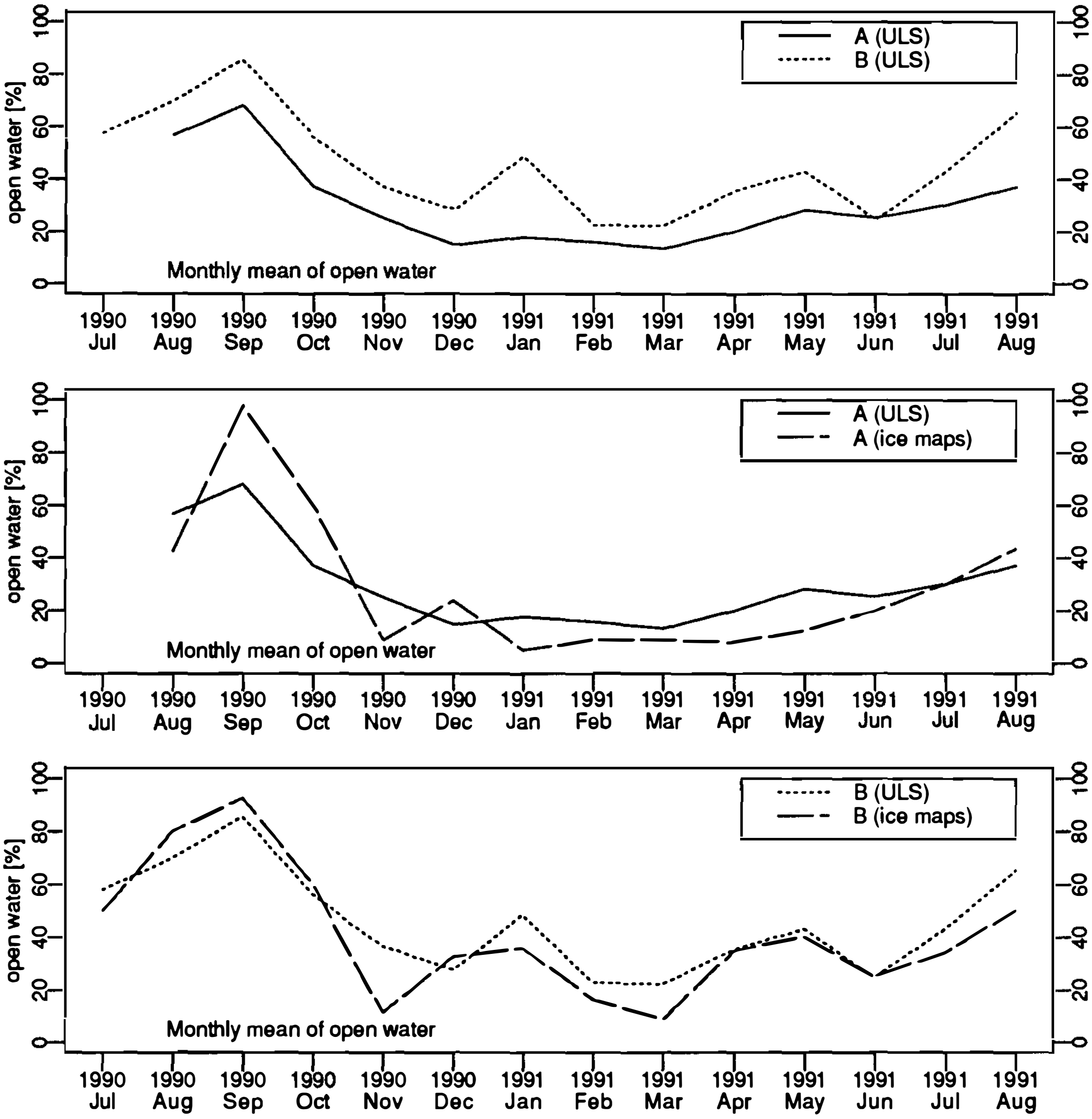



Fig. 5B. Monthly percentage of open water from the ULS observations and from the DNMI ice maps for the period July 1990 - August 1991 at N79°13' W3°17' (A) and N78°02' W4°47' (B) in the Fram Strait.

## REFERENCES

Foldvik A., Lossius T. & Østerhus S. 1990: Cruise with R/V LANCE. CTD data report. Soviet-Norwegian Oceanographic program. Geofysisk Institutt, Universitetet i Bergen, Norway.

Vinje T. & Finnekåsa Ø. 1986: The ice transport through the Fram Strait. Norsk Polarinstitutt Skrifter No. 186, Oslo, Norway.

Vinje T. & Berge T. 1989: Upward looking sonar recordings at 75°N - 12°W from 22 June 1987 to 20 June 1988. Norsk Polarinstitutt Rapportserie, No. 51, Oslo, Norway.

Wadhams P. 1983: Sea ice thickness distribution in Fram Strait. Nature, Vol. 305, No. 5930, pp. 108-111.

Wadhams P. 1992: Sea ice thickness distribution in the Greenland Sea and Eurasian Basin, May 1987. Journal of Geophysical Research, Vol. 97, No. C4, pp. 5331-5348.

Østerhus S. 1989: Cruise with R/V AKADEMIC SHULEYKIN to the Fram Strait, April - May 1989. Preliminary CTD data report. Norsk Polarinstitutt, Oslo, Norway.

Østerhus S. 1989: Cruise with R/V AKADEMIC SHULEYKIN to the Barents Sea, July - August 1989. Preliminary CTD data report. Norsk Polarinstitutt, Oslo, Norway.

Østerhus S. 1989: Cruise with R/V LANCE to the Barents Sea and the Fram Strait, August - September 1989. Preliminary CTD data report. Norsk Polarinstitutt, Oslo, Norway.

CTD - data from 1984-1988 from the Barents Sea and the Fram Strait. Contact person : Ø. Finnekåsa, Norsk Polarinstitutt, Oslo, Norway. Unpublished.

# APPENDIX A

## The observed ice draft for each month

Figs. A1-A22 show the observed ice drafts for each month for the various ULS. The top text of each figure describes :

- -Time (month,year)
- -Position (latitude, longitude)
- -Effective ice draft, i.e. mean ice draft with open water included.
- -Mean ice draft, i.e. mean ice draft with open water excluded.
- -Standard deviation (of the mean ice draft)
- -Maximum ice draft
- -Open water (percentage with no ice)
- -Missing values (percentage of error or missing measurements)

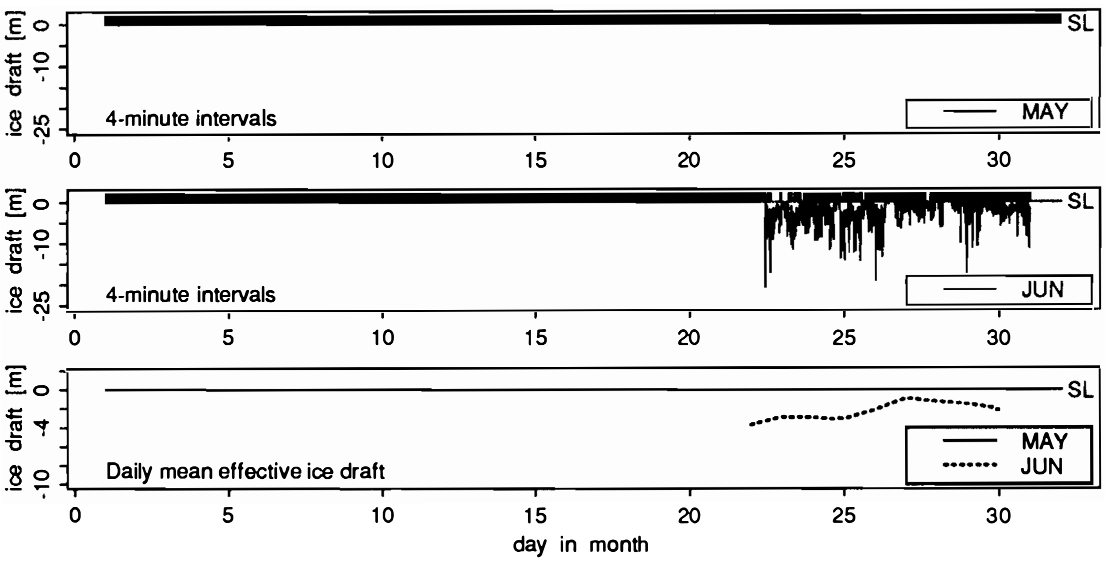
The corrected ice drafts and their daily mean values (effective ice draft) are plotted in a time series diagram as negative values (to simulate the view from beneath). Missing values are indicated by positive values (2 m) and may be seen in the figures as a thick black line in periods with many missing values. It must be emphasized that the measurements are only point measurements, and the line drawn between points is for the intention of increasing the readability only and must not be confused with the actual ice draft. The continuous line is broken when more than one hour passed between accepted measurements.

The frequency of occurrence is plotted for ice drafts greater than 0 m and less than or equal to 8 m, and for ice drafts larger than 8 m. The frequencies are relative to all measurements (including open water).

# MAY - JUNE 1987

| | MAY | JUN |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | | 2.30 m |
| **Mean ice draft** | | 3.16 m |
| **Standard deviation** | | 2.57 m |
| **Maximum ice draft** | | 20.64 m |
| **Open water** | | 27.23 % |
| **Missing values** | 100.00 % | 81.64 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

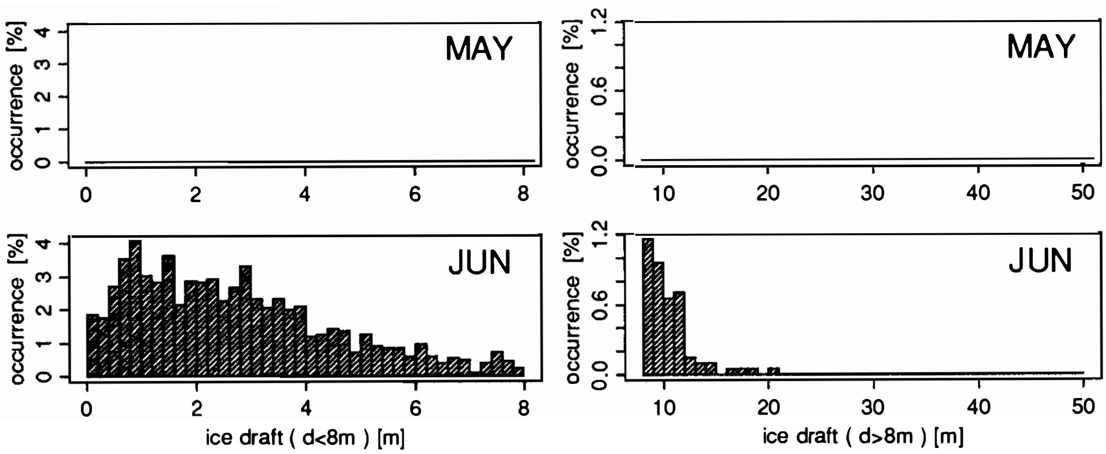
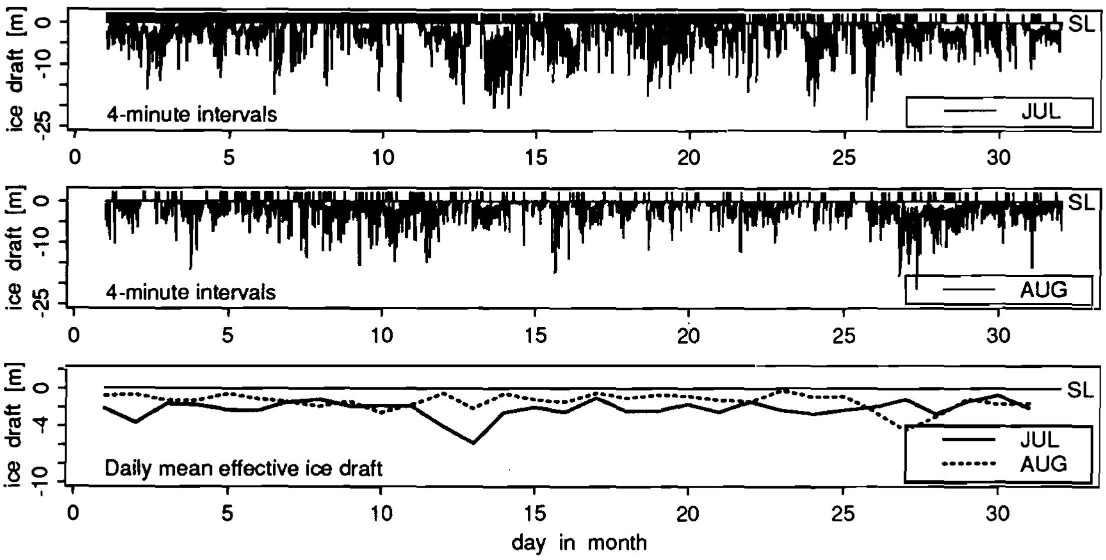



Fig. A1. Ice draft measurements. See Introduction to Appendix A.

