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Theme Session on the North Atlantic
Components of Global Programmes

The North Atlantic Current and Polar Front revisited: the WOCE Control Volume Experiment in the Newfoundland Basin, 1993-1995

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Abstract

The region to the east of the Grand Banks of Newfoundland is characterized by bifurcations and retroflections of major current systems, loops and eddies, and extremely intense frontal zones. The Newfoundland Basin WOCE Control Volume experiment was carried out during 1993-1995 to provide better estimates of the transports and variability of these various currents. The experiment was built around a mooring array of eight moorings (45 current meters) which crossed the North Atlantic Current System at around 42 30 N. This array was in place from August, 1993 to May, 1995. While the array was in place, three major hydrographic / tracer surveys were carried out. The hydrographic lines were, for the most part, occupied along Topex/Poseidon ground tracks and divide the region into four closed boxes for budget calculations. The western North Atlantic was also ensonified during this period, and some 80 RAFOS floats were deployed on two different density surfaces in the main thermocline within the North Atlantic Current.

Introduction

Maps of the net air-sea heat flux such as those by Isemer and Hasse (1985), show that the region of maximum heat transfer associated with the Gulf Stream, turns northward near 45°W so that the 100 W m^{-2} isoline crosses 50°N. This feature results from the North Atlantic Current carrying warm salty waters from the Gulf Stream extension region that lies along 40°N, northward along the 4000 metre isobath of the continental rise east of the Grand Banks of Newfoundland.

These charts also show that the waters inshore of the Gulf Stream and the North Atlantic Current are gaining heat from the atmosphere. The pathway of the cold low salinity Arctic outflows are found over the shelves and slopes in currents such as the Labrador Current. Dickson *et al* (1988) interpretation of the North Atlantic transport scheme first proposed by Dietrich shows the convergence of the Arctic outflow and the North Atlantic Current east of the Grand Banks.

It is important in this region to look at the circulation on the shelf as well as in the offshore. The Labrador Current flows south along the edge of the Labrador shelf as a well defined current jet and density, temperature and salinity front. Its core is found near the 1000 metre isobath. The current jet becomes somewhat less well defined when it encounters

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the deeper waters of the northeastern Newfoundland shelves but is sharpened up again when it encounters the northern edge of the Grand Banks. Most of the Labrador Current follows the bathymetry to flow southward along the western flank of Flemish Pass. (Some Labrador Current Water is found north of Flemish Cap.)

Circulation models for the Labrador and Newfoundland shelves driven by a pressure head across the Labrador shelf at its northern end reproduce the frontal and jet like structure of the Labrador Current until it reaches the Tail of the Grand Banks. In the model simulations, the Labrador Current turns westward to follow the bathymetry on the southern edge of the Grand Banks. Hydrographic data, ocean drifters, and ice berg trajectories indicate that most of the Labrador Current transport in fact turns offshore at this point to form a cyclonic circulation bounded on the north by Flemish Cap and on the east by the North Atlantic Current. Within this circulation is found a water that is known as mixed water that is a mixture of Labrador Current and North Atlantic water masses.

Because of the range of water masses in this region, is important to use density horizons rather than level surfaces when examining hydrographic and tracer fields. Clarke *et al* (1980) used $\sigma_\theta = 27.2$ to describe the circulation in the upper layers. This surface is found above 100 metres in the mixed water region just east of the Grand Banks, deeper than 700 metres in the Newfoundland Basin offshore of the North Atlantic Current and deeper than 800 metres in the Sargasso Sea to the south of the Gulf Stream.

A strong ridge is formed a little to the northeast of the axis of the Southeast Newfoundland Ridge reaching to 39°N 44°W where some of the isolines turn westward into the Sargasso Sea, some eastward toward the Azores and the rest northwestward to form the North Atlantic Current. The surface also exhibits anticyclonic circulation within the Newfoundland Basin. Inshore of the North Atlantic current suggests a weak cyclonic circulation within the mixed water region with the possibility that this is split into two cyclonic cells near the axis of the Newfoundland Seamounts.

Salinity on this surface ranges from less than 34 along the upper continental slop to greater than 35.3 in both the Sargasso Sea and the Newfoundland Basin and greater than 34.4 in the southeast corner. Salinity also decreases as one moves to the northeast toward Milne Seamount. The salinity contours mimic the surface topography near the Southeast Newfoundland Ridge. There is considerable variability on short spatial scales in the mixed water region suggesting the presence of small eddies or lenses of different waters in this region.

The transient tracer data taken in the North Atlantic in the last two decades, suggest that the intermediate and deep waters of the subpolar gyre of the North Atlantic are all rather well ventilated. The western boundary regions are only somewhat better ventilated than the interior. In the sub tropical gyre, tracers such as tritium and CFC's are still only found in significant concentrations in the deep western boundary currents.

This observation means that there is significant exchange between the deep western boundary currents and the interior within the sub-polar gyre. The simple conceptual model of North Atlantic Deep Water being formed in the Nordic Seas, overflowing the ridges, and forms a continuous deep boundary current down the western side of the North Atlantic to the equator and beyond is too simple. There must be significant recirculation of deep water north of the Tail of the Grand Banks. The Southeast Newfoundland Ridge may be a point that controls the exchange of deep waters into the rest of the North Atlantic basin.

The Bedford Institute of Oceanography, in collaboration with the University of Rhode Island, has just completed a two year field program to examine this complex part of the North Atlantic Circulation. This paper were provide an overview of the information collected.

The hydrographic station array

The hydrographic surveys was designed to divide the region into four closed boxes that would permit us to make transport estimates for the Labrador Current, Gulf Stream and North Atlantic Current and all their branches.

The 50 W, 48 N and Newfoundland Basin Mooring array hydrographic sections were chosen as repeats of sections that had been occupied several times in the past. The other sections running from southeast to northwest and from southwest to northeast were chosen to lie along Topex/ Poseidon ground tracks. Unfortunately, the ground tracks were incorrectly calculated when the fall, 1993 cruise was being planned and its sections fail to line up with the altimetry. We debated whether we should continue to use the 1993 sections during the 94 and 95 surveys or move them onto the intended ground tracks. We choose to move the sections.

Fall surveys were chosen because the upper ocean salinity reaches a minimum in late fall. The third and final survey was conducted in early summer. We wished to get estimates of the distribution of fresh water accumulation over the spring, summer, winter period to determine whether this accumulation is sufficient to account for the decreases in salinity observed in the North Atlantic Current system as one moves downstream and to denser surfaces. Figure 7, shows the low salinity surface layer on each station along the Newfoundland Basin mooring array section occupied in November, 1993.

Data was collected using a Seabird CTD mounted in a 24 bottle rosette. Profiles were obtained to within a few metres of the bottom except for a few stations where unfavourable current shears, wind and sea conditions forced us to terminate the cast several hundred metres off the bottom.

Water samples were collected at 24 depths using 8 and 10 litre sampling bottles. Water samples were analyzed for CFC's, total carbon dioxide, alkalinity, oxygen, nutrients and salinity. During 1993 and 1994, we were using bottles of a BIO design and some of these suffered from leakage. These were replaced by new bottles for the 1995 cruise, solving our leakage problems.

Through careful quality control of our rosette samples and comparisons with the CTD data, we believe that our final CTD data sets for all cruises have achieved WOCE standards for salinity, temperature and oxygen.

