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TECHNICAL REPORT

VARIABILITY IN THE MIXED LAYER DEPTH NEAR THE POLAR FRONT

William J. Teague
Ortwin H. von Zweck
Physical Oceanography Branch

OCEAN MEASUREMENTS PROGRAM

APRIL 1982

PREPARED BY
COMMANDING OFFICER,
NAVAL OCEANOGRAPHIC OFFICE
NSTL STATION, BAY ST. LOUIS, MS 39522

PREPARED FOR
COMMANDER
NAVAL OCEANOGRAPHY COMMAND
NSTL STATION, BAY ST. LOUIS, MS 39529

FOREWORD

This report describes in detail the temporal and spatial variability of the surface mixed layer depth in the Norwegian Sea and Iceland-Faeroe frontal area during the 1980 fall transition period. Detailed knowledge of mixed layer depth variability on scales unobtainable from historical data is critical in addressing Ocean Measurements Program requirements for characterizing the upper ocean environment. A subsequent report for this area is underway for the spring season. Similar analyses addressing these upper ocean environmental characteristics will be performed for other areas of principal interest to the Ocean Measurements Program.

C. H. BASSETT
Captain, USN
Commanding Officer

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
TR287

2. GOVT ACCESSION NO.
AD A111 154

3. RECIPIENT'S CATALOG NUMBER

4. TITLE *(and Subtitle)*
Variability in the Mixed Layer Depth near the Polar Front

5. TYPE OF REPORT & PERIOD COVERED
Technical Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
William J. Teague
Ortwin von Zweck

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Oceanographic Office
NSTL Station
Bay St. Louis, MS 39522

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE
April 1982

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*

15. SECURITY CLASS. *(of this report)*
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
Mixed Layer, Polar Front, Norwegian Current, Norwegian Sea, Mixed Layer Depth Definition, Fronts

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
The depths of the surface mixed layer are estimated for the fall season in the Norwegian Sea and the Iceland-Faeroe Gap areas using definitions of mixed layer depth based on temperature and Brunt-Vaisala frequency. Variability in the mixed layer depth was found to be both seasonally and regionally dependent. Differences between definitions occurred primarily in the frontal regions. As fall progressed, the mixed layer deepened more rapidly in the weakly stratified frontal regions than outside of those regions.

Acknowledgements

Special thanks are extended to Dr. Zachariah Hallock for his helpful suggestions and critical review. The illustrations were prepared by Donna Waters, who also assembled the report for publication. The final manuscript was typed by Donna Skipper.

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INTRODUCTION

Surface layers of the ocean are subjected to atmospheric events and other forces which result in a homogeneous layer, the surface mixed layer, overlying deeper layers which exhibit structure in temperature and salinity. The thickness of this surface mixed layer, the mixed layer depth (MLD), is of importance to the processes active in the upper ocean and is thus often used to characterize the upper ocean.

The mixed layer depth is affected on a large spectrum of temporal and spatial scales by heating and cooling (Kraus and Turner, 1967) and wind stress (Pollard and Millard, 1970). The response to wind stress is a downward stirring of energy which leads to a deepening of the mixed layer, with the base of the mixed layer often undulating, propagating internal waves. Deepening of the mixed layer has been investigated in a number of studies of the upper ocean (Niiler, 1975; Pollard, Rhines and Thompson, 1973).

A high variability in MLD is often associated with local dynamic features such as oceanic fronts. This study examines the temporal and spatial variability of the MLD near the front between Iceland and the Faeroes (Polar Front) and the front found on the western edge of the Norwegian Current (Norwegian Current Front). The Polar Front (figure 1) is closely associated with the Iceland-Faeroe Ridge and is characterized by large horizontal temperature and salinity gradients, and by dynamic activity (Kort and Tarasenko, 1977). This front is known to meander and eddies have been found nearby (Hansen and Meincke, 1979). The Norwegian Current Front with its weaker salinity and temperature gradients (figure 2) is less well defined and is not associated with topographic features. Extensive meanders of the Norwegian Current Front have been reported by Kort and Tarasenko (1977). These two fronts, which are part of the polar frontal system, effectively separate the warmer, saltier Atlantic waters from the colder, fresher Arctic and Subarctic waters.

The mixed layer can be defined as an isopycnal layer, or as is more common, an isothermal layer, extending downward from the surface. The two definitions need not coincide. Temperature changes may compensate salinity changes and result in an isopycnal but not an isothermal mixed layer. In addition, small differences in the formulation of definition may result in large changes in MLD.

Molinelli, Donelson, and Lilly (1980) calculated mixed layer depths for the region of the Polar and Norwegian Current Front from SVSTD (Sound Velocity, Salinity, Temperature, and Depth) data for summer and fall. This was done using four definitions of MLD based on temperature, sound speed, density, and vertical stability (Brunt-Vaisala frequency). With the exception of the MLD dependent on vertical stability, which is very sensitive to noisy density profiles, the differences between mixed layer depths were found to be relatively independent of region and season. The largest change in MLD occured with the change of season while only slight regional dependence was found.

This study reexamines the mixed layer depth in the region of the polar frontal system using CTD (Conductivity, Temperature, and Depth) data from Fall 1980. Definitions of temperature and stability mixed layers are used and compared in describing the seasonal and geographical distribution of MLD. The results of the present study differ greatly from the results of the earlier study by Molinelli _et al_. (1980).

DATA

The CTD data used in this study were collected from September to November 1980 using a Neil Brown Instrument Systems, Inc. Mark III CTD. The locations of the CTD stations are shown in figure 3 (Teague, 1981). The mixed layer depths were calculated from measured temperature profiles and derived Brunt-Vaisala frequency profiles. The profiles were decimated to one meter vertically-spaced data and low-pass filtered, with a half-power point at ten meters, prior to deriving mixed layer depths.

For this analysis, the data were grouped by month and region. Three regions were identified in terms of temperature and salinity (TS) characteristics: south of the front, north of the front, and the frontal zone (figure 3). Composite TS curves for each of the regions for the September data are shown in figure 4.

The region south of the front is characterized by North Atlantic water (NA) near the surface and Arctic Intermediate water (AI) at depth (figure 4a). The gap observed in the TS diagram near 35.1 ppt and 6.0 deg C is due to a weak narrow front oriented approximately northeast-southwest, about 300 nautical miles southwest of the Faeroes. The transition into the frontal zone from the south is marked by a noticeable change in the TS characteristics at depth.