# JULY - AUGUST 1987

| | JUL | AUG |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | 2.18 m | 1.37 m |
| **Mean ice draft** | 3.71 m | 2.66 m |
| **Standard deviation** | 3.16 m | 2.24 m |
| **Maximum ice draft** | 23.38 m | 21.21 m |
| **Open water** | 41.41 % | 48.39 % |
| **Missing values** | 20.34 % | 5.85 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

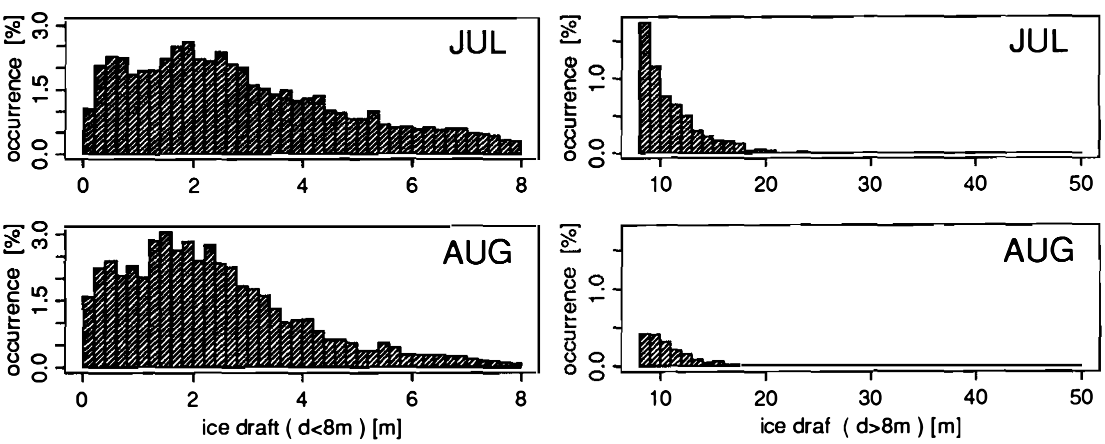
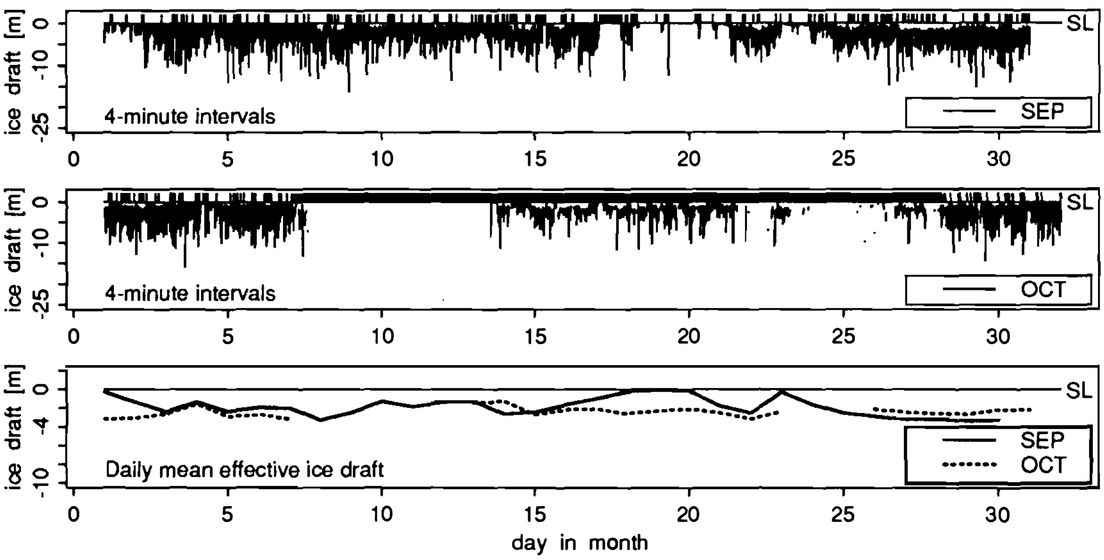



Fig. A2. Ice draft measurements. See Introduction to Appendix A.

# SEPTEMBER - OCTOBER 1987

| | SEP | OCT |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | 1.86 m | 2.48 m |
| **Mean ice draft** | 2.68 m | 2.61 m |
| **Standard deviation** | 1.86 m | 1.87 m |
| **Maximum ice draft** | 16.10 m | 15.70 m |
| **Open water** | 30.48 % | 5.21 % |
| **Missing values** | 7.97 % | 59.39 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

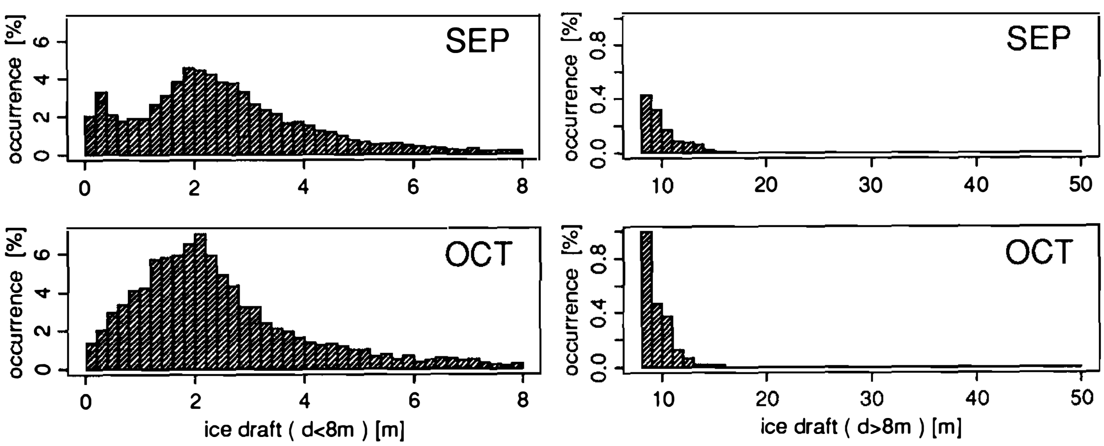
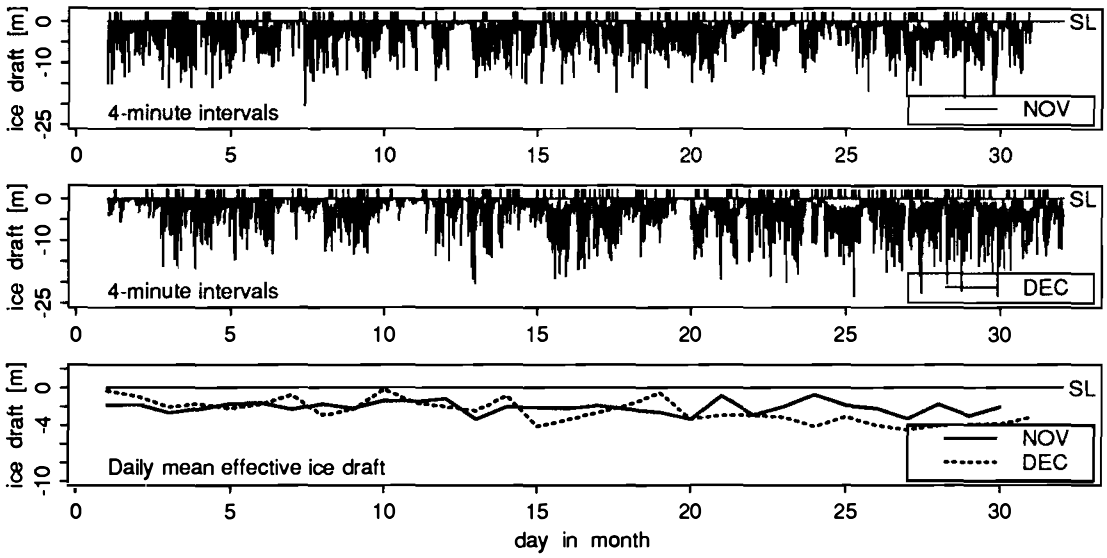



Fig. A3. Ice draft measurements. See Introduction to Appendix A.

# NOVEMBER - DECEMBER 1987

| | NOV | DEC |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | 2.10 m | 2.51 m |
| **Mean ice draft** | 2.71 m | 3.25 m |
| **Standard deviation** | 2.65 m | 3.14 m |
| **Maximum ice draft** | 20.45 m | 23.23 m |
| **Open water** | 22.48 % | 22.70 % |
| **Missing values** | 5.68 % | 6.25 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

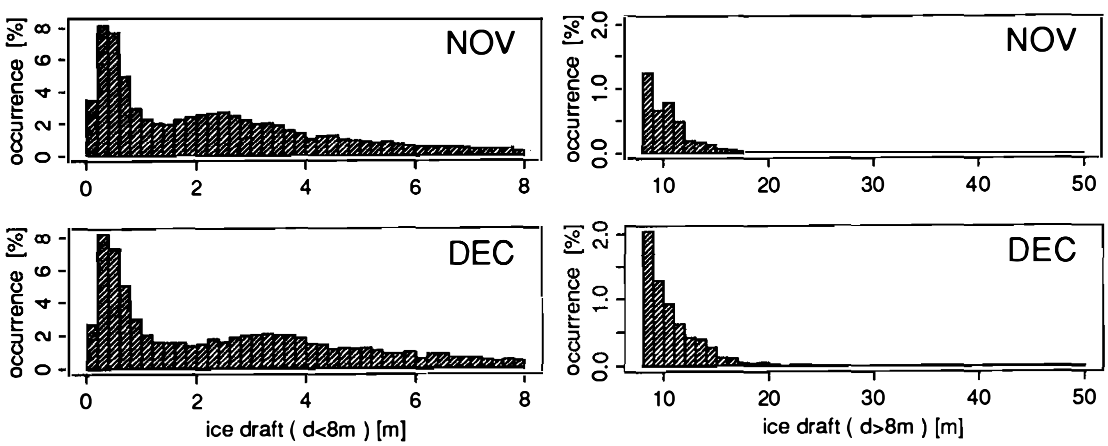
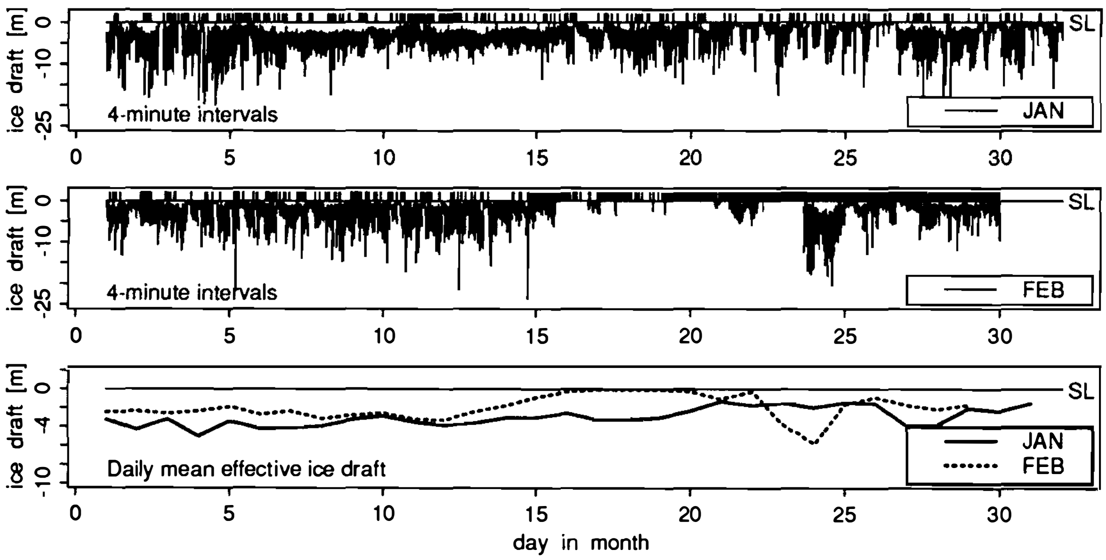



Fig. A4. Ice draft measurements. See Introduction to Appendix A.