The Mooring Array

An array of 8 current meter moorings and six inverted echo sounders was set across the North Atlantic Current between the Southeast Newfoundland Ridge and the Newfoundland Seamounts in August 1993. The depths of the aanderaa current meters were chosen in order to estimate the transport of the various water masses within the western boundary region of the Newfoundland Basin (figure 8). Pressure sensors were included on the upper current meters to monitor mooring deflection in the expected strong currents. Conductivity sensors were also added to upper meters to determine the properties of the waters being transported, especially on the inshore side of the current.

Six of the current meter moorings were recovered in early June, 1995. The releases failed on two of the moorings; however, they were successfully recovered by dragging in July, 1995 with the loss of only one current meter and one release.

Two of the moorings recovered in early June, 1995 had lost their upper buoyancy packages. The splice on the short length of jacketed wire connecting the float to the uppermost current meter suffered corrosion. These losses occurred in February and March of 1995. Two of the current meters flooded through failure of their pressure sensors when they fell below 2000 metres after the loss of the buoyancy. Data from the older tape recording instrument was successfully recovered; the data stored on the newer solid state memory was lost.

Because many of these moorings were more than 4000 metres in length, we were concerned that they would be pulled down considerably in the strong currents and eddies expected in this region. The longest moorings were stiffened by increasing the mooring line tension. For the moorings expected to lie on the axis of the North Atlantic Current, the upper 300 metres of line faired to reduce drag.

In spite of these precautions, considerable pull down was observed on a few occasions. The greatest pull down occurred on mooring 1128 (figure 9). Here the upper current meter was pulled from 400 metres to 950 metres for a period of 2 days. This mooring was 4400 metres in length and used the increased line tension. Its upper section was not faired.

On each of the hydrographic occupations of the mooring section, mooring 1128 was seen to be near the centre of the Mann eddy. This is evidenced by the temperature and salinity measured by its upper instrument which was nominally at 400 metres depth. The plateau like structure of both temperature and salinity suggests that the temperature and salinity at 400 metres changed little throughout the record. Some of the cold, fresh events are clearly associated with the instrument being pulled down into cooler temperatures and fresher salinities. Events such as that around day 190 in 1994 must involve movement of colder fresher water through the mooring location. The event occurring around day 300 of 1993 is especially interesting. Here considerably warmer and saltier water flowed ESE past the mooring.

Mooring pull down has a mixed blessing. Because we were using a considerable number of older tape recording instruments which were approaching the end of their useful lifetime, we had periods of missing data on a number of the records. Pull down events provided us with unambiguous timing markers throughout the record that allowed us to line up records at different depths on the moorings.

The current meters were also prepared with the incorrect gear ratio in their rotor followers. This resulted in the counter being reset to zero at least once during the measuring time if the water velocity exceeded 0.3 ms^{-1}. The upper meters encountered currents that exceeded that threshold by factors of 3 and 4 on occasion. We spent considerable effort detecting and correcting our speed estimates for these wrap arounds. An example of the unwrapped speed records from mooring 1128 in shown in figure 10. We plan to verify the unwrapping using our mooring motion model and corrected velocities to calculate mooring pull down and to compare this with the pressure records.

The problem with the rotor speeds has slowed the analysis of the data. What is remarkable from preliminary inspection of the data is that the currents offshore of the North Atlantic Current (moorings 1126, 1127 and 1128) flow largely in the same northerly direction from 400 metres from the sea surface to 50 metres from the bottom. Clarke *et al* (1980) remarked that the near bottom currents appeared to line up parallel with the dynamic height of the surface over 2000 dbars in the Mann eddy.

The deep current meters on moorings 1121 to 1125 also clearly show the southward flow of the deep western boundary current system along the continental slope and rise. We will shortly begin to calculate the transports across the section of the various water masses and currents.

Float releases

Four new enhanced range sound sources were moored in the western North Atlantic during July, 1993 (Rossby *et al*, 1993). These sources ensonified the entire Newfoundland Basin and southern Labrador Sea. These instruments were successfully recovered in July, 1995 for examination by the manufacturer for possible engineering improvements. The instruments were all recovered in excellent condition and are being reused this October to ensonify the Labrador Sea.

The RAFOS floats (Rossby *et al*, 1986) were ballasted for two potential density levels σ_θ = 27.2 and σ_θ = 27.5. The upper density level is that shown earlier in figures 3 and 4 and is found in the main pycnocline within the North Atlantic Current and offshore waters. The deeper layer lies near the bottom of the main thermocline. The floats were deployed during summer, 1993, later fall 1993 and fall 1994. One hundred floats in total were released. Floats were programmed to surface in six to nine months from their launch dates.

The floats were released along the inshore and offshore edge and in the core of the North Atlantic Current as the vessel occupied hydrographic sections across the current. All floats were launched within the Newfoundland Basin. By this we mean, to the northeast of the Southeast Newfoundland Ridge and south of Flemish Cap. In spite of a deployment strategy focused on the western boundary region of the basin, floats found themselves throughout the western North Atlantic north of 40 N during the course of their trajectories.

Generally a shallow and deep float were launched at the same location. The floats tended to move together for the first three weeks and then begin to diverge.

The float trajectories reaffirm earlier pictures of the North Atlantic Current as a well defined current system which has preferred locations for the growth of meanders and eddies. The traditional spaghetti diagram of this new data set simply fills the region. Instead, figure 11 shows the locations where the instantaneous float speed exceeds 0.4 and 0.6 ms^{-1}.

These diagrams trace the quasi-permanent meanders of the North Atlantic current from the Newfoundland Basin as it follows the 4000 metre isobath around the northern end of the western North Atlantic basin. In examining these figures, it is important to remember that the data represents three float deployments over a 16 month period. While the shallower level is more energetic that the deeper, the location of the strongest velocities are quite similar.

The floats outline an intense meander extending offshore over the Newfoundland Seamount chain accompanied by cyclonic eddies inshore of the current. This meandering and eddy activity was identified by remote sensing experiments conducted in this area in the early 1980's (La Violette, 1982). South of Flemish Cap, the North Atlantic Current seems to flow as a stable jet locked on the bathymetry.

The current establishes a large cyclonic meander of varying amplitude as it turns north along the eastern edge of Flemish Cap. Suspicion that this meander existed was the reason why WOCE section A2 along 47-48 N was diverted southward in the western basin to cross the western boundary currents along the Newfoundland Basin mooring section defined by this control volume study.

The floats also delineate the anticyclonic loop known as the Northwest Corner (Lazier, 1994) before moving eastward toward the Charlie Gibbs fracture zone.

The Lagrangian trajectories of the floats are similar in a way to the trajectories of the drogued argos drifters deployed in great numbers in this region through the 1980's and 90's by IFM, Kiel (Krauss, 1986). The RAFOS floats also record their temperature and depth each time they are positioned. Consequently, this new data set provides a wealth of information that can be used to explore questions related to the dynamics of the current and its eddies, the mixing and movement of water masses into and across the current and the relationship between the large scale density structure and the currents and eddies.

Conclusions

This paper is intended simply to indicate scope of the data which has been collected during this Control Volume Experiment. In the analysis of this data set, we are conscious of the other data collected in the region over the decades by ourselves, the International Ice Patrol, the Soviet Sections programme, Kiel's Warmwasser Sphere program, Geosecs, TTO and Longlines. It is our intention combine our new insitu measurements with satellite altimetric measurements to provide the best possible description of the three dimensional circulation field of this part of the North Atlantic for 1993-1995. With this information, we will then begin to work with the historical data to examine the variability of this region over the past three to four decades.

