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WARM WATER TO COLD WATER CONVERSION IN THE NORTHERN NORTH ATLANTIC AND ITS RELATION TO THE GENERAL CIRCULATION

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Abstract

The surface circulation of the northern North Atlantic is seen to be generally cyclonic and consists of a progression of pycnostads, the Subpolar Mode Water. The temperature and salinity of the Subpolar Mode Water decrease from 14.7°C, 36.08 ‰ to 3.4°C, 34.88 ‰ due to excess precipitation and winter cooling and overturn. The coldest pycnostad is the Labrador Sea Water which spreads at mid-depth from the Labrador Sea. Mixing with other, higher salinity, water masses increases its salinity and potential vorticity. We estimate a production rate of $8 \times 10^6 m^3/sec$ of Labrador Sea Water from the warmest Subpolar Mode Water, allowing $9 \times 10^6 m^3/sec$ of the Subpolar Mode Water to flow into the Labrador Sea.

Résumé

La circulation de surface du nord de l'Océan Atlantique Nord est en majeure partie cyclonique, et consiste d'une progression de pycnostades, "the Subpolar Mode Water". Sous l'influence d'un surplus de précipitation et d'un refroidissement et renversement hivernal, la température et la salinité vont de 14,7°C et 36,08 ‰ à 3,4°C et 34,88 ‰. Le pycnostade le plus froid est le Labrador Sea Water qui émerge à mi-profondeur de la mer du Labrador. Des mélanges avec d'autres masses d'eau aux salinités plus élevées augmentent sa salinité et sa vorticité potentielle. Nous estimons que l'eau la plus chaude du Subpolar Mode Water contribue $8 \cdot 10^6 m^3/sec$ du Labrador Sea Water, ce qui permet à $9 \cdot 10^6 m^3/sec$ du Subpolar Mode Water de passer dans la mer de Norvège.

I. Introduction

In and above the pycnocline in many of the world's oceans are found thick layers of nearly homogeneous water. These columns are formed by wintertime convective overturn. Because of their nearly homogeneous density, they are termed pycnostads, and because of their appearance as isolated modes in volumetric temperature salinity analyses, the water masses that are made up of these pycnostads are termed Mode Waters.

There are two types of Mode Waters, the Subtropical Mode Water and the Subpolar Mode Water. This paper will describe the Subpolar Mode Water of the North Atlantic--where it is found, what its characteristics are, how it is formed, and how it circulates. Its end products are the Labrador Sea Water, a low salinity intermediate water mass, and a warm input into the Norwegian Sea. The distribution and circulation of the Labrador Sea Water will also be discussed and a simple box model for the northern North Atlantic proposed.

Previously described Mode Waters are the Subtropical Mode Waters of the North Atlantic and Pacific and the Subpolar Mode Water of the Southern Ocean. Subtropical Mode Water is found in the anticyclonic Gulf Stream gyre of the North Atlantic, where it is known as Eighteen Degree Water because of its characteristic temperature (Worthington, 1959; 1976) and in the anticyclonic Kuroshio gyre in the North Pacific where its temperature is 16°C to 17°C (Masuzawa, 1969). The Subtropical Mode Waters are only weakly formed in the Southern Hemisphere where the subtropical gyres are also weak. The southern hemisphere instead is dominated by a Subpolar Mode Water (McCartney, 1977), the Subantarctic Mode Water. It is found on the warm water side of the Antarctic Circumpolar Current and is characterized by temperatures and salinities which decrease from about 14°C, 35.75 ‰ in the western South Atlantic to about 4°C, 34.15 ‰ in the eastern South Pacific. Recirculation of the Mode Water in the anticyclonic gyres in the basins north of their formation regions is seen in addition to direct zonal circulation around the Southern Ocean. Freshening, cooling and thickening are due to excess precipitation and large air-sea heat exchange resulting in wintertime overturn. An end product of this Subantarctic Mode Water is the Antarctic Intermediate Water, a low salinity water mass which influences a large portion of the ocean at mid-depth. Its influence in the Atlantic reaches as far north as the Mediterranean Water. North of the Mediterranean tongue, intermediate depths are influenced by the low salinity Labrador Sea Water, the product of the North Atlantic Subpolar Mode Water. The North Atlantic Subpolar Mode Water thus has many similarities to the Subantarctic Mode Water.