# JANUARY - FEBRUARY 1988

| | JAN | FEB |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | 2.95 m | 1.95 m |
| **Mean ice draft** | 3.26 m | 2.62 m |
| **Standard deviation** | 2.36 m | 2.34 m |
| **Maximum ice draft** | 19.65 m | 23.51 m |
| **Open water** | 9.53 % | 25.37 % |
| **Missing values** | 6.28 % | 18.08 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

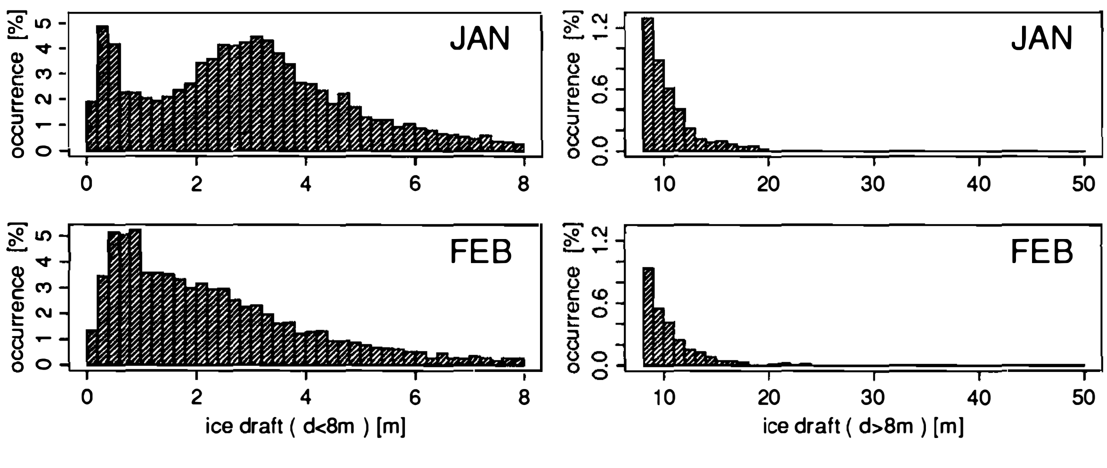
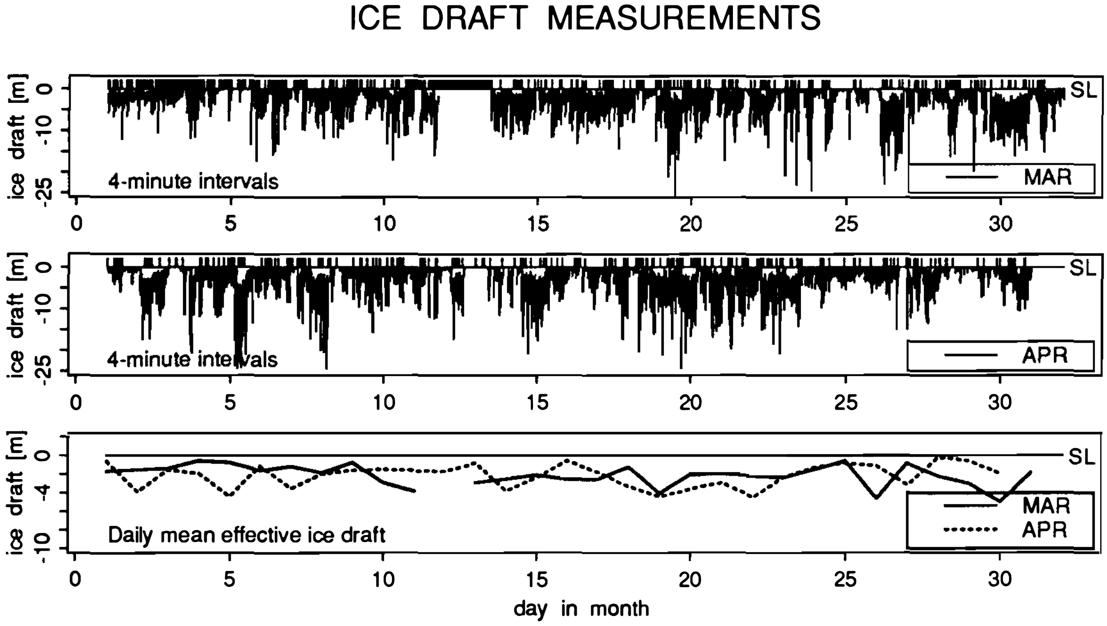



Fig. A5. Ice draft measurements. See Introduction to Appendix A.

# MARCH - APRIL 1988

| | MAR | APR |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | 2.09 m | 2.14 m |
| **Mean ice draft** | 2.71 m | 2.95 m |
| **Standard deviation** | 2.80 m | 3.15 m |
| **Maximum ice draft** | 26.80 m | 24.38 m |
| **Open water** | 23.04 % | 27.39 % |
| **Missing values** | 15.02 % | 6.14 % |



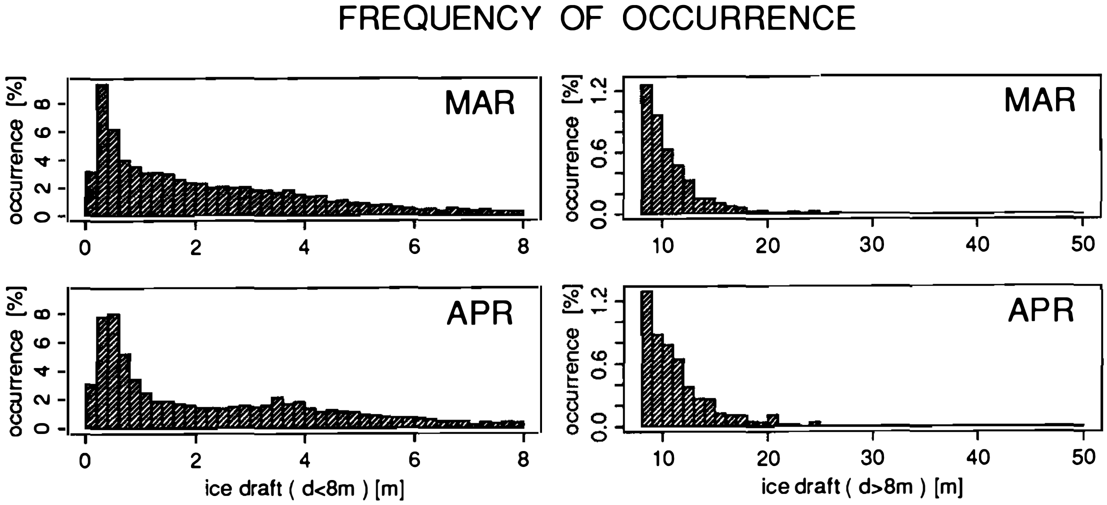
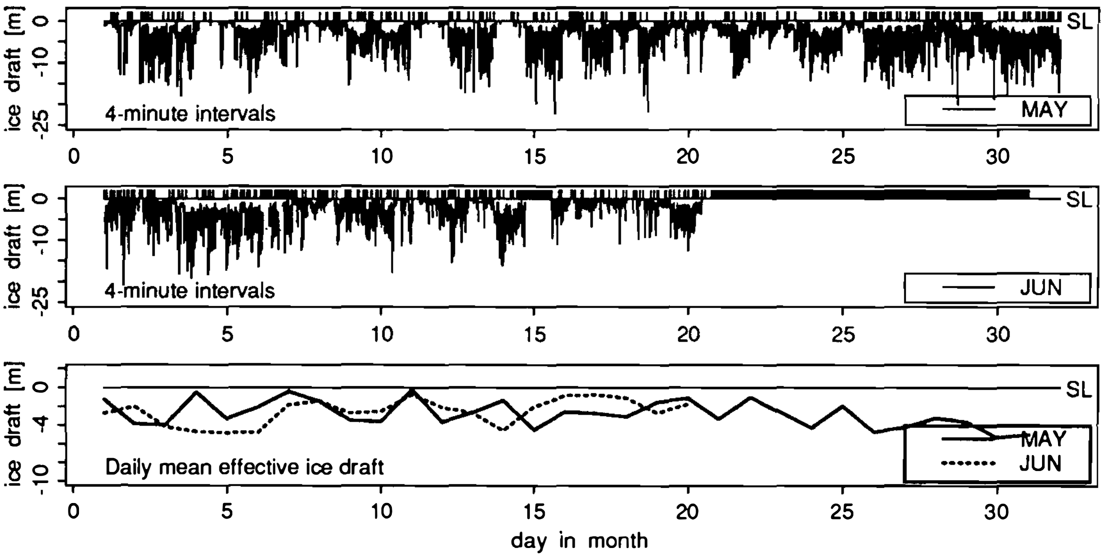




Fig. A6. Ice draft measurements. See Introduction to Appendix A.

# MAY - JUNE 1988

| | MAY | JUN |
|---|---|---|
| **Latitude** | N 75°03' | N 75°03' |
| **Longitude** | W 12°09' | W 12°09' |
| **Effective ice draft** | 2.77 m | 2.47 m |
| **Mean ice draft** | 3.34 m | 3.18 m |
| **Standard deviation** | 2.75 m | 2.71 m |
| **Maximum ice draft** | 21.98 m | 20.75 m |
| **Open water** | 17.29 % | 22.26 % |
| **Missing values** | 6.00 % | 42.56 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

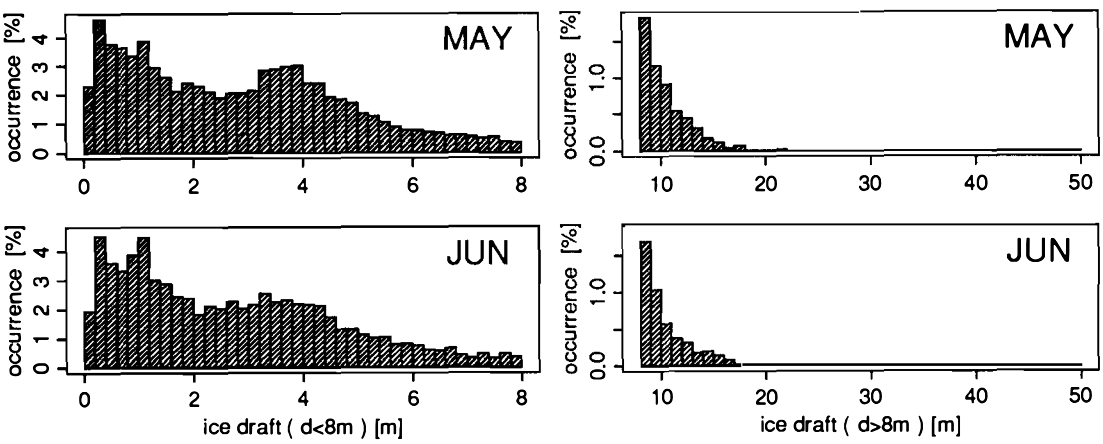
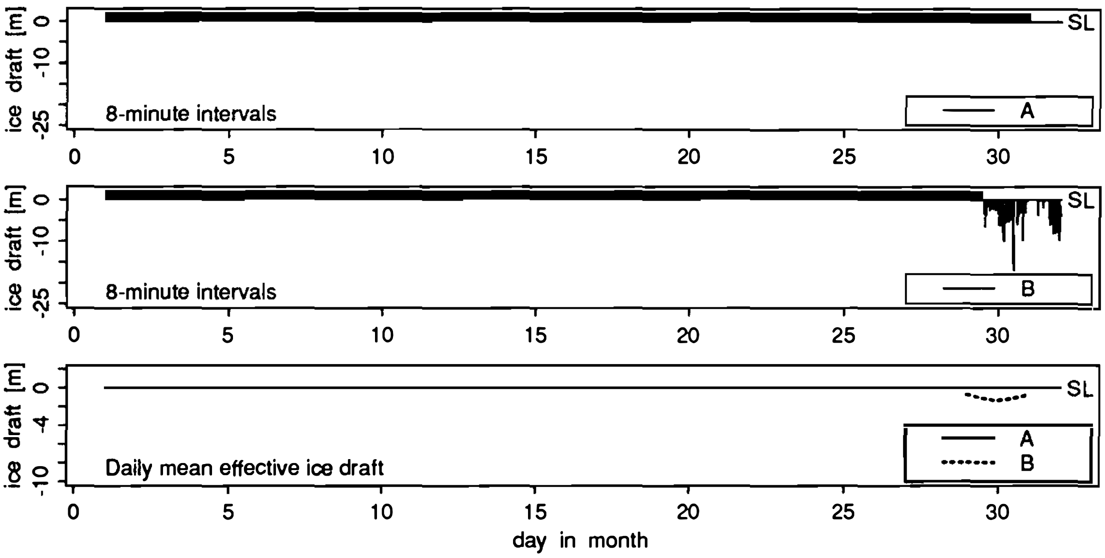



Fig. A7. Ice draft measurements. See Introduction to Appendix A.