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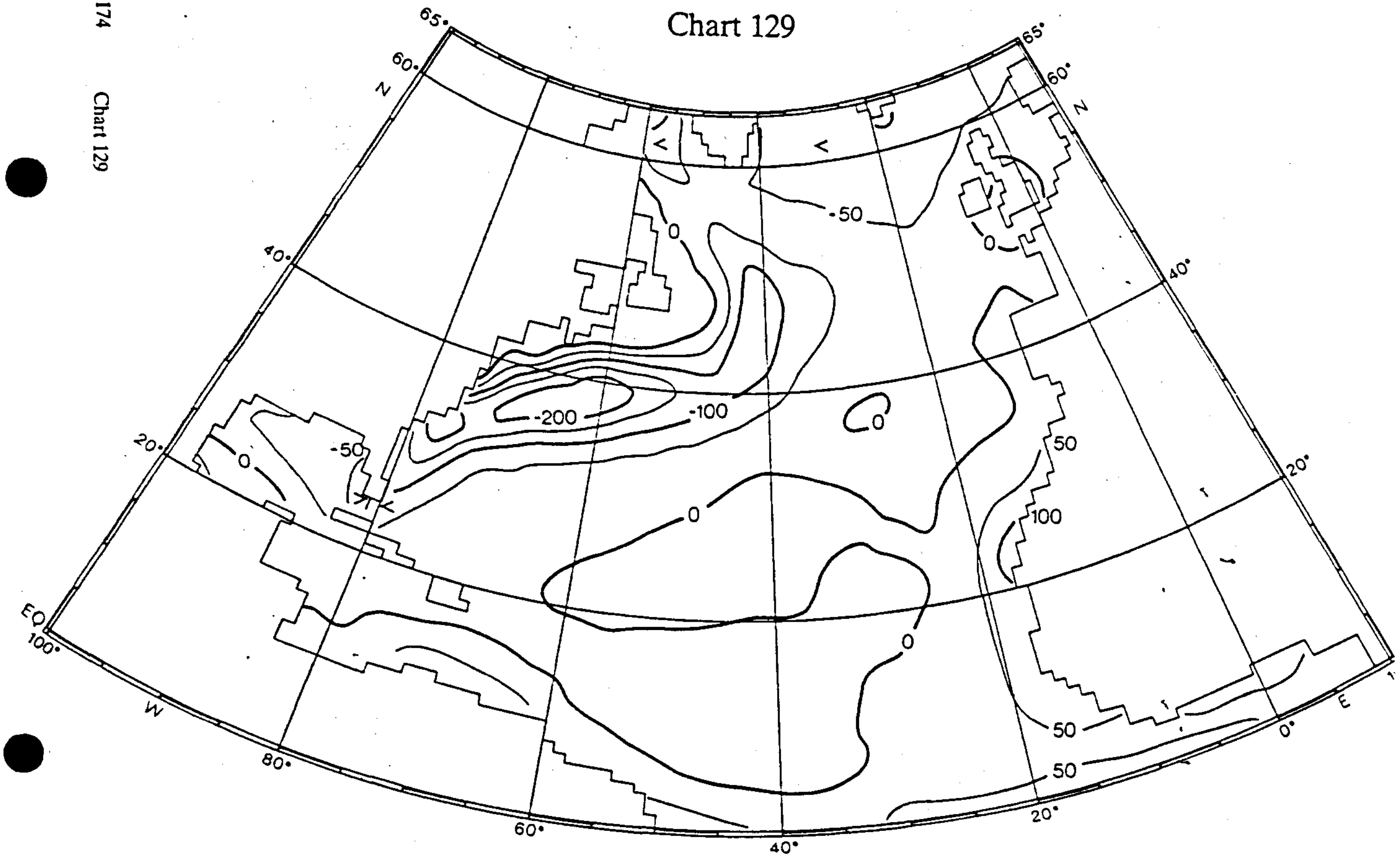
Chart 129



Net air-sea heat flux [W m^{-2}]
Year

Figure 1: Net annual air-sea heat flux [Wm^{-2}] for the North Atlantic (Chart 129 of Isemer and Hasse ,1985)

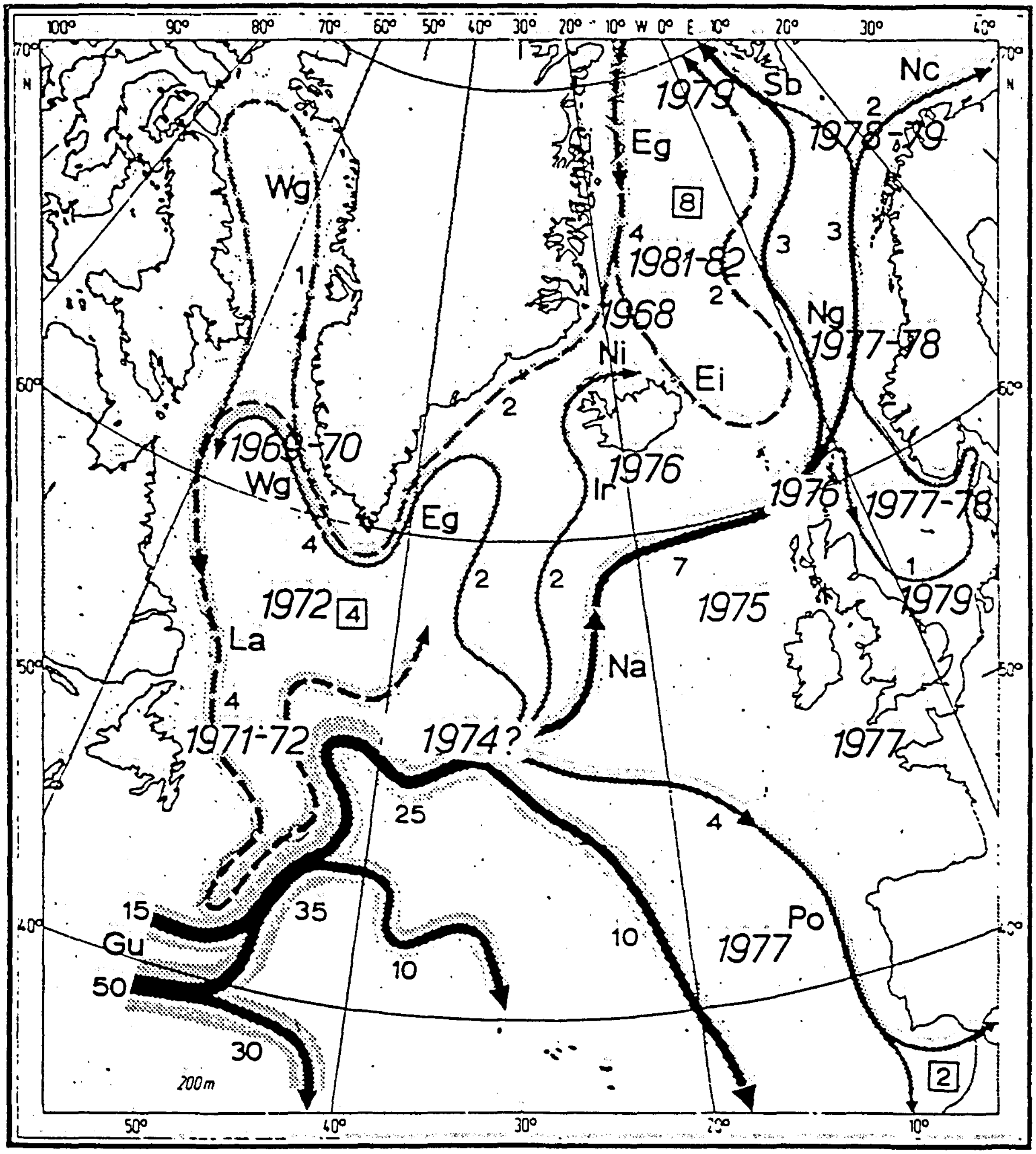


Figure 2: Transport scheme for the 0-1000 metre layer of the northern North Atlantic with the dates of the salinity minimum superimposed. (figure 7 of Dickson *et al* ,1988, after analysis by Dietrich)