The 100 nautical mile wide frontal zone is marked by a gradual, continuous transition in water mass from south to north indicated by the composite TS curves in figure 4b. The transition from the frontal zone to the region north of the front occurs abruptly, over a distance of about 5 nautical miles. In terms of water-mass characteristics the region north of the Polar Front is dramatically different from that south of the front. The northern region (figure 4c) is dominated by the East Icelandic Current (EIC) near the surface, North Icelandic Winter (NIW) and Arctic Intermediate Water at depth, and Norwegian Sea Deep Water (NS) near the bottom.

METHODS

The following two definitions of mixed layer depth are used in this study:

1. Temperature Mixed Layer Depth (MLD(T))

This is the depth at which the absolute value of the temperature gradient exceeds 0.005 deg C/m and at which the temperature differs by at least 0.15 deg from the temperature measured at the top of the profile, usually at 5 to 10 meters in depth.

2. Stability Mixed Layer Depth (MLD(N))

This is the depth at which the Brunt-Vaisala frequency, N, exceeds a selected threshold, N_0, chosen at 2 cph for this analysis. Surface skin layers with an initial value of N exceeding the threshold are disregarded. In case of multiple relative maxima in N, such as found in a double pycnocline, the first occurence of the threshold determines MLD(N).

Another measure of stratification used in this analysis is NMAX, the value of the first relative maximum in N exceeding N_0. Normally this value corresponds to the absolute maximum of N, often occurring just below the mixed layer. For profiles in which the Brunt-Vaisala frequencies do not exceed the threshold N_0, the threshold needs to be reexamined. The choice of an appropriate value for N_0 depends upon the stratification of the area considered. In areas of high vertical stability a larger value of N_0 may be chosen.

With the exception of the frontal zone, the stability mixed layer depths in this study were relatively insensitive for N_0 between 2 and 7 cph. The stratification in the frontal zone was weak with a Brunt-Vaisala frequency maximum often less than 3 cph. A 2-cph threshold fell within the range of N for all but one profile.

DISCUSSION

Mixed layer depths were calculated using the above definitions for all CTD stations collected in Fall 1980. Representative vertical sections of MLD(N), MLD(T), and NMAX are presented for a number of transects (figure 3) through the fronts in figures 5 and 6. The sections between Iceland and the Faeroes include section IA from September (figure 5a), sections IIA and IIB in October (figures 5b and 5c), and section IIIB in November (figure 6c). The sections in and near the Norwegian Current Front are section IIC in October (figure 6a) and section IIIA in November (figure 6b).

A contour section of the Brunt-Vaisala frequency for transect IA from September (figure 7) illustrates the stratification encountered in the North Atlantic and Norwegian Sea across the Polar Front. The shallowest 2-cph contour shows the general deepening of the stability mixed layer depth to the south. This deepening is also evident for MLD(N) and MLD(T) in figure 5a. The reduced vertical stability in the frontal zone indicated in figure 7 is also reflected in the low values of NMAX in figure 5a.

In the frontal zone significantly deeper mixed layers are indicated by the October and November sections (figures 5b, c, 6a, b, c). For the three months, the poorest agreement between the two definitions of MLD and the lowest values of NMAX occurred in the frontal zones.

Mean mixed layer depths were computed from all stations for each region and month, using both the temperature and stability definitions of mixed layer depth (figure 8a). The two definitions produced similar mixed layer depths except in the frontal zone during November. Mean mixed layer depth did not change appreciably among regions during September. In October and November, the mixed layer deepened rapidly everywhere but more so in the frontal zone. The mean MLD was deeper in the frontal zone than north of the frontal zone by more than 50 m in October and by more than 100 m in November.

The stability of the vertical structure, as described by the mean value of NMAX, decreased north of the front and within the front from September to November, while the uniformity within these areas, as indicated by the standard deviation of NMAX, increased during this time frame (figure 8b). A similar situation is expected to occur south of the front but insufficient data from this area preclude a conclusion. The mean values of NMAX and their standard deviations for the three regions over the entire three month period, given in Table I, again show a lower vertical stability in the frontal zone.

A horizontal section of the stability mixed layer depth from the CTD grid in the northern portion of the frontal zone is shown in figure 9. The deepening of the mixed layer into the frontal zone to the south is again evident.

SUMMARY AND CONCLUSION

The definitions of mixed layer depth work well in regions characterized by large vertical gradients in temperature or density. For these conditions, the MLD is relatively insensitive to definition or to the choice of threshold values. Good agreement between the MLD(N) and MLD(T) is obtained when the density structure is controlled by temperature, and the pycnocline and thermocline coincide as is the case for most of the area north and south of the frontal zone (figure 10a). In regions of weak vertical stratification, as was encountered in the frontal zone (figure 10b), the mixed layer depth is very sensitive to the mixed layer definition and the choice of thresholds. The large differences in MLD(N) and MLD(T) result from the separation of the pycnocline and thermocline.

During September, the mean mixed layer depth was independent of region, in agreement with the findings of Molinelli _et al_. (1980). However, the mean mixed layer deepened significantly from September to November both inside and outside of the frontal zone with a larger increase in mean mixed layer depth inside the frontal zone (figure 8). During October and November the frontal zone also exhibited a larger scatter of mixed layer depths than was encountered outside the frontal area.

The frontal zone is also characterized by a consistent low vertical stability, as indicated by the mean NMAX, from September to November. The stability in the Norwegian Sea decreases from its initial high value in September to an observed low in November.

In the frontal region between Iceland and the Faeroes, the surface manifestation of the front, on the northern extremity of the frontal zone, is readily discernable by surface temperatures and temperature gradients (0.5 to 1.0 deg C over one nautical mile). A temperature difference of this magnitude can be determined not only from ship and aircraft measurements, but also from satellite measurements. South of the surface front, the broader subsurface front is not easily defined by temperature alone. A temperature-salinity relationship is needed for a complete description of the front.

In using the results of this analysis in other studies, such as those involving internal wave and acoustical propagation, it must be kept in mind that the depth of the mixed layer is difficult to categorize and to predict. Weather conditions and local surface forcing can rapidly and significantly affect the MLD. Furthermore, as shown by Simpson and Paulson (1979), horizontal advection and other near-surface changes in salinity and temperature unassociated with local surface forcing affect the mixed layer depth.