# JULY 1990

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | | 1.00 m |
| **Mean ice draft** | | 2.39 m |
| **Standard deviation** | | 2.38 m |
| **Maximum ice draft** | | 16.85 m |
| **Open water** | | 57.95 % |
| **Missing values** | 100.00 % | 91.77 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

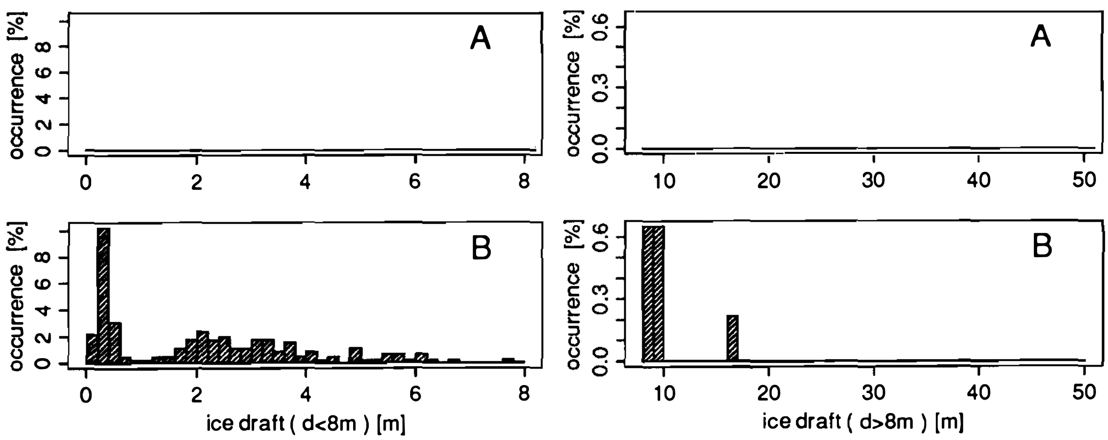
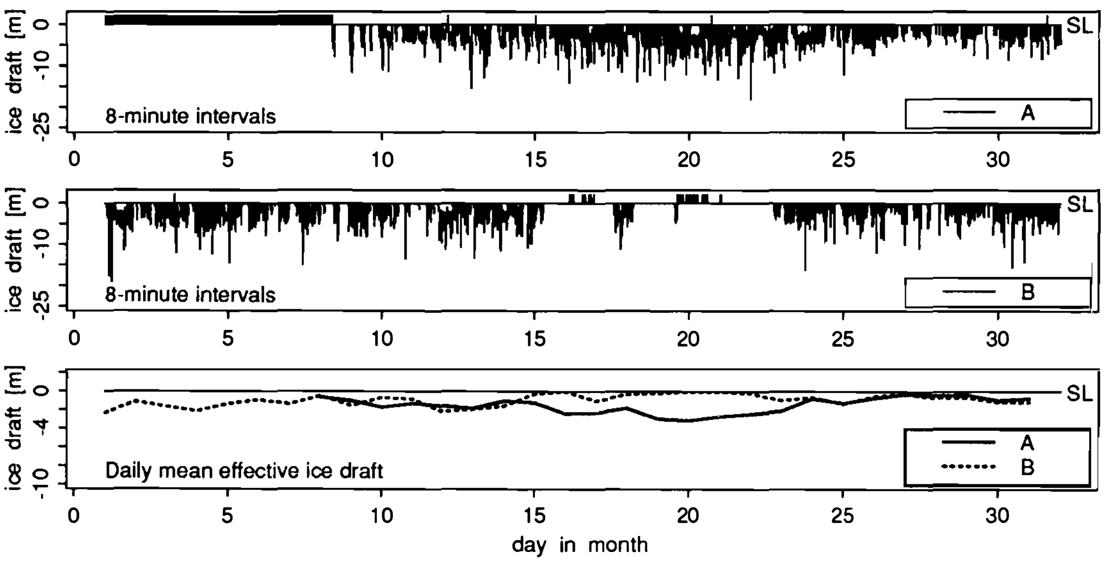



Fig. A8. Ice draft measurements. See Introduction to Appendix A.

# AUGUST 1990

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 1.49 m | 0.95 m |
| **Mean ice draft** | 3.45 m | 3.17 m |
| **Standard deviation** | 2.11 m | 2.14 m |
| **Maximum ice draft** | 17.99 m | 18.79 m |
| **Open water** | 56.76 % | 70.03 % |
| **Missing values** | 23.91 % | 0.61 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

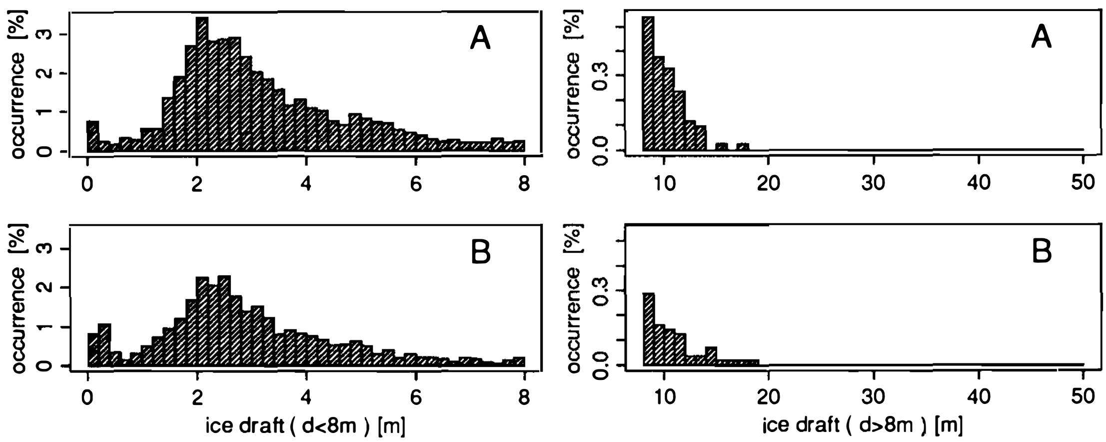
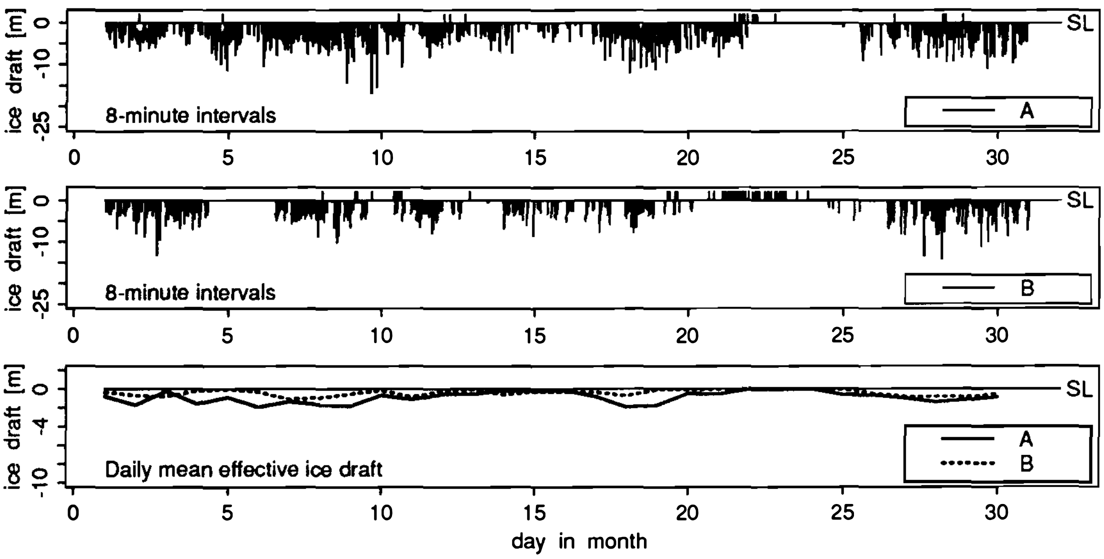



Fig. A9. Ice draft measurements. See Introduction to Appendix A.

# SEPTEMBER 1990

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 0.89 m | 0.40 m |
| **Mean ice draft** | 2.79 m | 2.79 m |
| **Standard deviation** | 1.95 m | 1.91 m |
| **Maximum ice draft** | 16.88 m | 14.21 m |
| **Open water** | 68.10 % | 85.59 % |
| **Missing values** | 0.39 % | 1.28 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

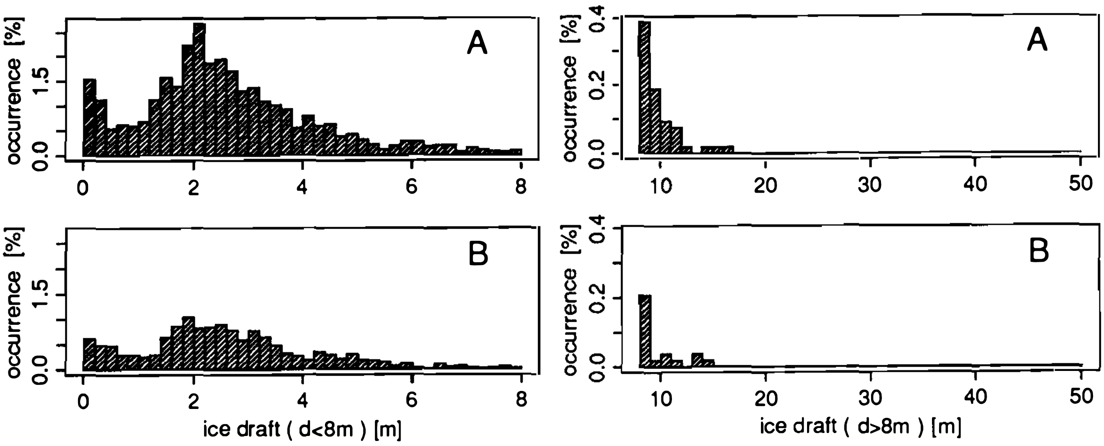
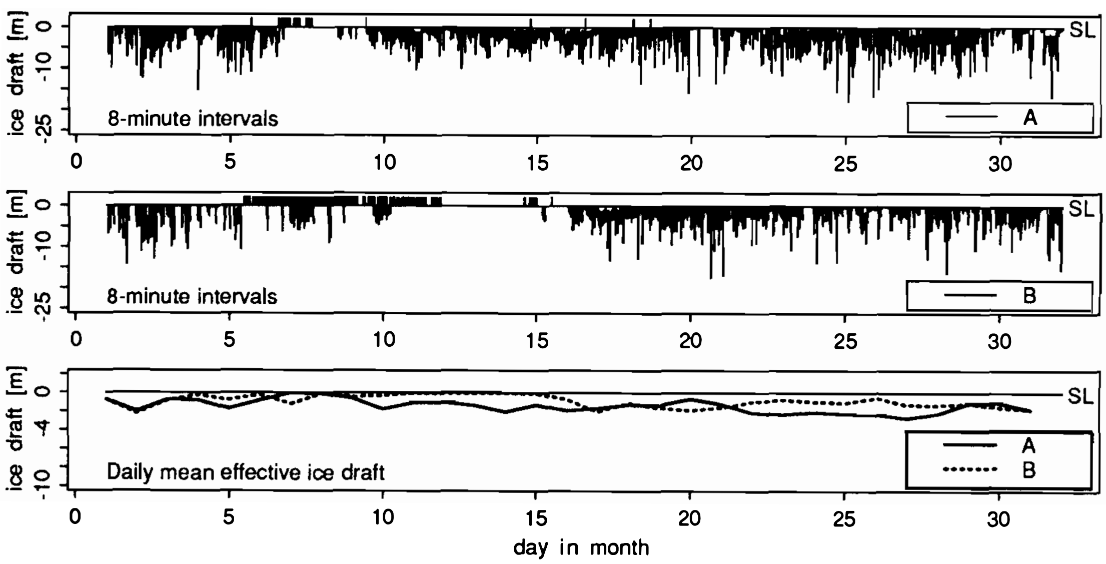



Fig. A10. Ice draft measurements. See Introduction to Appendix A.