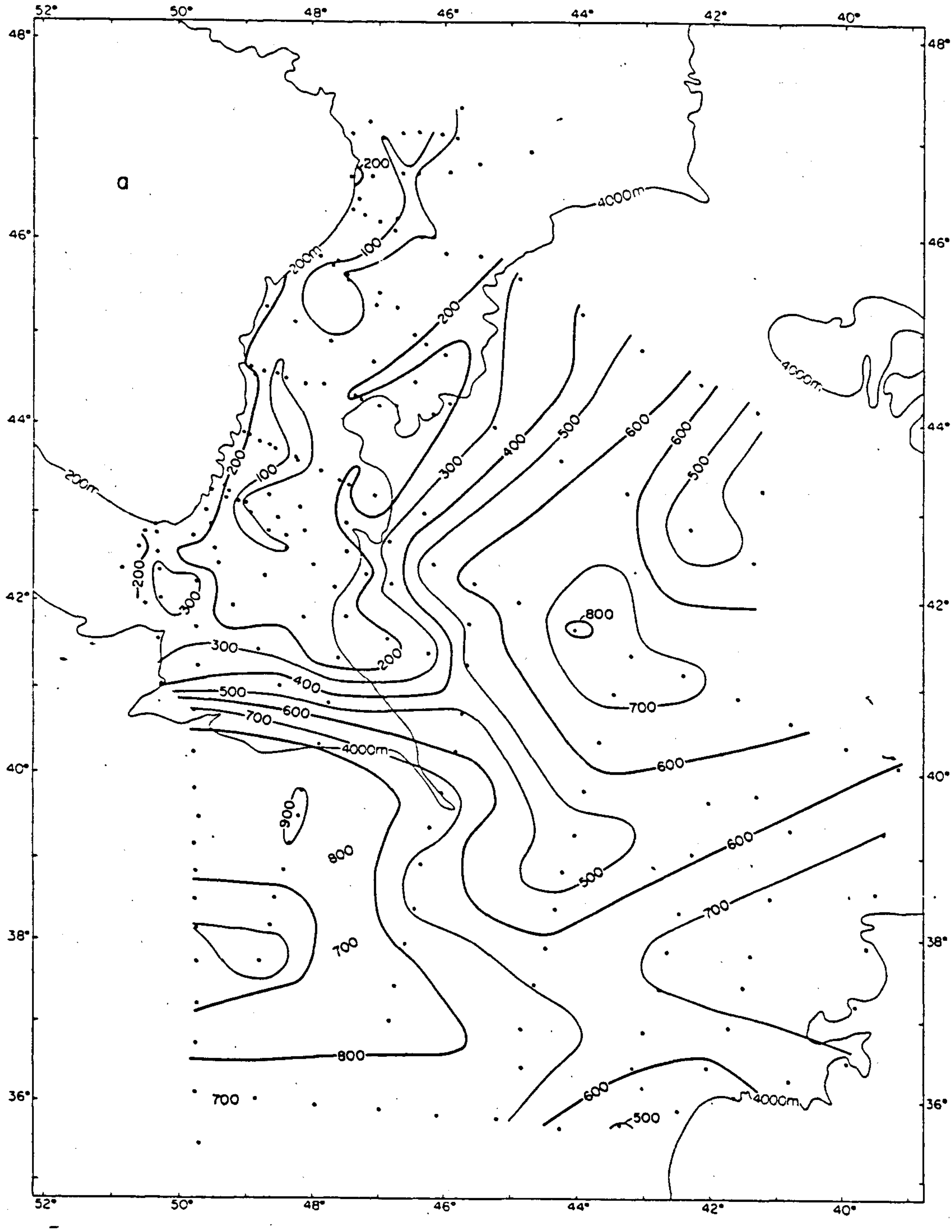


Figure 3: Depth of the $\sigma_\theta = 27.2$ isopycnal south and east of the Grand Banks of Newfoundland during April-June, 1972. (from Clarke *et al* ,1980)