TABLE I

AREA	MEAN NMAX ± STANDARD DEVIATION	NO. OF OBSERVATIONS
North of Frontal Region	9.1 ± 2.9	58
Frontal Region	3.7 ± 1.4	61
South of Frontal Region	12.2 ± 1.9	16

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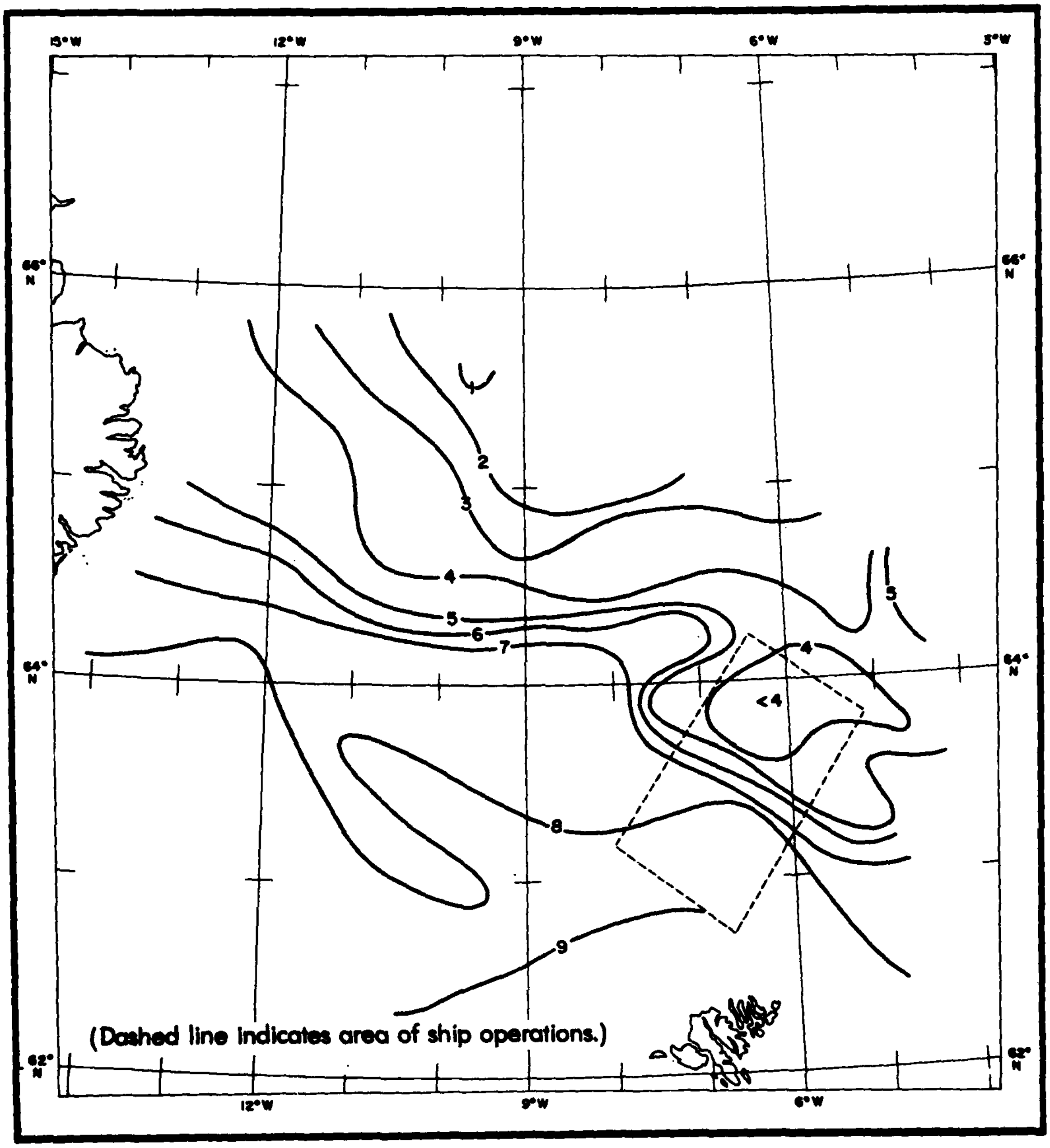


(Dashed line indicates area of ship operations.)

Figure 1 Temperature at 100 meters taken from an airborne expendable bathythermograph survey on 6 October 1980