We discuss first the method used for identifying convectively formed water masses, followed by a discussion of the North Atlantic Subpolar Mode Water and the Labrador Sea Water.

II. Method

The characteristic feature of a pycnostad, by definition, is a weak vertical density gradient which is presumed to arise from active mixing at the surface. The signature of a pycnostad is thus a vertical minimum of the density gradient $\frac{\partial \rho}{\partial z}$. The Brunt-Väisälä period, a measure of the stability of the water column, will therefore exhibit a maximum at the pycnostad. For conservative ocean basin scale circulation, a more dynamically relevant quantity is the potential vorticity, which reduces to $\frac{f}{\rho}\frac{\partial\rho}{\partial z}$, if relative vorticity is presumed small, where f is the Coriolis parameter. This quantity also will have a minimum in the vertical at the pycnostad.

We have used a large hydrographic data set covering the northern North Atlantic and northward along the Norwegian Coast. The data was interpolated to standard potential density levels (referenced to the surface) separated by potential density increments of .02. The Brunt-Väisälä period in minutes was obtained for each of these increments by referencing the in situ temperature and salinity to the pressure between the density surfaces. Potential vorticity in $(cm\ sec)^{-1}$ was obtained in the same manner.

The Subpolar Mode Waters were identified by Brunt-Väisälä period maxima since they are subject to continuous modification. The Labrador Sea Water, which circulates at mid-depth where seasonal influence and mixing are much reduced compared with advection, was identified as a minimum in potential vorticity.

A vertical profile for late winter stations in the Central North Atlantic Ocean east of Newfoundland is shown in Fig. 1 to illustrate the use of this method. The upper layer is extremely well mixed (it would be capped off by a warmer layer at lower Brunt-Väisälä period in other seasons) and is the local North Atlantic Subpolar Mode Water. At mid-depth near 1600 to 2000 m is a second maximum in Brunt-Väisälä period which corresponds to the salinity minimum and oxygen maximum, more familiar tracers of the Labrador Sea Water.

III. Subpolar Mode Water (McCartney and Talley, 1980)

Figures 2, 3, and 4 show the Brunt-Väisälä period, potential density and temperature of the Subpolar Mode Water in late winter (January-April). Identification of the pycnostads was limited to those with period greater than 100 minutes so the darkened exterior region is the region where there are no such pycnostads. The pycnostads are arranged in an annular distribution around the basin. The separation between the Subpolar Mode Water and the Subtropical Mode Water on the southwest, although relegated to one station in this data set, appears to be real--there is no connection between the warmer than 17°C Subtropical Mode Water and the warmest 14° Subpolar Mode Water. The annular distribution is broken only by the eastward North Atlantic Current which separates the warm Subpolar Mode Waters to the south from the cold Labrador Sea Water to the north. Proceeding counterclockwise around the ring, temperature and salinity decrease from 14.7°C, 36.08 ‰ to 3.4°C, 34.88 ‰, potential density increases from less than 26.9 mg/cm^3 to greater than 27.7 mg/cm^3, and the Brunt-Väisälä period shows a general, although irregular, increase.

This distribution is interpreted as a general cyclonic flow. The Subpolar Mode Waters, being at or near the surface, are subject to the excess precipitation of the region, which decreases the salinity, and to excess wintertime heat flux into the atmosphere which cools and convects them. The final product of this Subpolar Mode Water at the end of its cyclonic path is the Labrador Sea Water which is the freshest and coldest Subpolar Mode Water. This is formed in the Labrador Sea, sinking and spreading out at mid-depths, as detailed in the next section. Two addiitional components of the flow are: 1) flow into the Norwegian Sea through Faeroe-Shetland Channel, estimated at $8 \times 10^6 m^3/sec$ (Worthington, 1970), with hints of additional northward flow between Iceland and The Faeroe Islands, not mentioned before, and west of Iceland, estimated at $1 \times 10^6 m^3/sec$ (Stefansson, 1962), and 2) weak recirculation of the warm 11°C to 15°C pycnostads in an anticyclonic gyre south and east of their formation region.