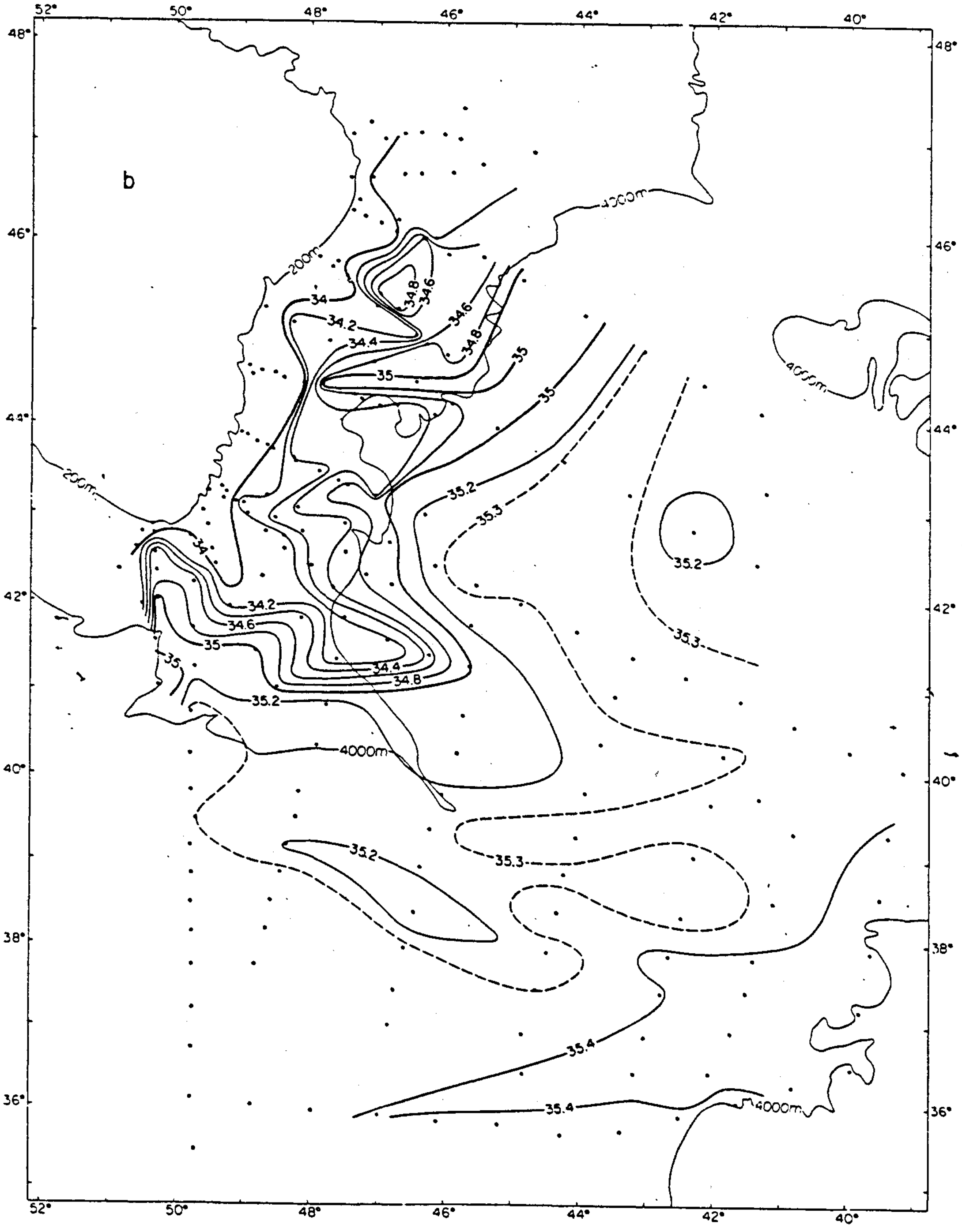


Figure 4: Salinity on the $\sigma_\theta = 27.2$ isopycnal south and east of the Grand Banks of Newfoundland during April-June, 1972. (from Clarke *et al,* 1980)

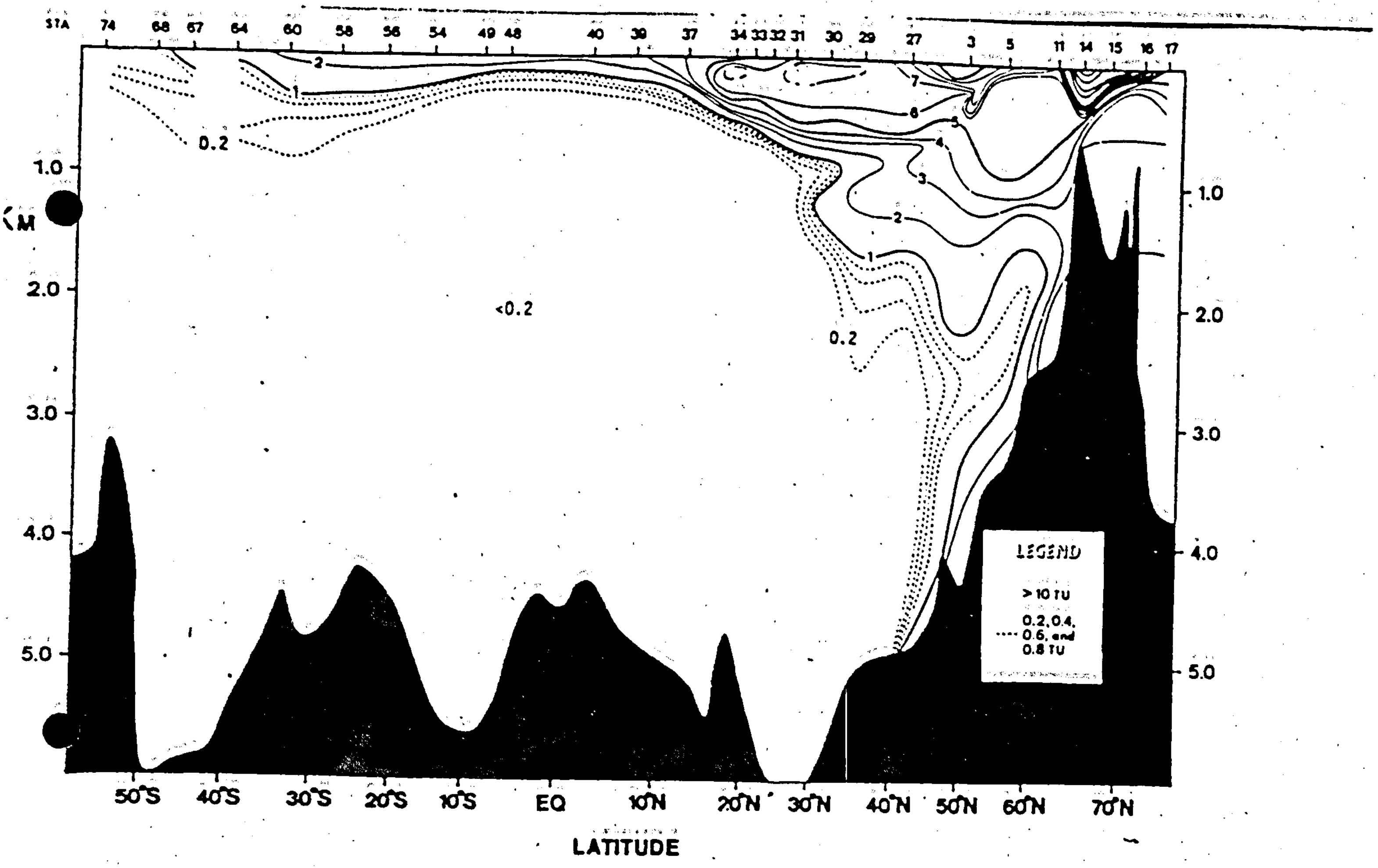
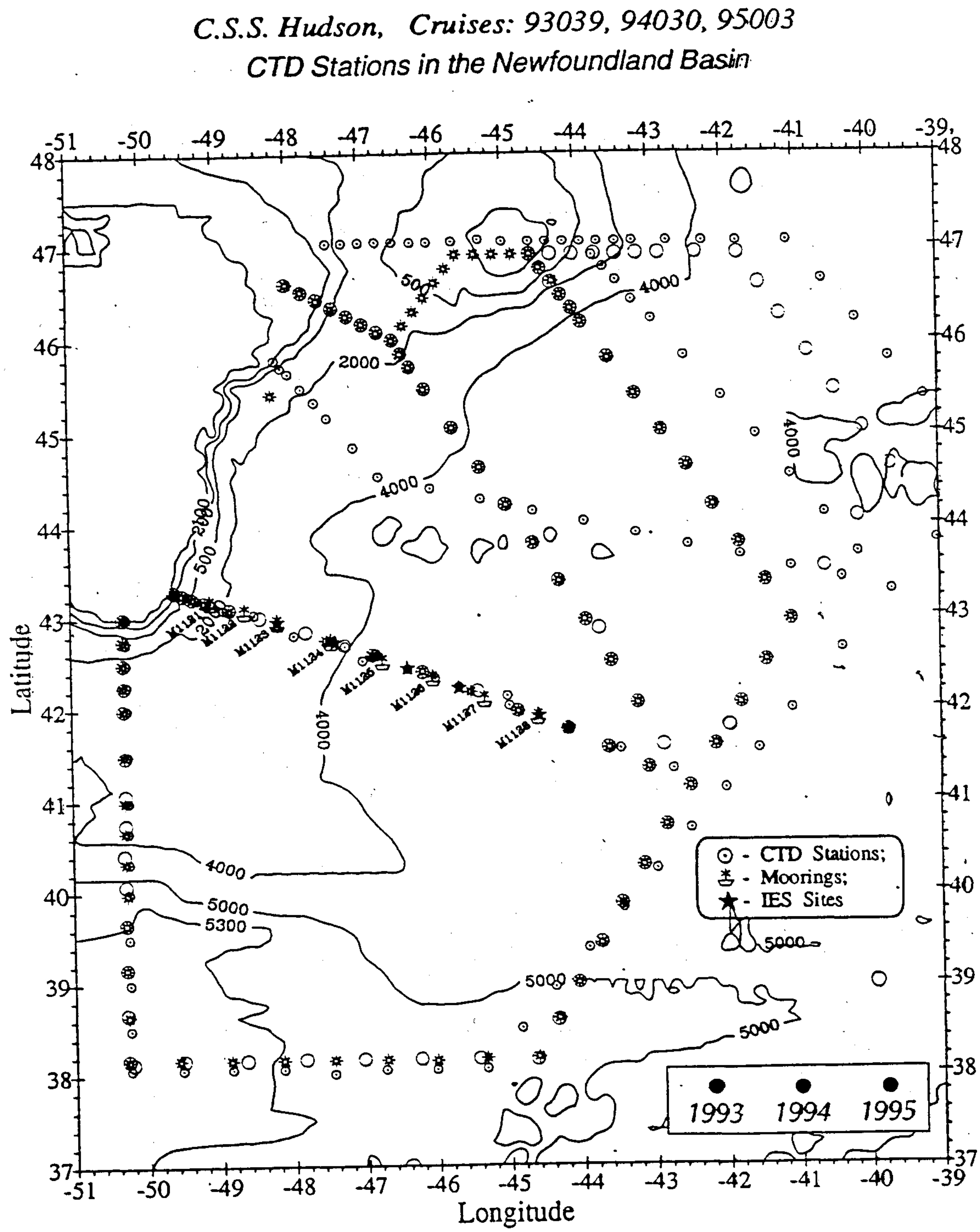