# OCTOBER 1990

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 1.41 m | 0.89 m |
| **Mean ice draft** | 2.23 m | 2.02 m |
| **Standard deviation** | 2.16 m | 2.07 m |
| **Maximum ice draft** | 17.83 m | 17.31 m |
| **Open water** | 37.00 % | 56.02 % |
| **Missing values** | 0.66 % | 4.36 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

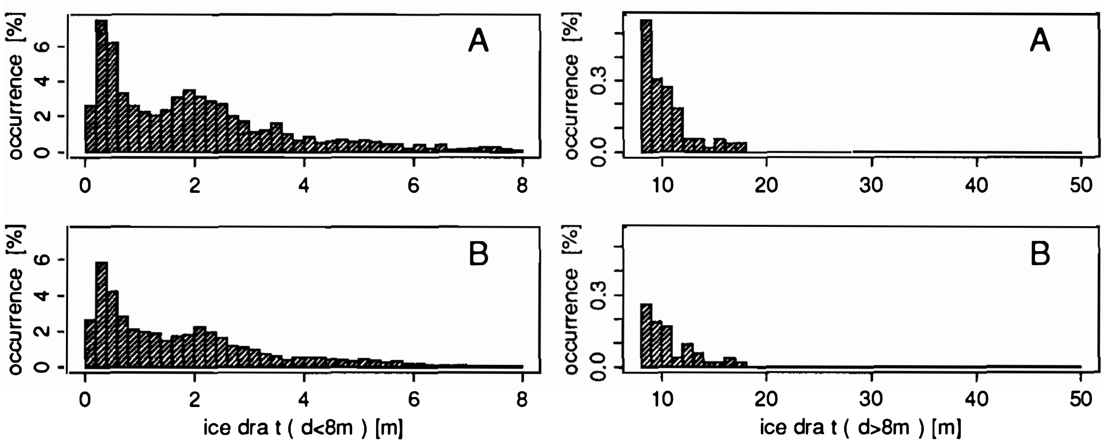
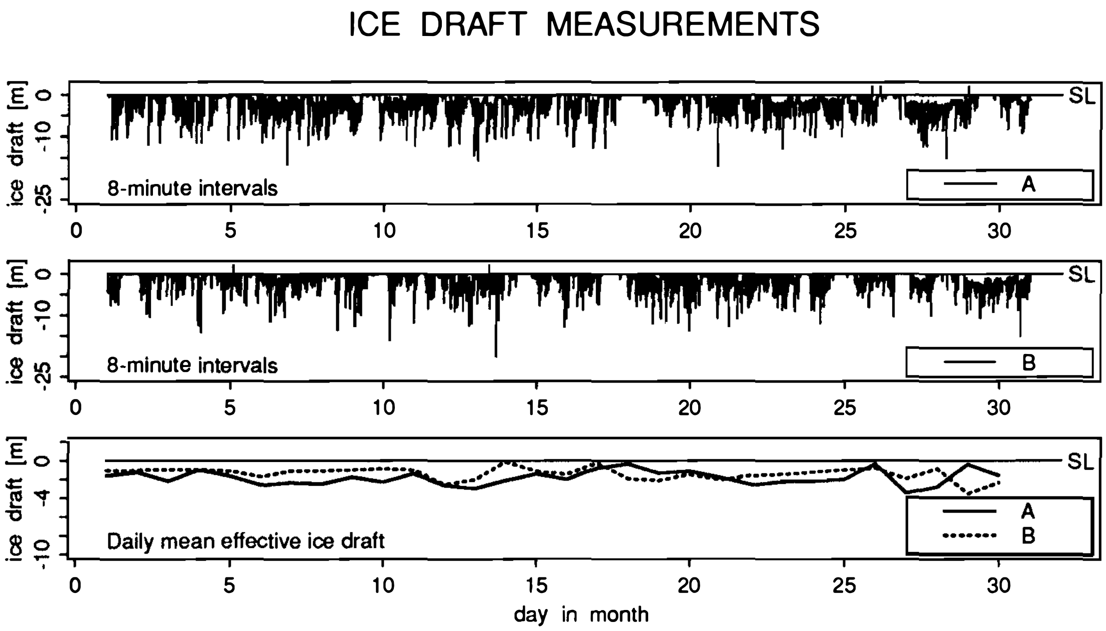



Fig. A11. Ice draft measurements. See Introduction to Appendix A.

# NOVEMBER 1990

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 1.82 m | 1.38 m |
| **Mean ice draft** | 2.42 m | 2.19 m |
| **Standard deviation** | 2.14 m | 2.11 m |
| **Maximum ice draft** | 16.98 m | 19.98 m |
| **Open water** | 25.05 % | 37.00 % |
| **Missing values** | 0.06 % | 0.04 % |



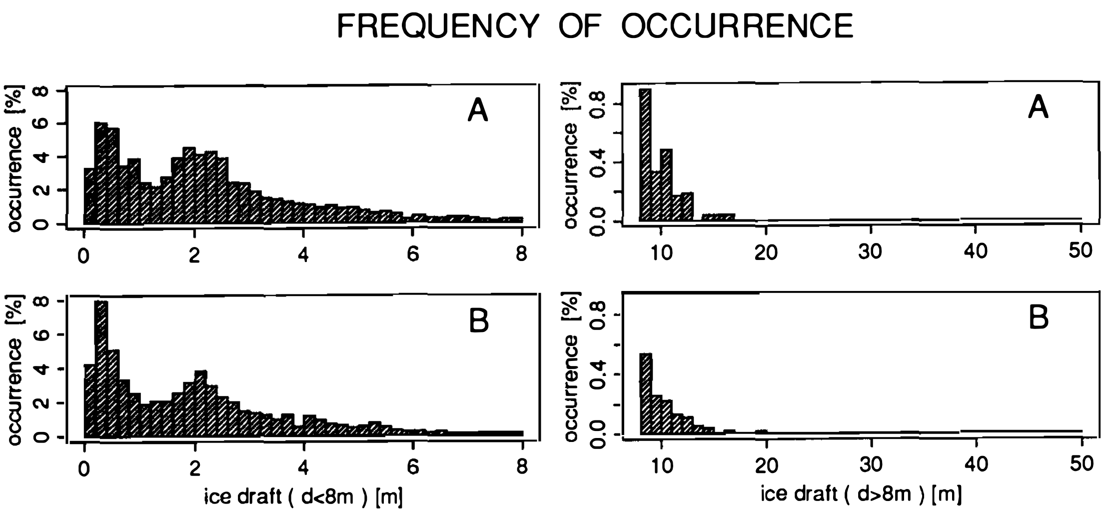
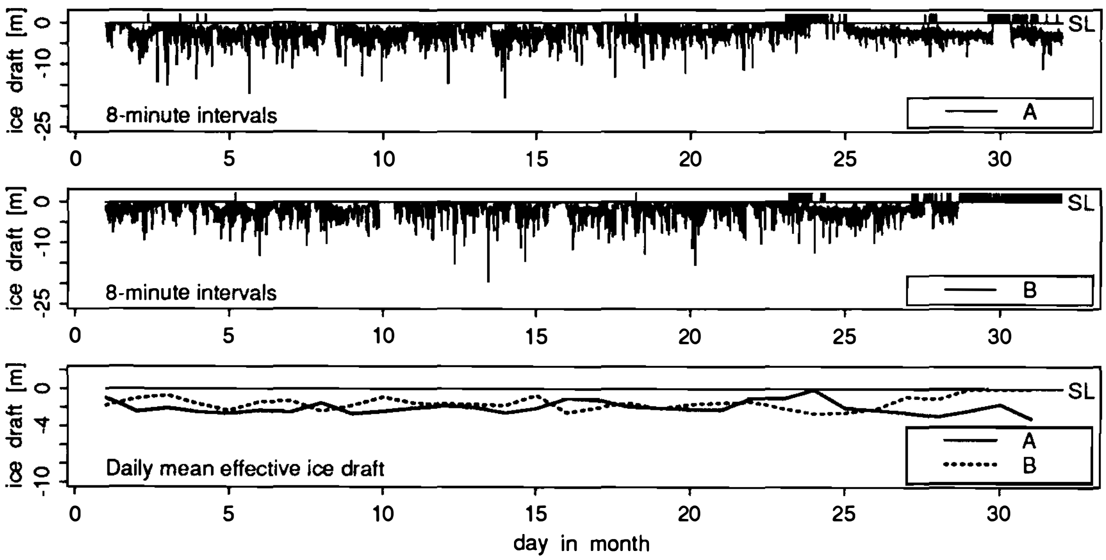




Fig. A12. Ice draft measurements. See Introduction to Appendix A.

# DECEMBER 1990

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.01 m | 1.53 m |
| **Mean ice draft** | 2.36 m | 2.13 m |
| **Standard deviation** | 1.70 m | 1.73 m |
| **Maximum ice draft** | 17.96 m | 19.31 m |
| **Open water** | 14.76 % | 28.03 % |
| **Missing values** | 2.49 % | 4.28 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

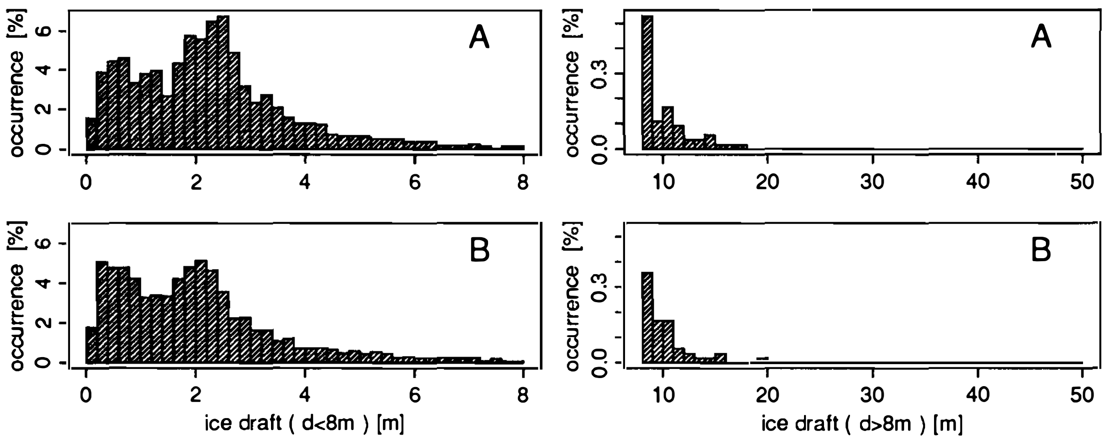
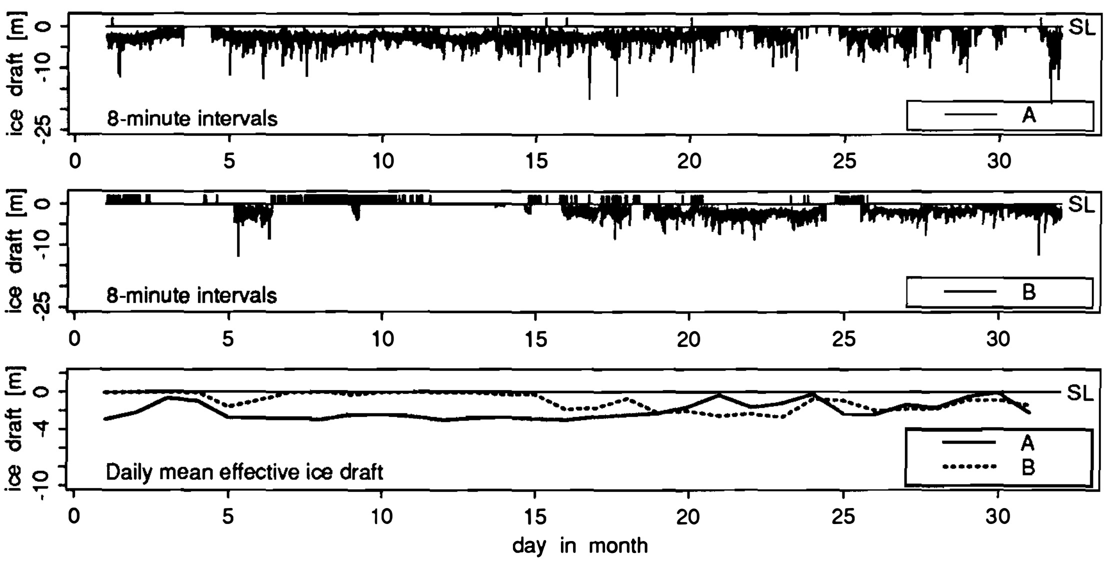



Fig. A13. Ice draft measurements. See Introduction to Appendix A.