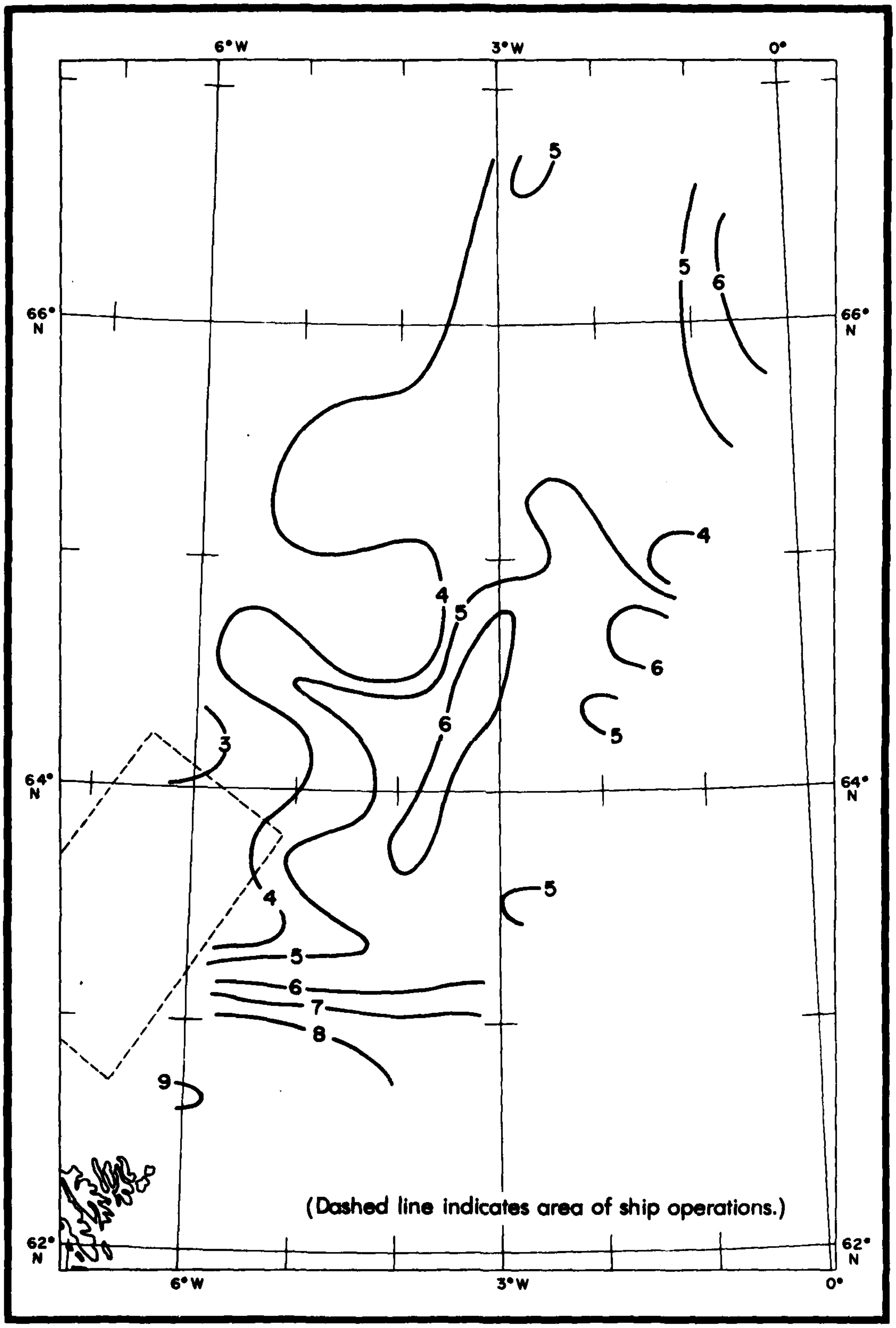


Figure 2 Temperature at 100 meters taken from an airborne expendable bathythermograph survey on 8 October 1980

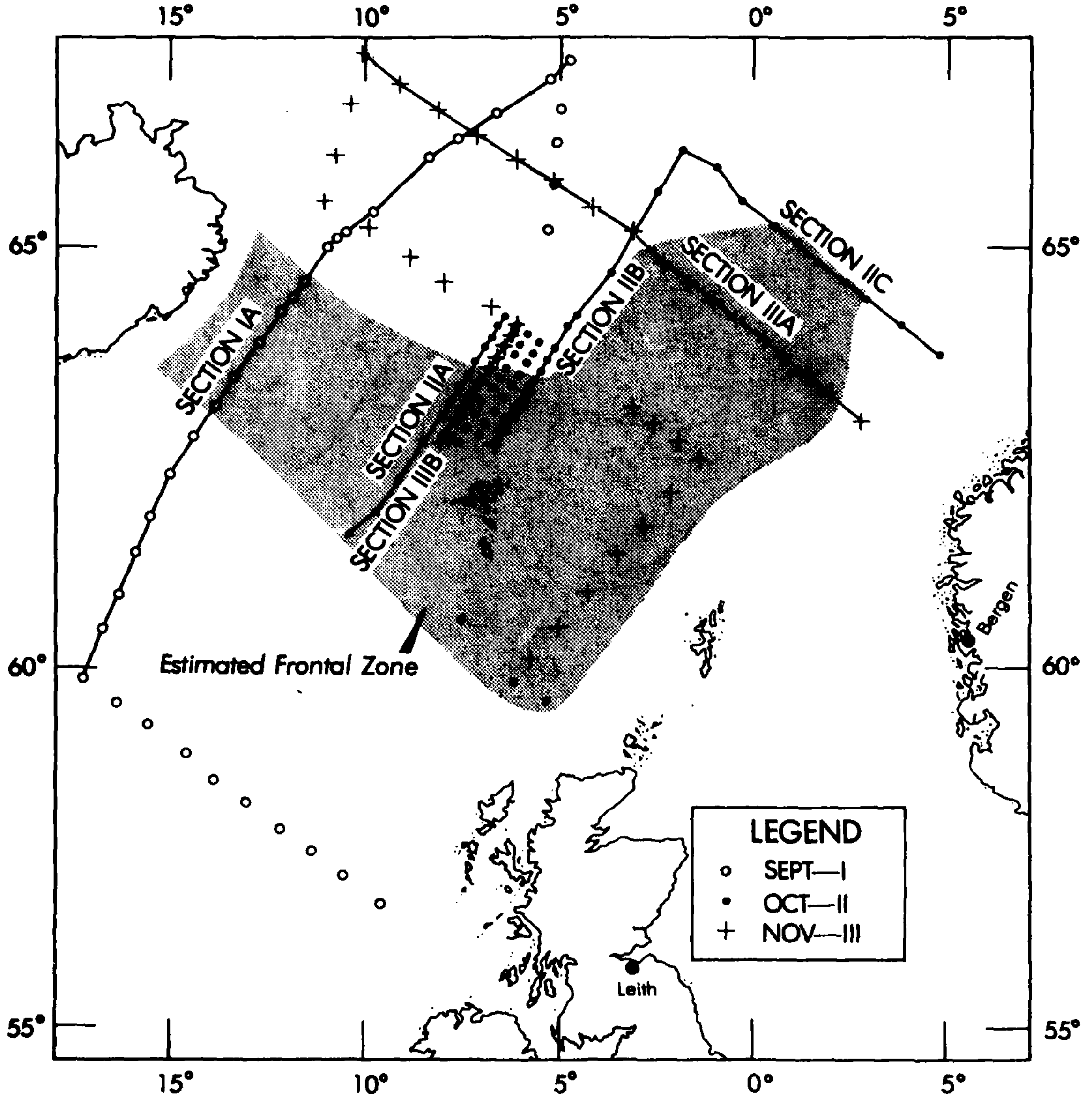
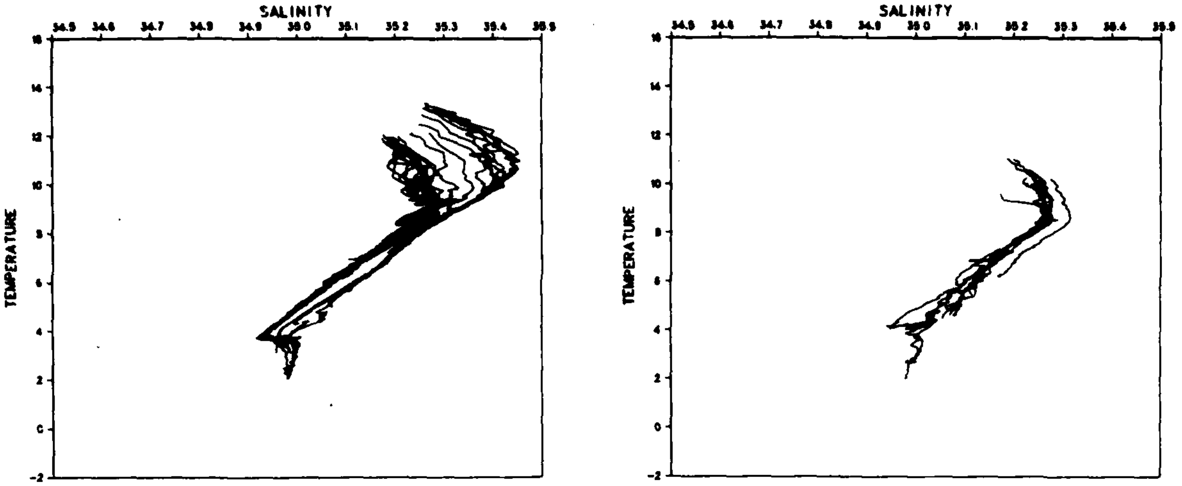
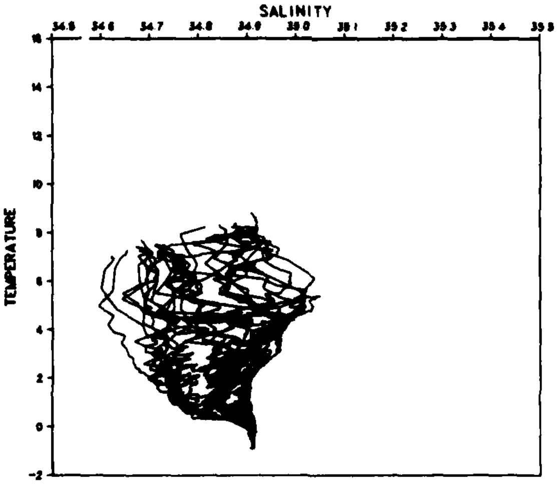