Figure 5: Tritium in the western Basin of the Atlantic Ocean from measurements taken in 1972-73 (from Ostlund and Brescher, 1982).



C.S.S. Hudson, Cruises: 93039, 94030, 95003
CTD Stations in the Newfoundland Basin

Figure 6: Mooring sites and hydrographic stations occupied by BIO in the Newfoundland Basin during 1993-95.

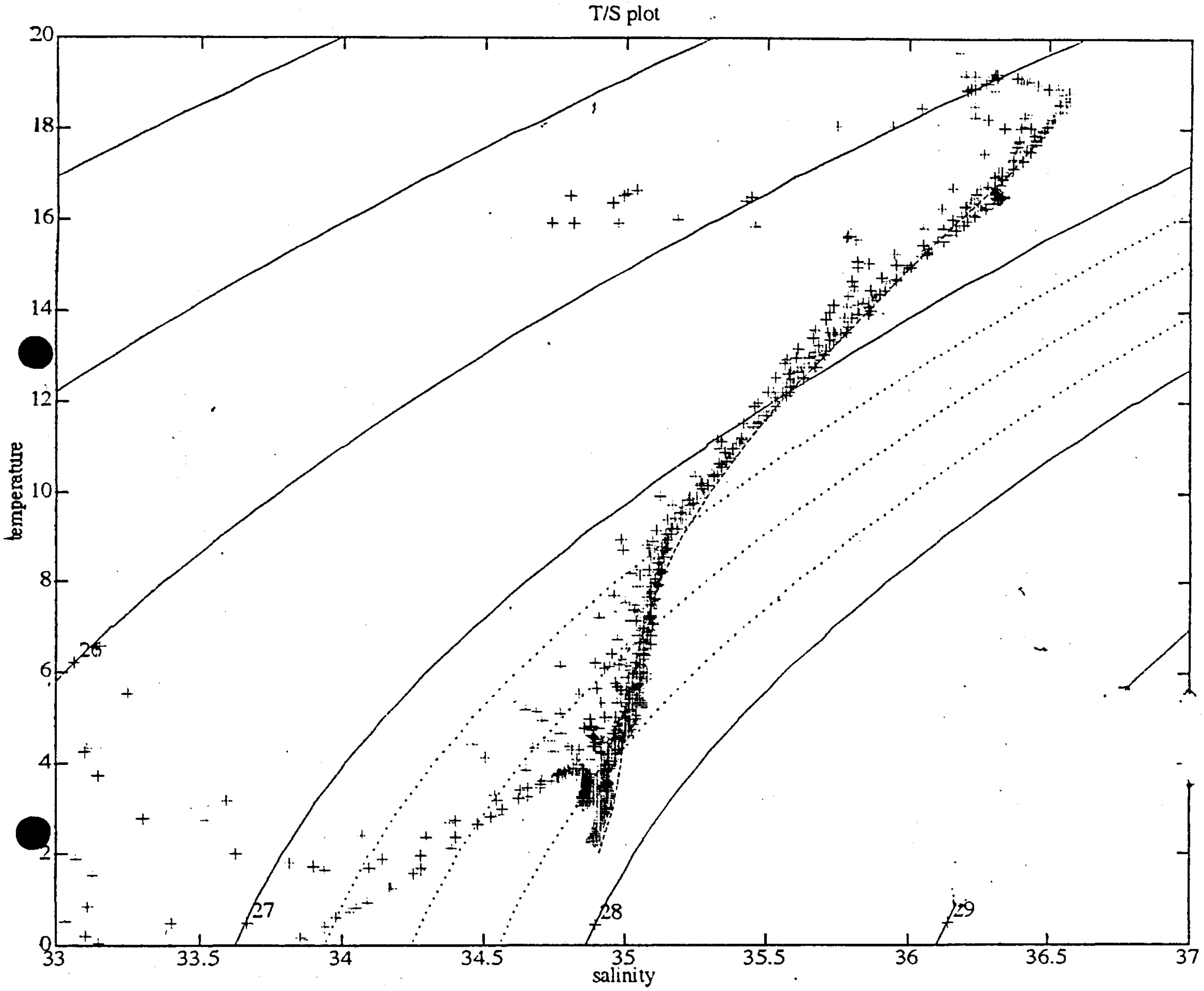


Figure 7: Potential temperature / salinity distributions from Newfoundland Basin Mooring Section observed in October, 1993.