# JANUARY 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.03 m | 1.00 m |
| **Mean ice draft** | 2.46 m | 1.95 m |
| **Standard deviation** | 1.52 m | 1.13 m |
| **Maximum ice draft** | 18.45 m | 12.70 m |
| **Open water** | 17.65 % | 48.74 % |
| **Missing values** | 0.11 % | 6.38 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

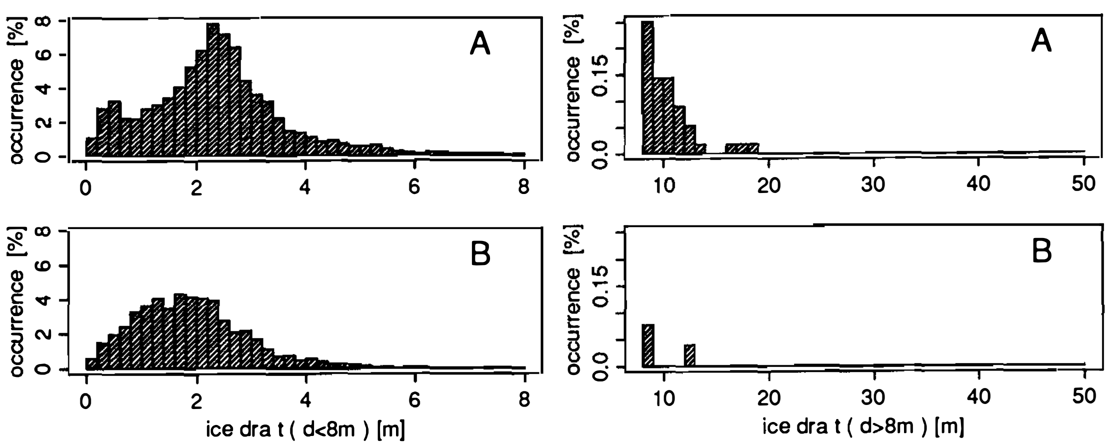
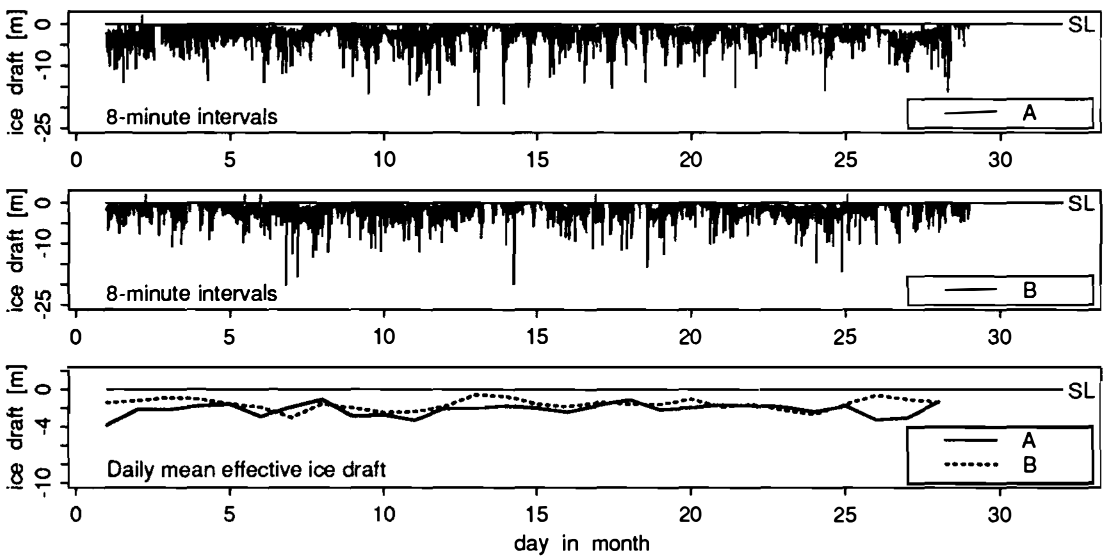



Fig. A14. Ice draft measurements. See Introduction to Appendix A.

# FEBRUARY 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.14 m | 1.58 m |
| **Mean ice draft** | 2.55 m | 2.04 m |
| **Standard deviation** | 2.18 m | 1.85 m |
| **Maximum ice draft** | 19.36 m | 20.08 m |
| **Open water** | 15.90 % | 22.76 % |
| **Missing values** | 0.02 % | 0.10 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

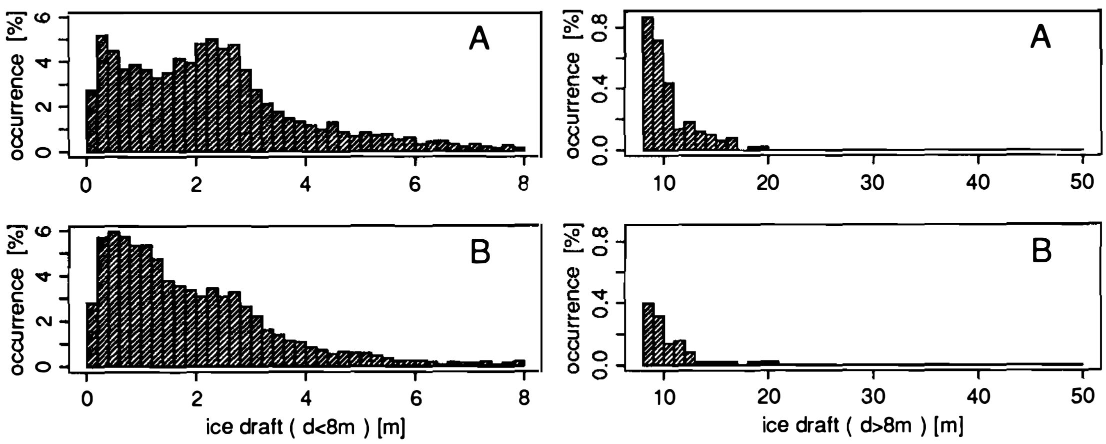
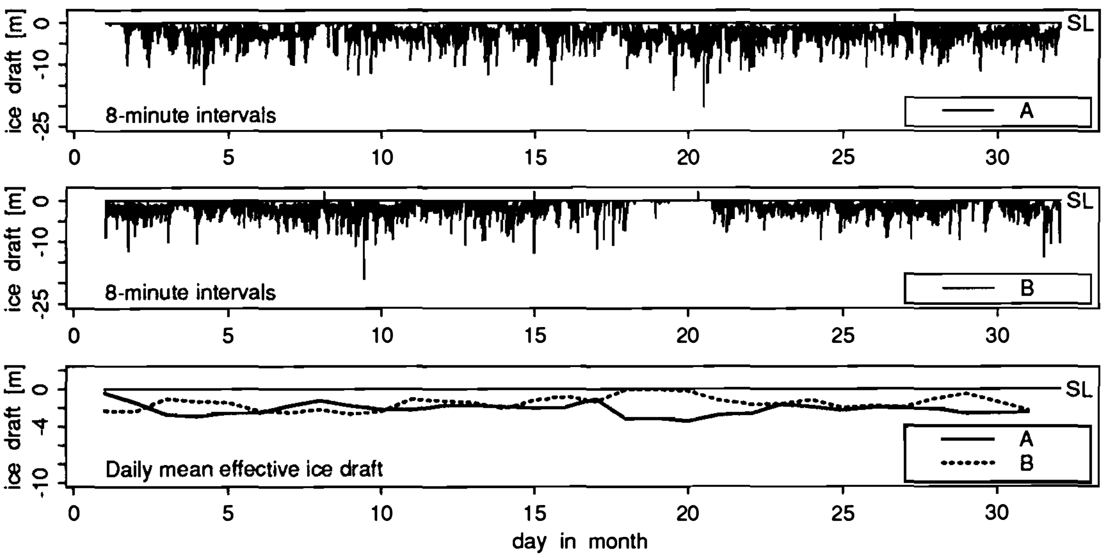



Fig. A15. Ice draft measurements. See Introduction to Appendix A.

# MARCH 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.16 m | 1.50 m |
| **Mean ice draft** | 2.49 m | 1.93 m |
| **Standard deviation** | 1.89 m | 1.61 m |
| **Maximum ice draft** | 20.26 m | 19.07 m |
| **Open water** | 13.30 % | 22.04 % |
| **Missing values** | 0.02 % | 0.05 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

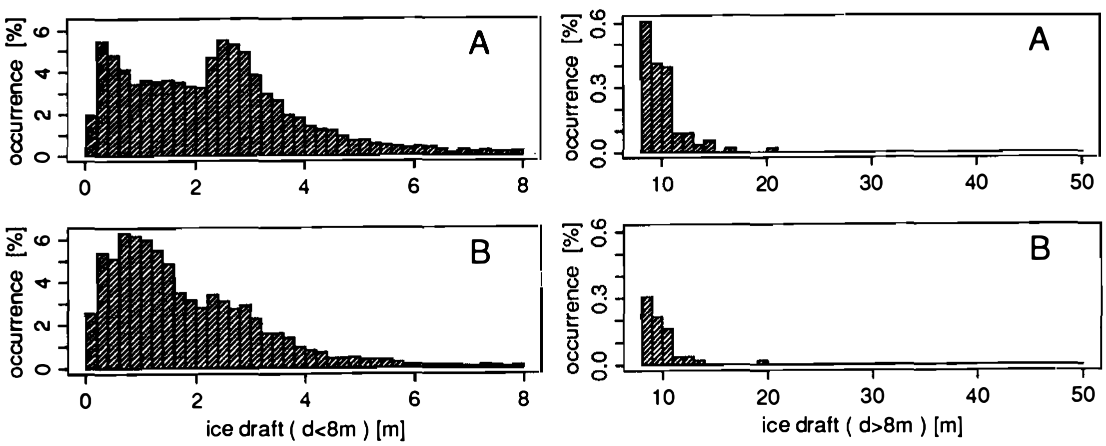
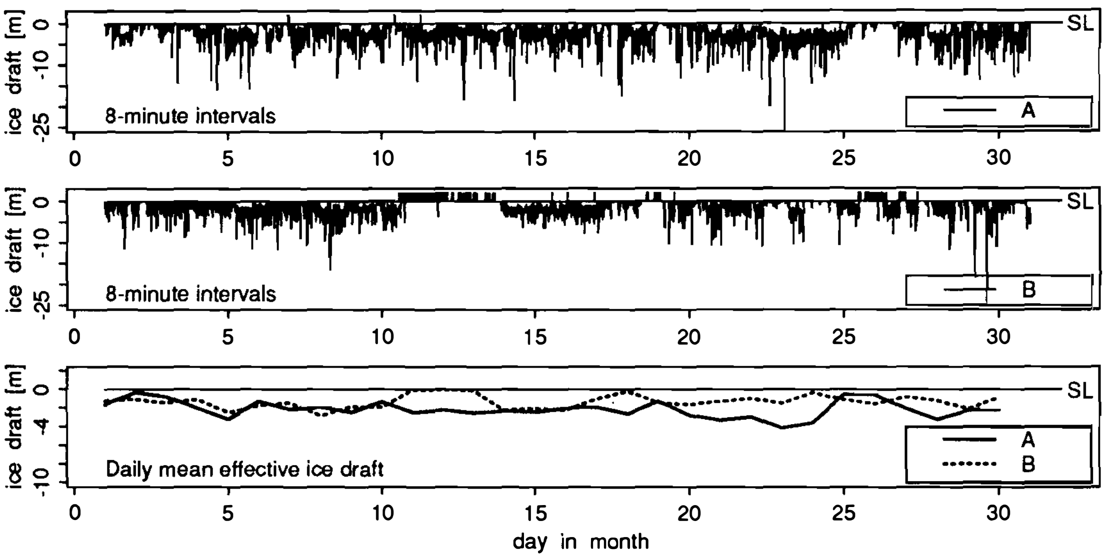



Fig. A16. Ice draft measurements. See Introduction to Appendix A.