Figure 3 CTD station locations



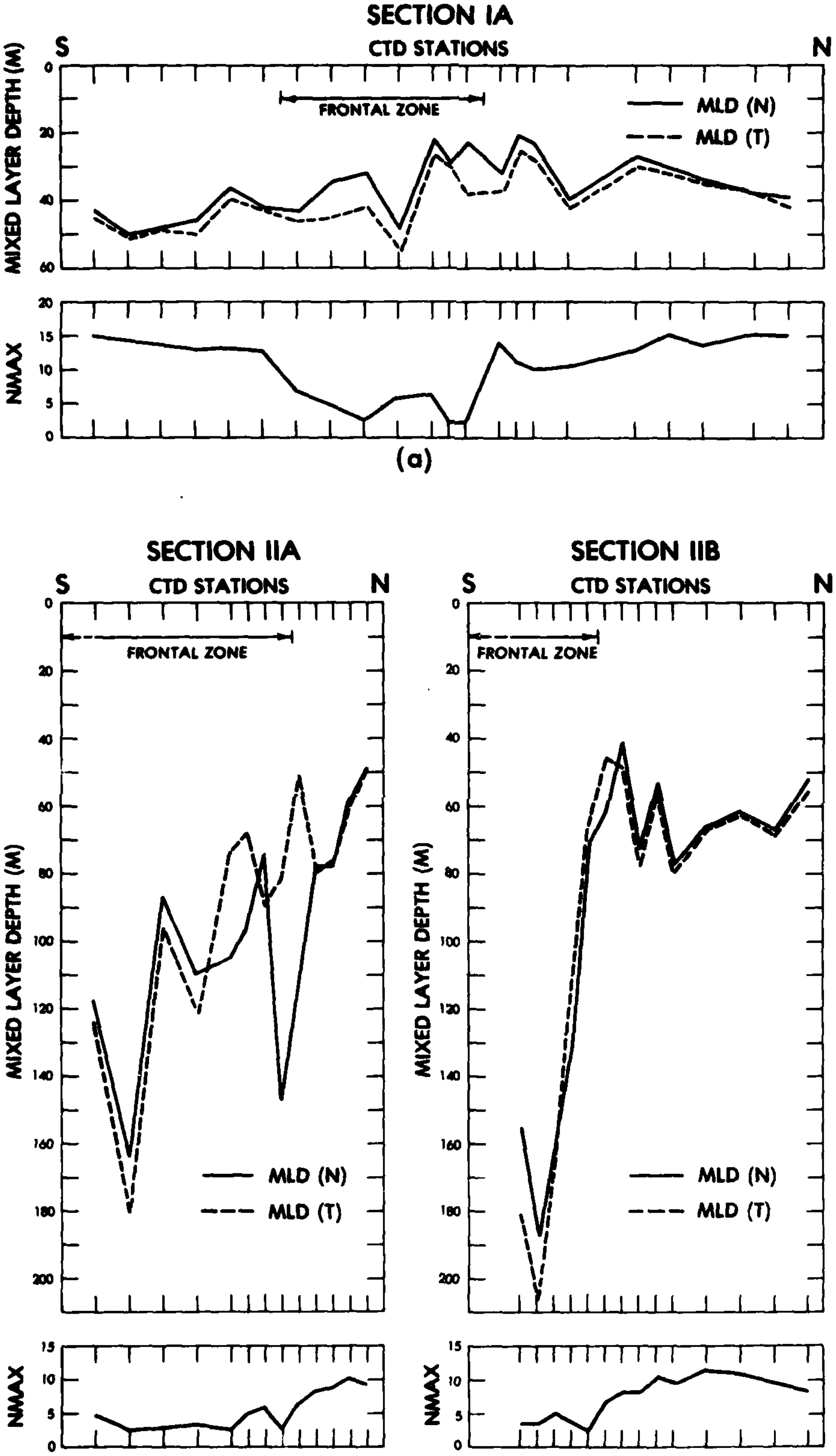
(a) South of frontal zone

(b) Frontal zone



(c) North of frontal zone

Figure 4 Composite Temperature-Salinity diagrams (September data)



(a)

(b)

(c)