The transport stream function is not presented to support our contention of cyclonic flow for two reasons. The first is the familiar reference level problem. The second is that the implied change in density of the pycnostads along the path produces large errors in transport estimates based on the (conservative) geostrophic method. Estimates of the air-sea exchanges indicate that the observed change in dynamic height along the path is of the same order of magnitude as the changes that could be induced by the air-sea exchange itself.

Estimates of transport and conversion are given in the summary box model following a discussion of the Labrador Sea Water.

IV. Labrador Sea Water (Talley and McCartney, 1980)

The Labrador Sea Water is the last and densest of the succession of Subpolar Mode Waters. It is formed in the Labrador Sea as a result of wintertime convection (Clark and Gascard, 1980). The rate of formation and characteristics of the Labrador Sea Water can vary greatly--analysis of Ocean Weather Station Bravo data in the central Labrador Sea (Lazier, 1980) indicates that formation does not necessarily occur every year.

For example, Clark and Gascard (1980) found newly formed Labrador Sea Water at the low temperature of 2.9°C in 1976, and no evidence of new Labrador Sea Water in 1978. Our conclusion that Labrador Sea Water is the end product of the Subpolar Mode Waters clearly indicates that climatological conditions over the whole of the northern North Atlantic are important in determining the formation rate for Labrador Sea Water. Figure 5 shows the monthly and annually averaged heat flux at O.W.S. Bravo from 1948 to 1972. There has been a decrease in heat loss over that period with an increase after 1970. An increase in 1971 suggests that Labrador Sea Water formation could have been possible although at lower temperatures than 3.4°C because of a low salinity cap which built up during the warming years.

Figures 6 and 7 show the distribution of potential vorticity and salinity at the core of the Labrador Sea Water, defined as a potential vorticity minimum. Both salinity and potential vorticity increase away from the Laborador Sea, indicative of erosion and mixing of the water mass. The potential density of the core referenced to 1500 meters is nearly uniform although it increases somewhat along the salinity and potential vorticity. (Secondary minima at higher densities are found in the northwest region of the distribution, possibly indicative of recirculation.) The heavy line denotes the maximum extent of recognizable Labrador Sea Water.

A notable feature of this distribution is the tongue of Labrador Sea Water which reaches around the Grand Banks and southward along the western boundary, probably as the upper part of the Deep Western Boundary Current. This has interesting implications for the arguments concerning the separation of the Gulf Stream and the North Atlantic Current systems (Worthington, 1976) since there must then be a compensating northward flow.

A circulation pattern that would be consistent with this Labrador Sea Water distribution, assuming that a certain amount of mixing occurs, could be the following. Labrador Sea Water leaves the Labrador Sea via the eastward flowing North Atlantic Current and the southward flowing Labrador Current. The North Atlantic Current carries Labrador Sea Water across the North Atlantic. There is a hint of a southwestward turning at the eastern side along the boundary with the Mediterranean water. Branches of the North Atlantic Current carry the Labrador Sea Water northward into the Irminger Sea, Iceland-Scotland Channel and Rockall Channel where it joins the general circulation there, eventually recirculating back into the Labrador Sea. The Labrador Current transports Labrador Sea Water southward to the Grand Banks where it intermittently flows around the Tail of the Grand Banks into the western North Atlantic. In the Gulf Stream region, it is probably circulated and recirculated, with some of it possibly escaping eastward with an eastward extension of the Gulf Stream. Mixing with adjoining waters horizontally or vertically, in all regions and particularly in intense currents inertially raises its salinity, density, and potential vorticity.

Although it is difficult to examine this distribution for time dependence because of the sparsity of data, indications from repeatedly occupied sections eastward from the Grand Banks and in the Gulf Stream region are that recent formation is identifiable as an increase in number of potential vorticity minima in the vertical and a higher incidence of very low salinity modes compared with the average Labrador Sea Water for these areas.

Where does the Labrador Sea Water go? Much of it recirculates in the northern North Atlantic. Mixing with Mediterranean Water along the southeastern side to form an input into North Atlantic Deep Water is one sink. Some of it flows south along the western boundary and is identifiable in sections far to the south as a potential vorticity minimum alongside the salty Mediterranean influenced core. There must also be upwelling to complete the balance.