# APRIL 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.14 m | 1.33 m |
| **Mean ice draft** | 2.67 m | 2.07 m |
| **Standard deviation** | 2.16 m | 1.78 m |
| **Maximum ice draft** | 27.68 m | 24.14 m |
| **Open water** | 20.00 % | 35.58 % |
| **Missing values** | 0.07 % | 4.28 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

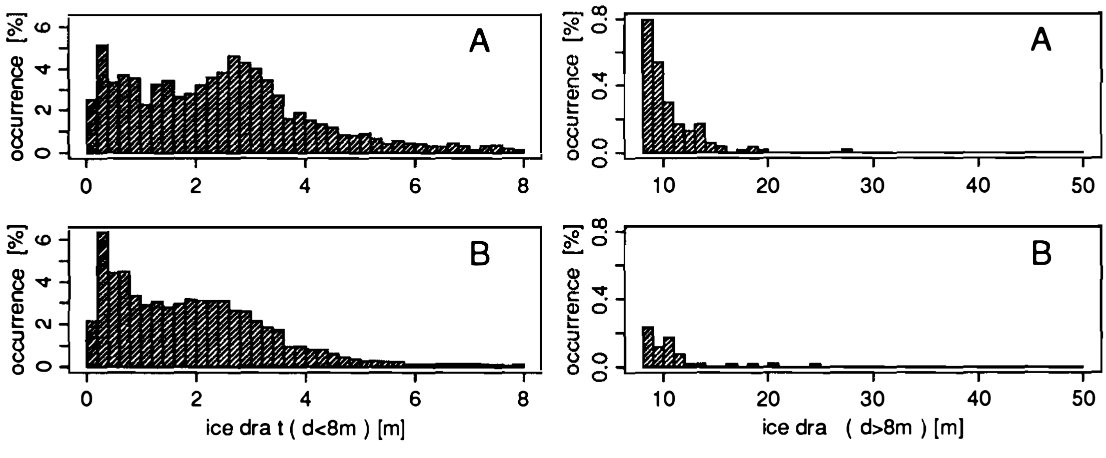
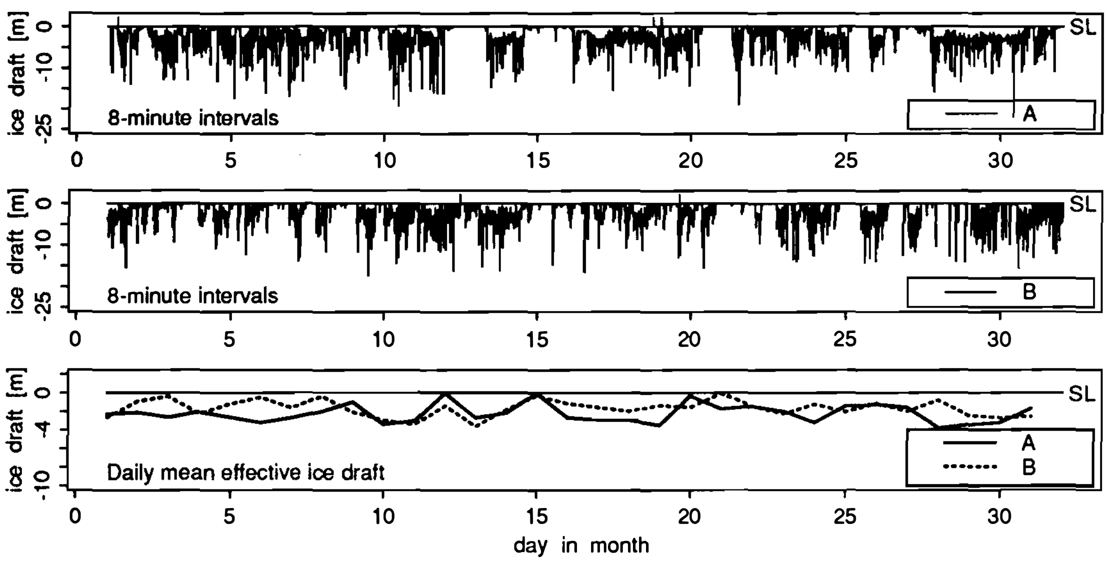



Fig. A17. Ice draft measurements. See Introduction to Appendix A.

# MAY 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.21 m | 1.65 m |
| **Mean ice draft** | 3.08 m | 2.89 m |
| **Standard deviation** | 2.43 m | 2.44 m |
| **Maximum ice draft** | 21.89 m | 17.37 m |
| **Open water** | 28.23 % | 42.94 % |
| **Missing values** | 0.07 % | 0.04 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

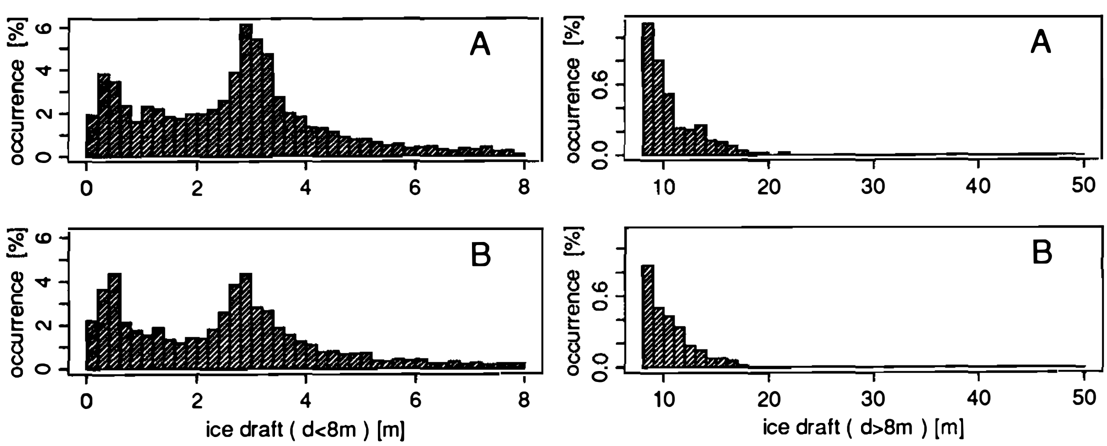
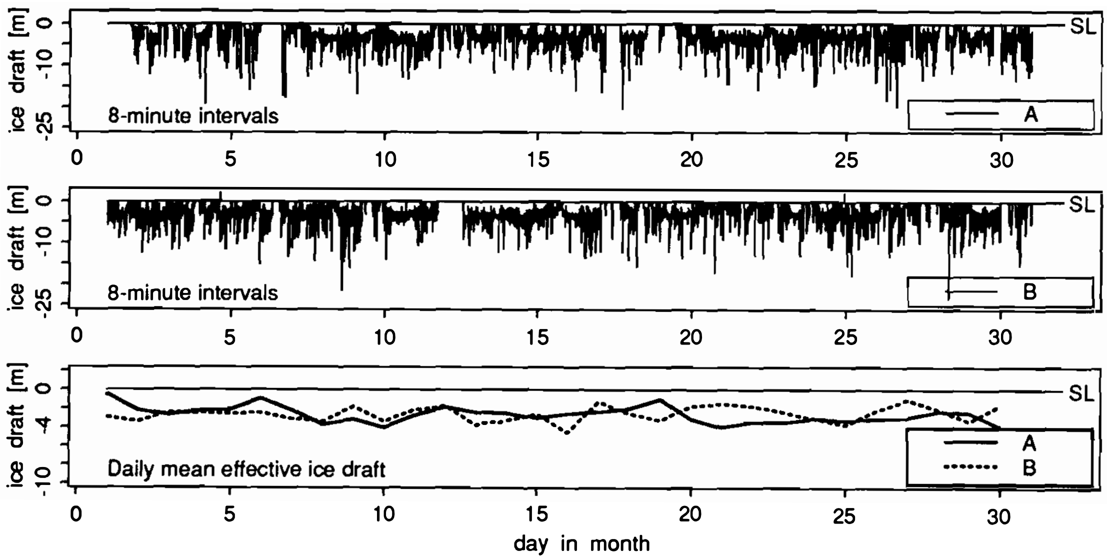



Fig. A18. Ice draft measurements. See Introduction to Appendix A.

# JUNE 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.63 m | 2.57 m |
| **Mean ice draft** | 3.52 m | 3.40 m |
| **Standard deviation** | 2.26 m | 2.24 m |
| **Maximum ice draft** | 20.25 m | 23.18 m |
| **Open water** | 25.30 % | 24.57 % |
| **Missing values** | 0.00 % | 0.04 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

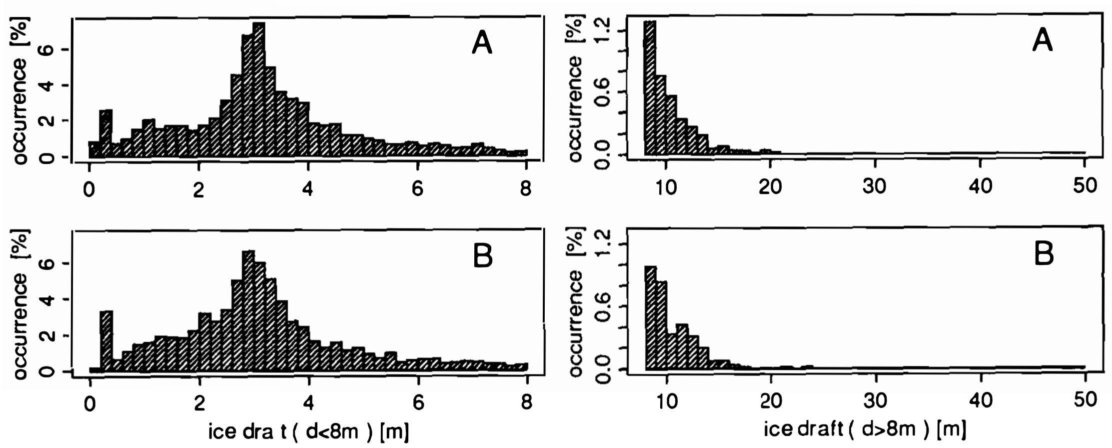
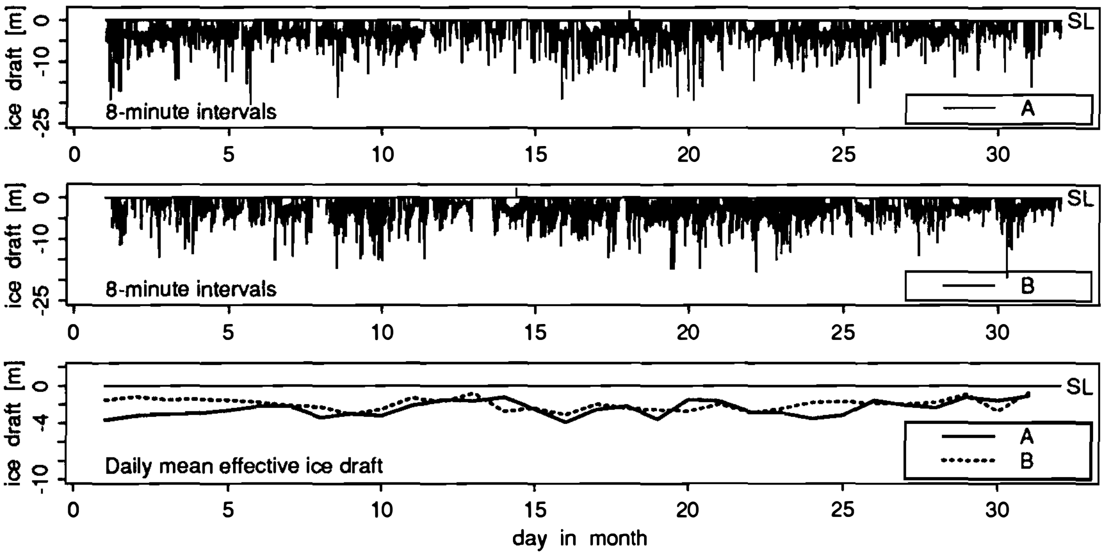



Fig. A19. Ice draft measurements. See Introduction to Appendix A.