Figure 5 Sections of mixed layer depth and NMAX across frontal regions

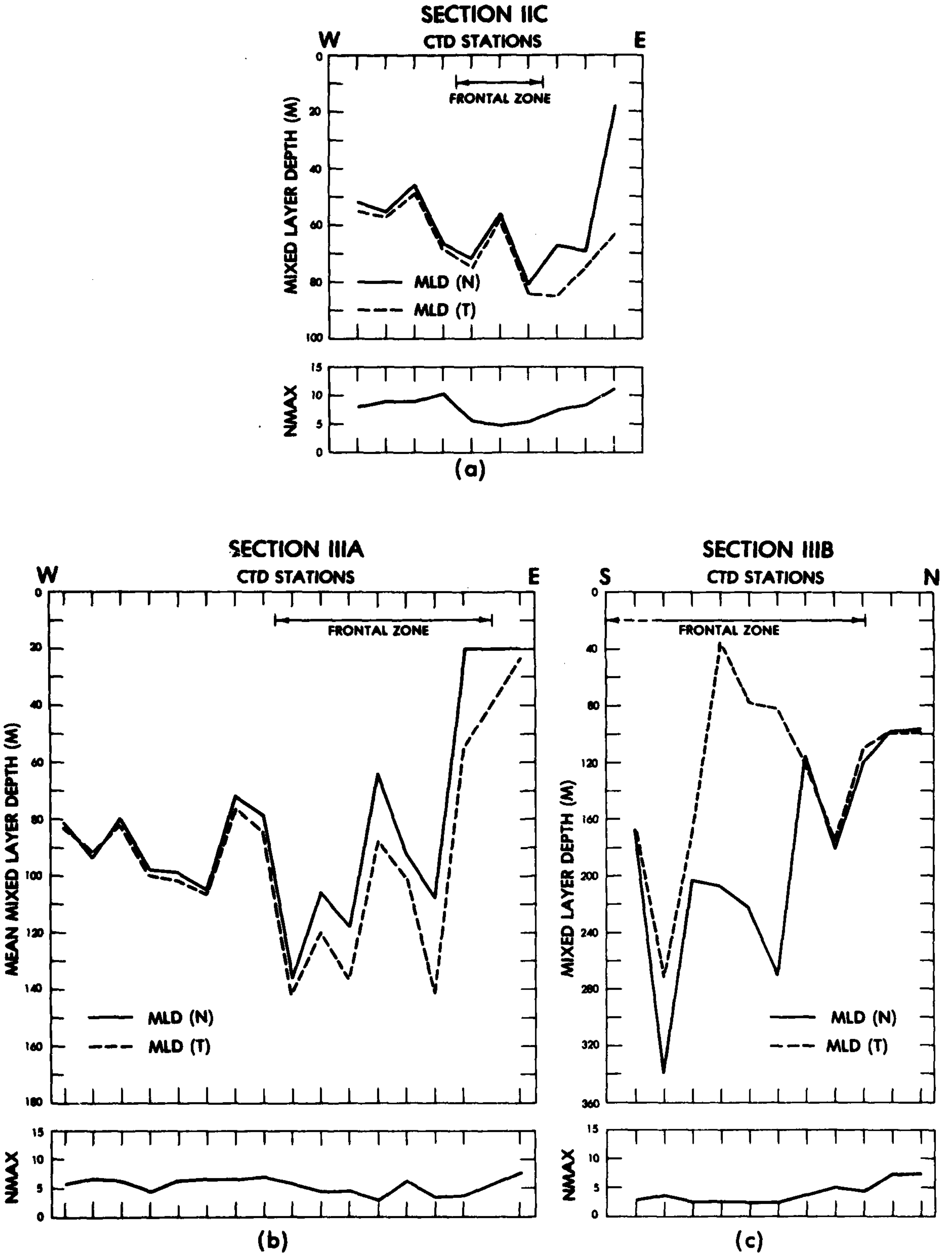


Figure 6 Sections of mixed layer depth and NMAX across frontal regions