V. Summary and Box Model

The surface circulation of the northern North Atlantic is cyclonic. The water mass involved in the surface circulation is the Subpolar Mode Water, a series of pycnostads ranging in temperature and salinity from about 14.7°C, 36.08 ‰ to 3.4°C, 34.88 ‰. The coldest of these pycnostads is identified by a second name, the Labrador Sea Water which spreads out from the Labrador Sea at mid-depths, primarily along the Labrador and North Atlantic Currents. Subsequent mixing with the higher salinity water, particularly the Mediterranean Water, raises its salinity and erodes its signal as a water mass.

An estimate of the net annual production rate for Labrador Sea Water can be made based on the assumption that the net annual heat flux into the atmosphere in the North Atlantic north of 50°N is all involved in conversion of the Subpolar Mode Waters into Labrador Sea Water. Between 50°N and the Scotland-Greenland-Canada sills, the ocean loses 8.7×10^3 cal/sec (Bunker, 1979, personal communication). If $8 \times 10^6 m^3$/sec of 3.5°C and $1 \times 10^6 m^3$/sec of 6.5°C water enters the Norwegian Sea, the production rate of LSW at 3.5°C from 11.5°C water is $7.5 \times 10^6 m^3$/sec.

Figure 8 is a comparison of Worthington's (1976) box model with a box model which represents the smallest modification based on our estimates of conversion of Subpolar Mode Waters from one temperature class to another. The biggest difference is that we estimate a total of $17 \times 10^6 m^3$/sec undergoing pycnostadal conversion. Of this, $9 \times 10^6 m^3$/sec flows into the Norwegian Sea and $8 \times 10^6 m^3$/sec are converted into Labrador Sea Water. This implies an increase in upwelling in the system if all other estimates are retained.

Salinity is not included in Figure 7. Our system requires an input of $.20 \times 10^6 m^3$/sec of fresh water in order to decrease the salinity from 35.55 ‰ at 11.5°C to 34.88 ‰ at 3.5°C. Baumgartner and Reichel (1975) estimate the fresh water input from 50°N to 65°N as $.13 \times 10^6 m^3$/sec. North of 65°N, there is an additional input of $.13 \times 10^6 m^3$/sec, some of which could come south in the East Greenland Current. The box model thus appears to work for salinity also.

References

1. Baumgartner, A. and E. Reichel, 1975. The World Water Balance. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, 179 p.

2. Bunker, A. F. and L. V. Worthington, 1976. Energy exchange charts of the North Atlantic Ocean. Bulletin of the American Meteorological Society 57, 670-678.

3. Clark, R. A. and J. C. Gascard, 1980. Deep convection in the Labrador Sea. To be submitted to Journal of Phys. Ocean.

4. Lazier, J. R. N., 1980. Oceanographic conditions at O.W.S. Bravo 1964-1974. Submitted to

5. Masuzawa, J., 1969. Subtropical Mode Water. Deep-Sea Res. 16, 453-472.

6. McCartney, M. S., 1977. Subantarctic Mode Water. A Voyage of Discovery. Supplement to Deep-Sea Res. George Deacon 70th Anniversary Vol., Editor, Martin Angel, 103-119.

7. McCartney, M. S. and L. D. Talley, 1980. The Subpolar Mode Water of the North Atlantic Ocean. To be submitted to Journal of Phys. Oceanography.

8. Talley, L. D., M. S. McCartney, and C. Pilskaln, 1980. On the distribution and circulation of Labrador Sea Water. To be submitted to Journal of Phys. Oceanography.

9. Stefansson, U., 1962. North Icelandic waters. Rit Fiskideilar 3, 269 pp.

10. Worthington, L. V., 1959. The 18° Water in the Sargasso Sea. Deep-Sea Res. 5, 297-305.

11. Worthington, L. V., 1970. The Norwegian Sea as a mediterranean basin. Deep-Sea Res. 17, 77-84.

12. Worthington, L. V., 1976. On the North Atlantic circulation. Johns Hopkins Oceanographic Studies, Vol. VI. The Johns Hopkins University Press, Baltimore and London, 110 pp.

Figure Captions

Figure 1. Profiles of potential density and bulk Brunt-Väisälä period for a Central Water Station in the central North Atlantic Ocean east of Newfoundland, offshore of the North Atlantic Current: R/V ATLANTIS II Station 354, March 24, 1964, 49°25.0'N, 40°34.0'W.