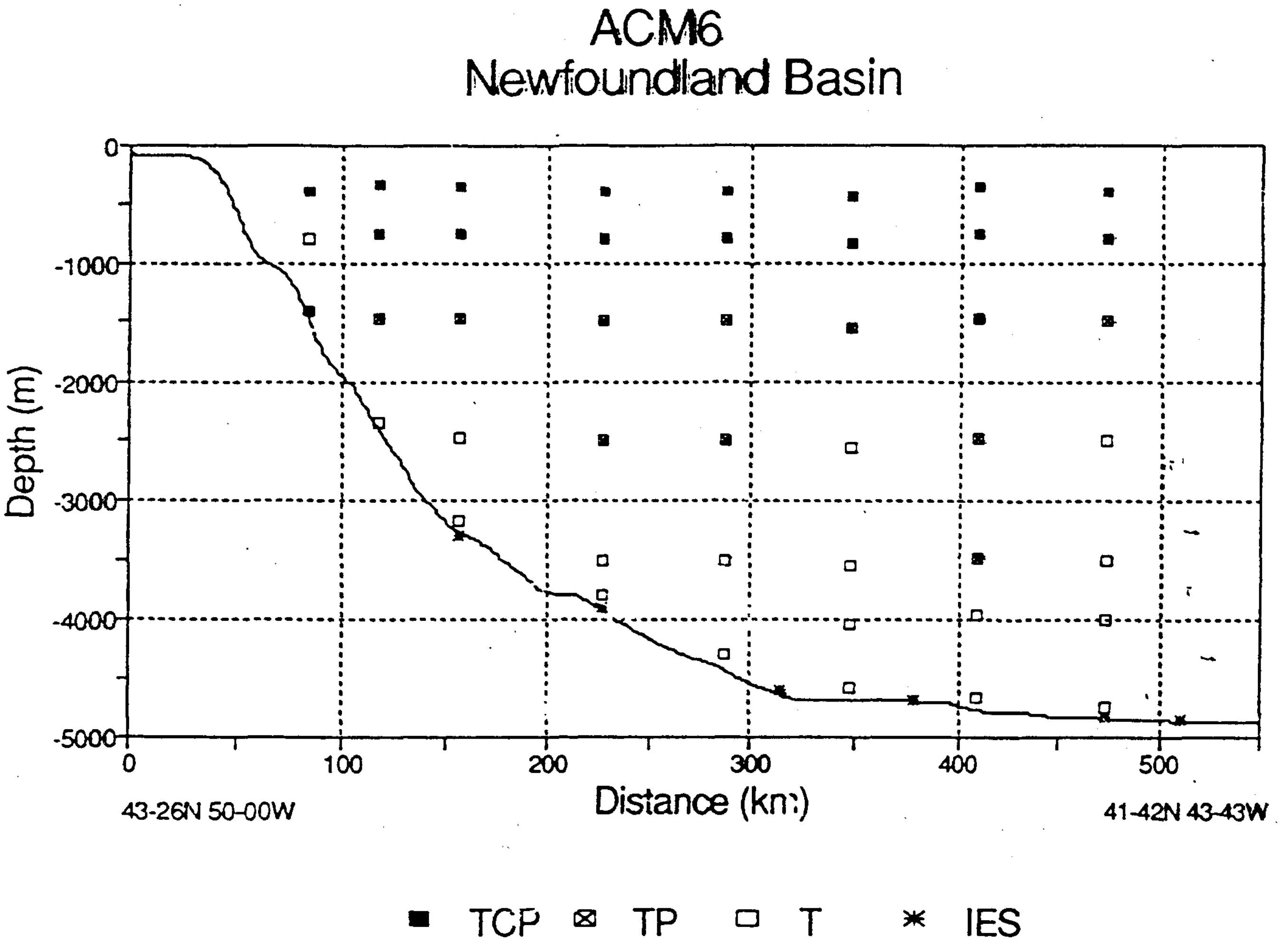


Figure 8: The North Atlantic Current Transport Array.

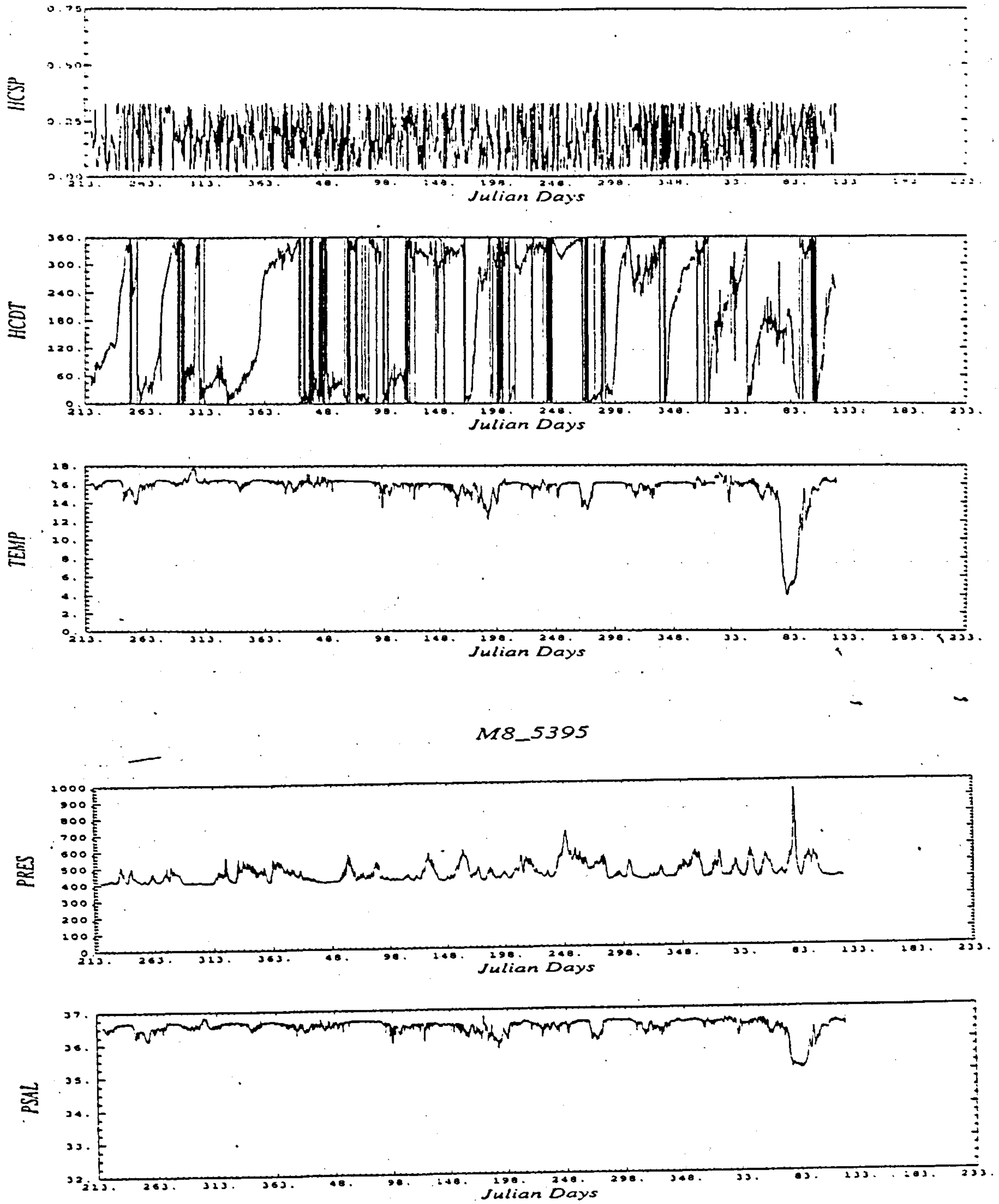


Figure 9: Pressure, temperature and salinity from the uppermost current meter on mooring 1128.