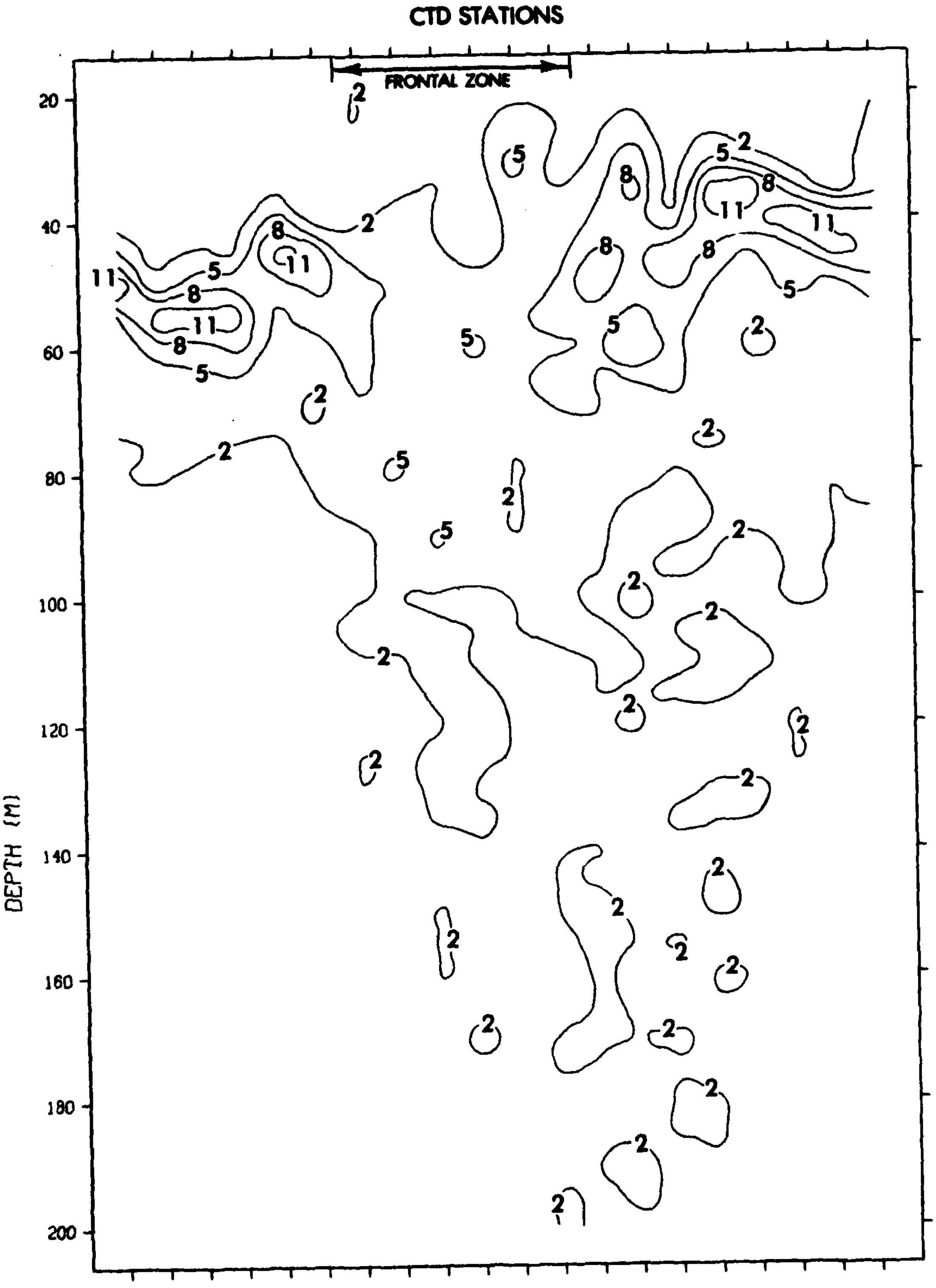


Figure 7 Contours of Brunt-Vaisala frequency for frontal crossing IA

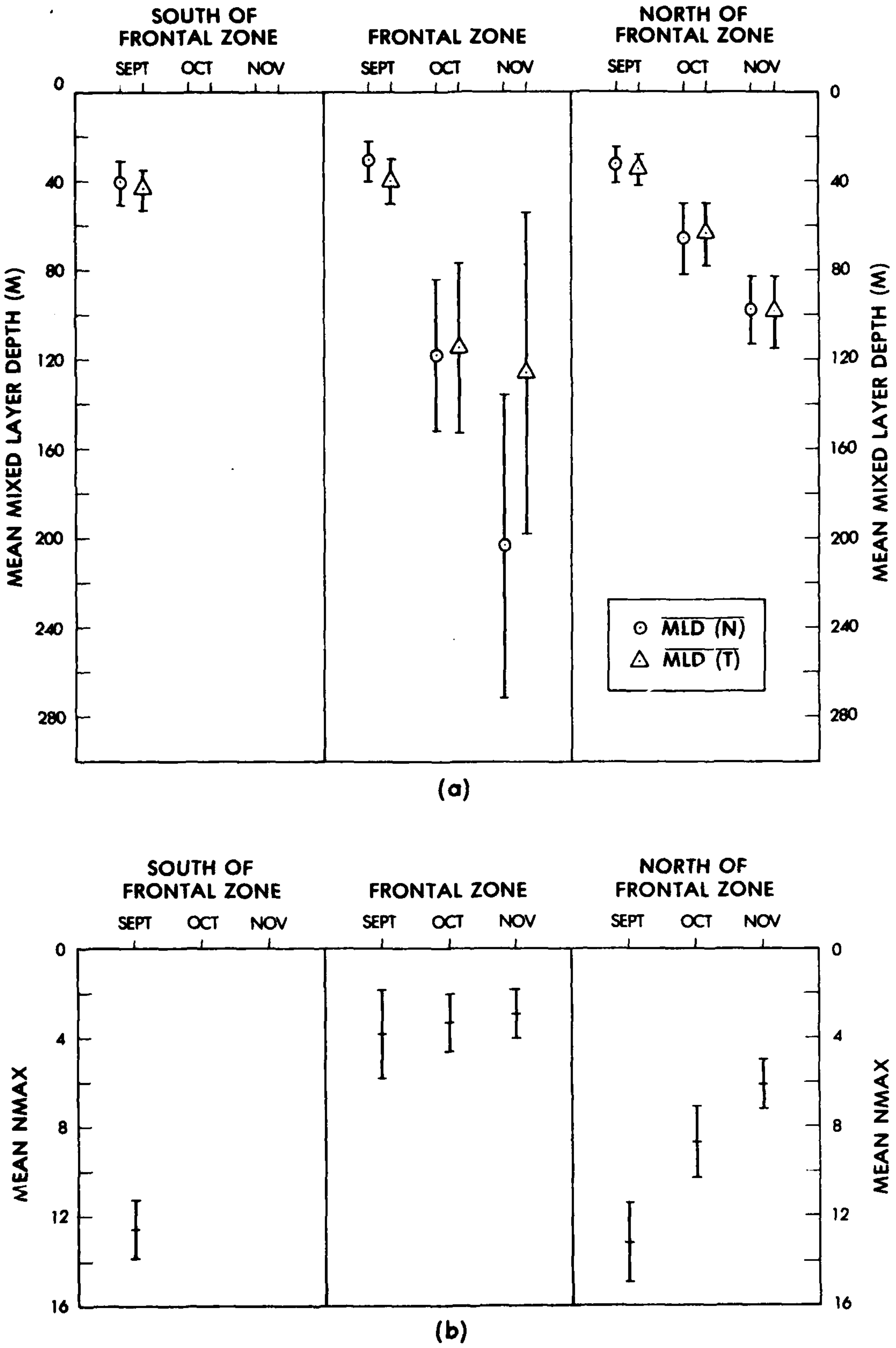


Figure 8 Mean mixed layer depths (a) and mean NMAX (b)