# JULY 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 2.46 m | 1.98 m |
| **Mean ice draft** | 3.52 m | 3.48 m |
| **Standard deviation** | 2.40 m | 2.26 m |
| **Maximum ice draft** | 20.40 m | 19.43 m |
| **Open water** | 30.11 % | 43.04 % |
| **Missing values** | 0.02 % | 0.02 % |

ICE DRAFT MEASUREMENTS




FREQUENCY OF OCCURRENCE

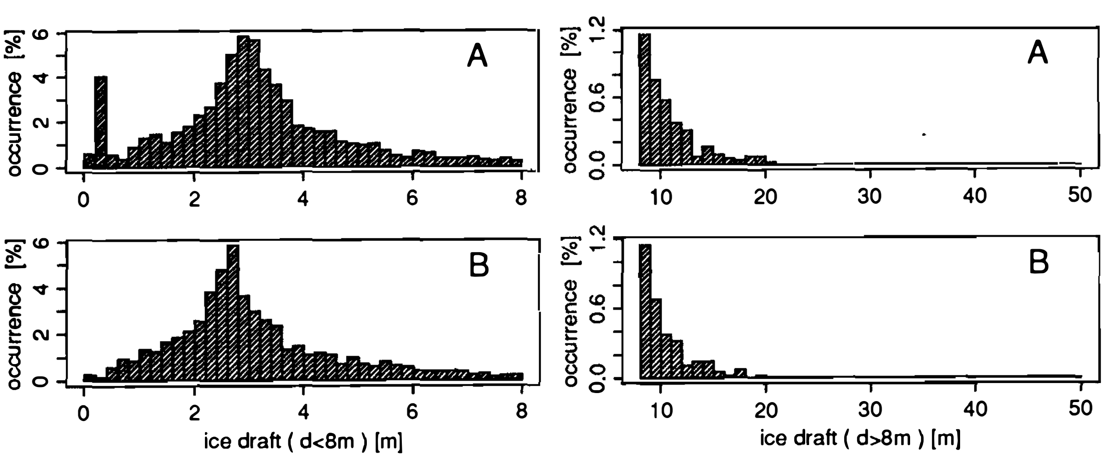
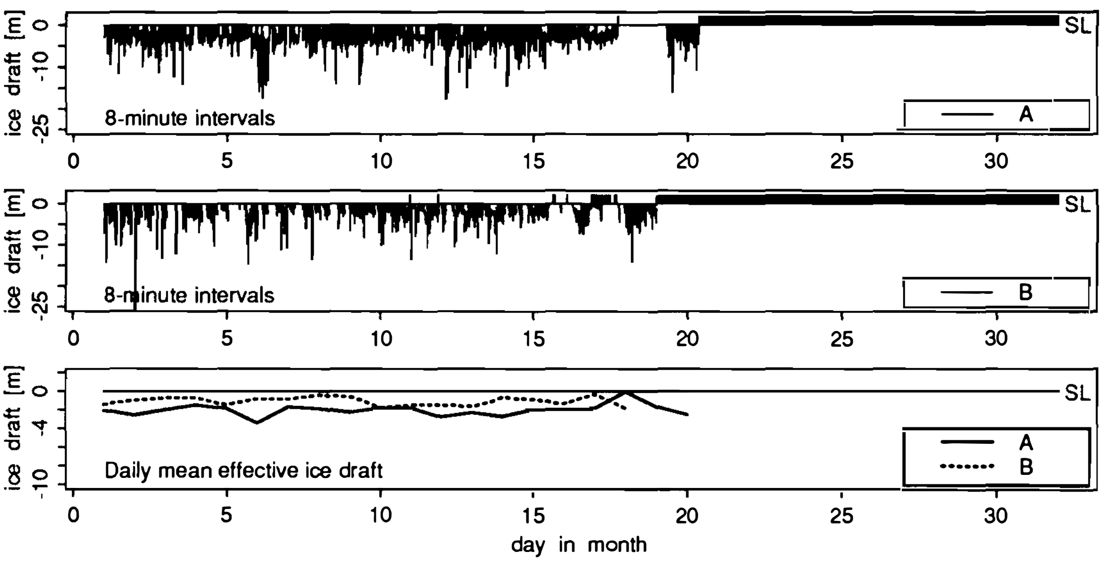



Fig. A20. Ice draft measurements. See Introduction to Appendix A.

# AUGUST 1991

| | st. A | st. B |
|---|---|---|
| **Latitude** | N 79°13' | N 78°02' |
| **Longitude** | W 3°17' | W 4°47' |
| **Effective ice draft** | 1.98 m | 1.06 m |
| **Mean ice draft** | 3.15 m | 3.06 m |
| **Standard deviation** | 2.06 m | 2.10 m |
| **Maximum ice draft** | 17.75 m | 29.47 m |
| **Open water** | 37.00 % | 65.29 % |
| **Missing values** | 37.47 % | 42.38 % |

## ICE DRAFT MEASUREMENTS




## FREQUENCY OF OCCURRENCE

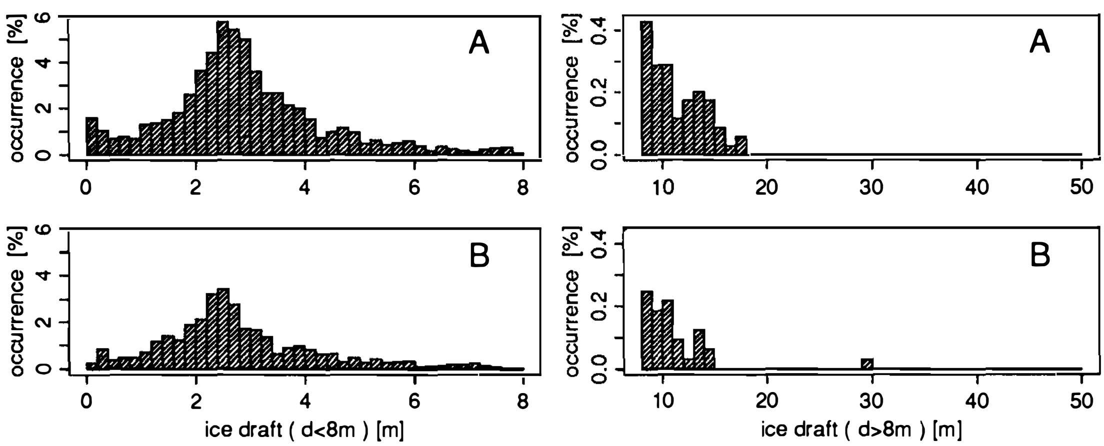
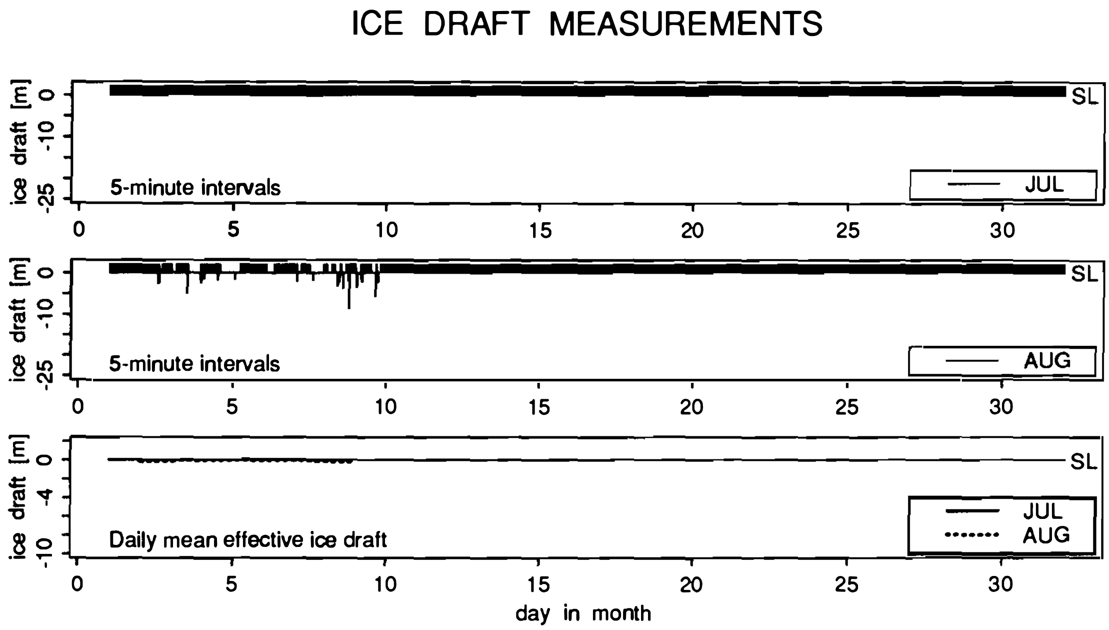



Fig. A21. Ice draft measurements. See Introduction to Appendix A.

# JULY - AUGUST 1991

| | JUL | AUG |
|---|---|---|
| **Latitude** | N 79°27' | N 79°27' |
| **Longitude** | E 30°16' | E 30°16' |
| **Effective ice draft** | | 0.08 m |
| **Mean ice draft** | | 2.39 m |
| **Standard deviation** | | 1.54 m |
| **Maximum ice draft** | | 8.58 m |
| **Open water** | | 96.77 % |
| **Missing values** | 100.00 % | 86.46 % |



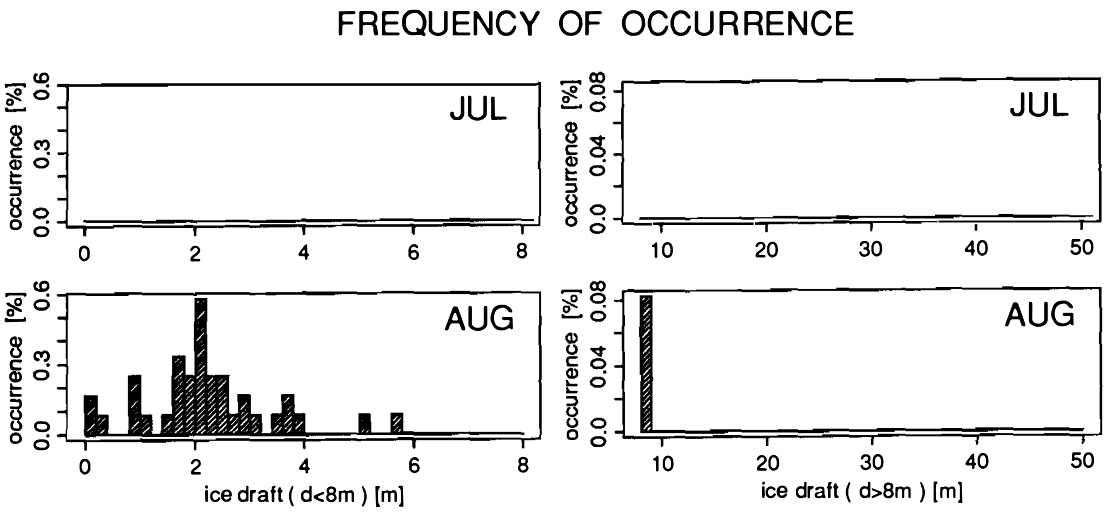




Fig. A22. Ice draft measurements. See Introduction to Appendix A.

GCS A/S, Oslo