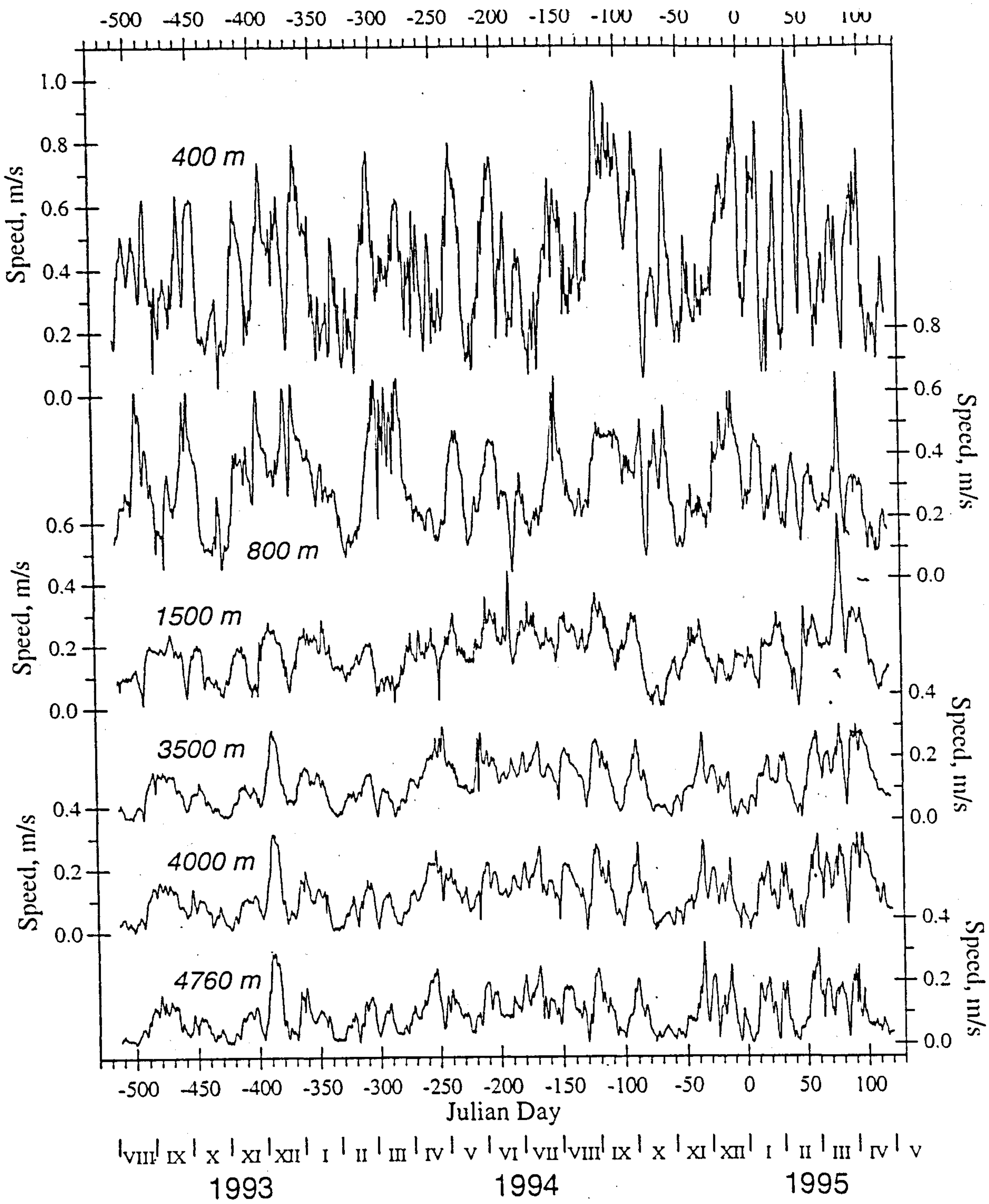


Figure 10: Unwrapped speed records from mooring 1128

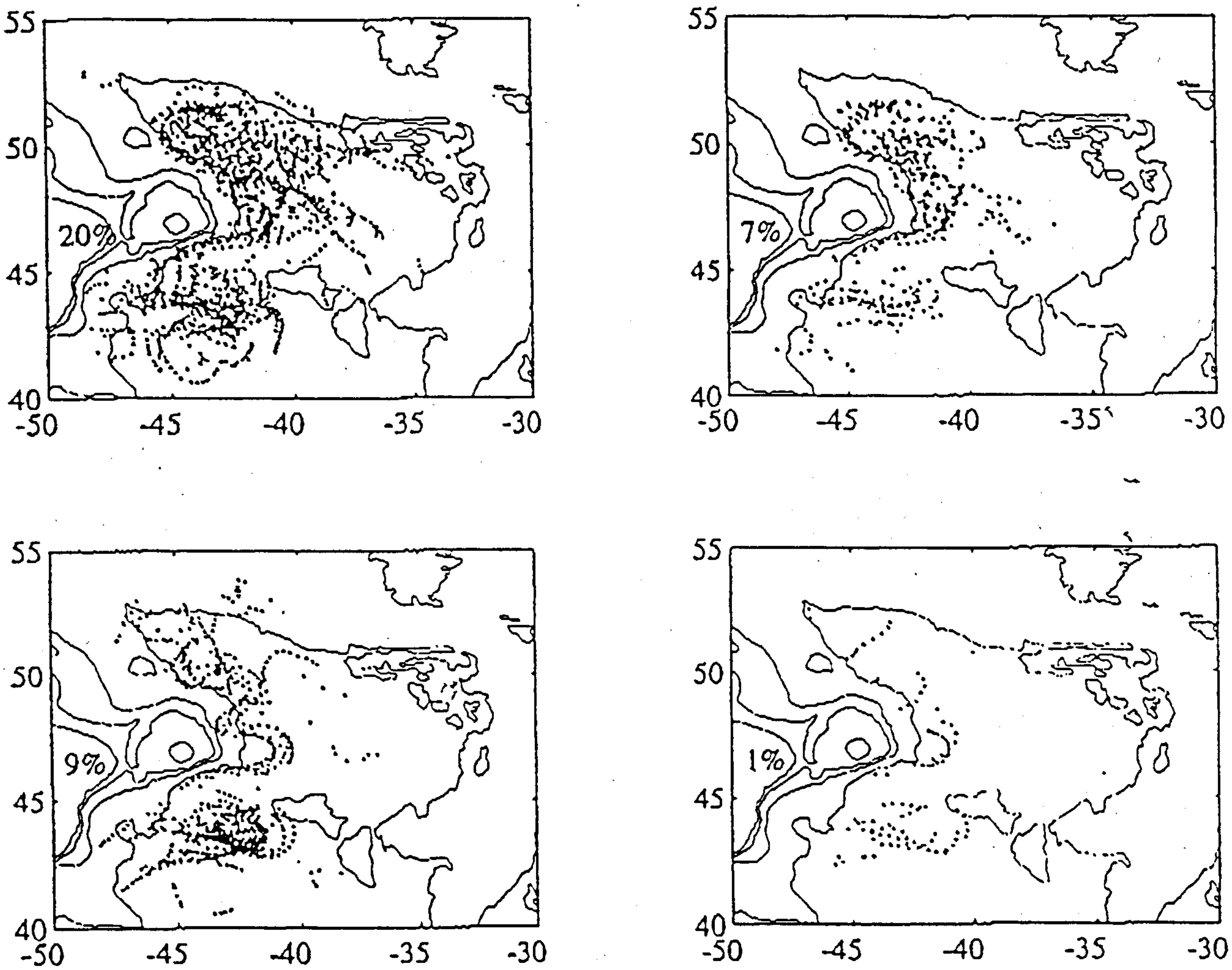


Figure 11: Dot distribution of float speeds in excess of .4 ms^{-1} (left panels) and .6 ms^{-1} (right panels) for floats on the 27.2 (top) and 27.5 (bottom) σ_θ surfaces. The thin lines indicate the 200, 1000, 2000 and 4000 metre isobaths. The percentages in each panel indicate the fraction of all observations exceeding the threshold. (From Rossby, 1996)