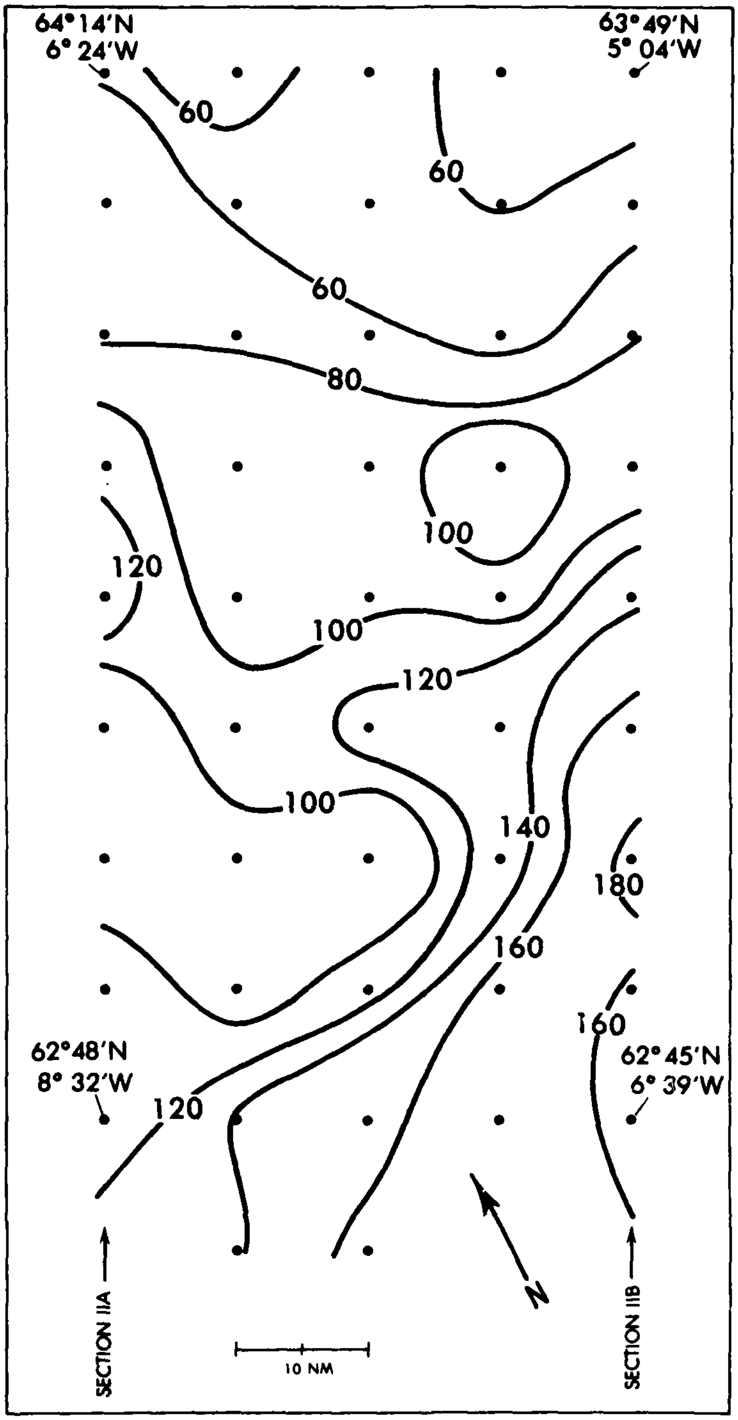
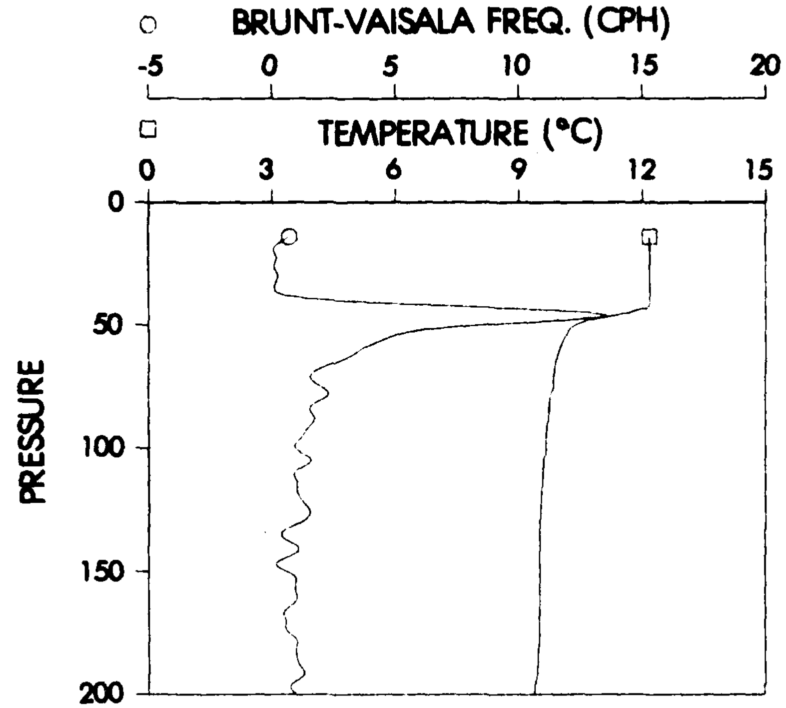
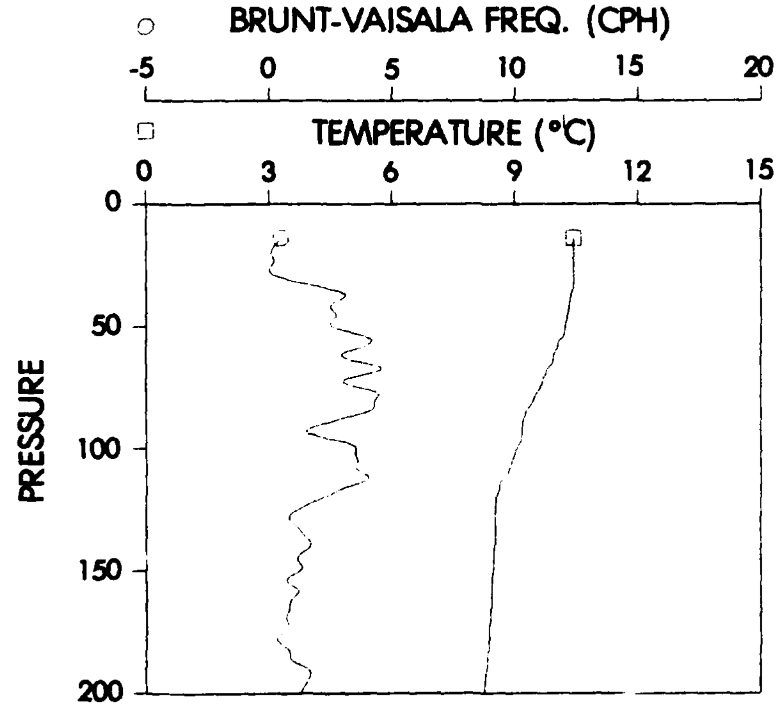


Figure 9 Horizontal map of mixed layer depth for October frontal crossings



(a) South of frontal region



(b) Frontal region

Figure 10 Typical profiles of Brunt-Vaisala frequency and temperature south of the frontal region (a) and in the frontal region (b)

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