Figure 2. Brunt-Väisälä period of the late winter Subpolar Mode Water.

Figure 3. Potential density of the late winter Subpolar Mode Water.

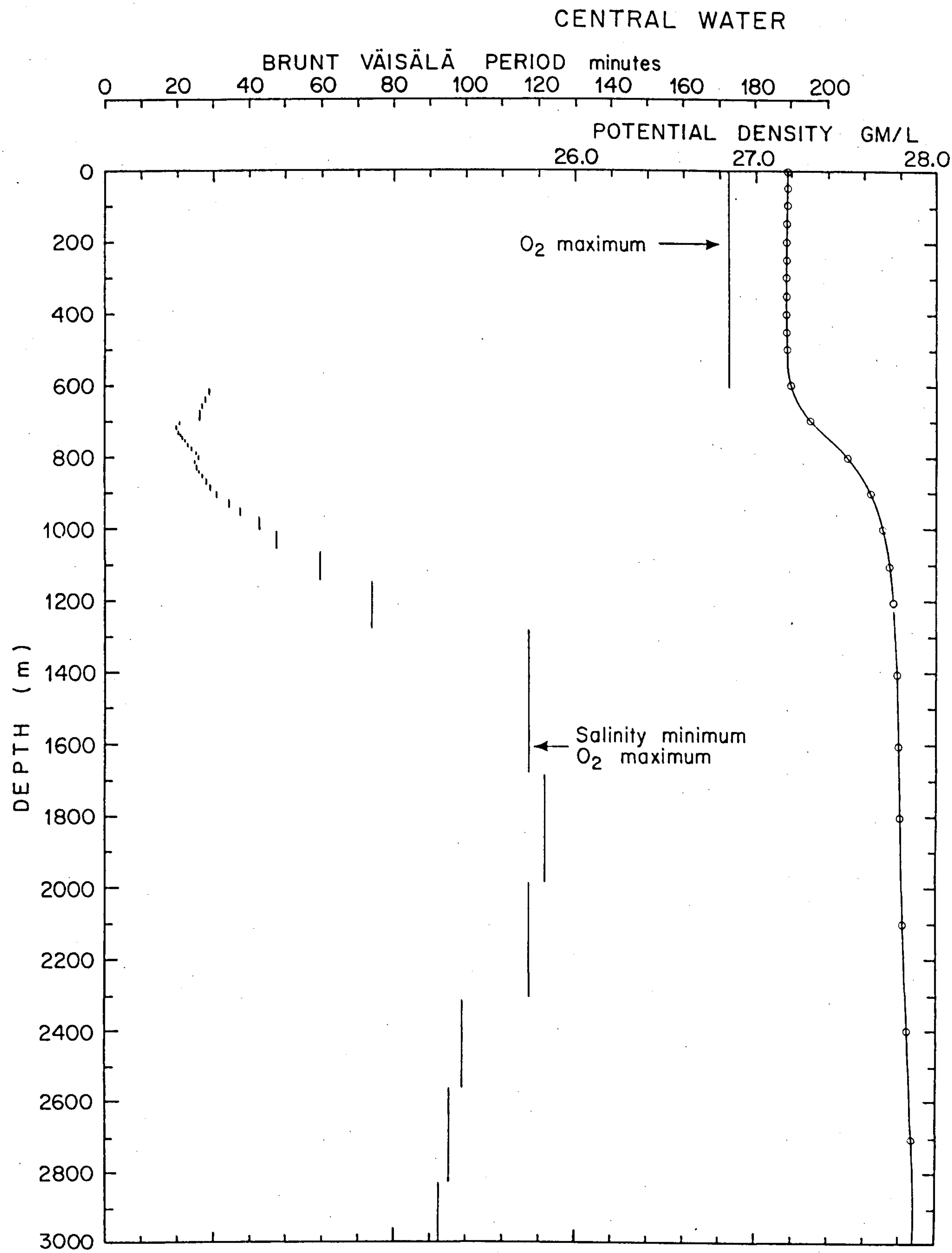
Figure 4. Potential temperature of the late winter Subpolar Mode Water.

Figure 5. Monthly and annually averaged heat flux at Ocean Weather Station Bravo.

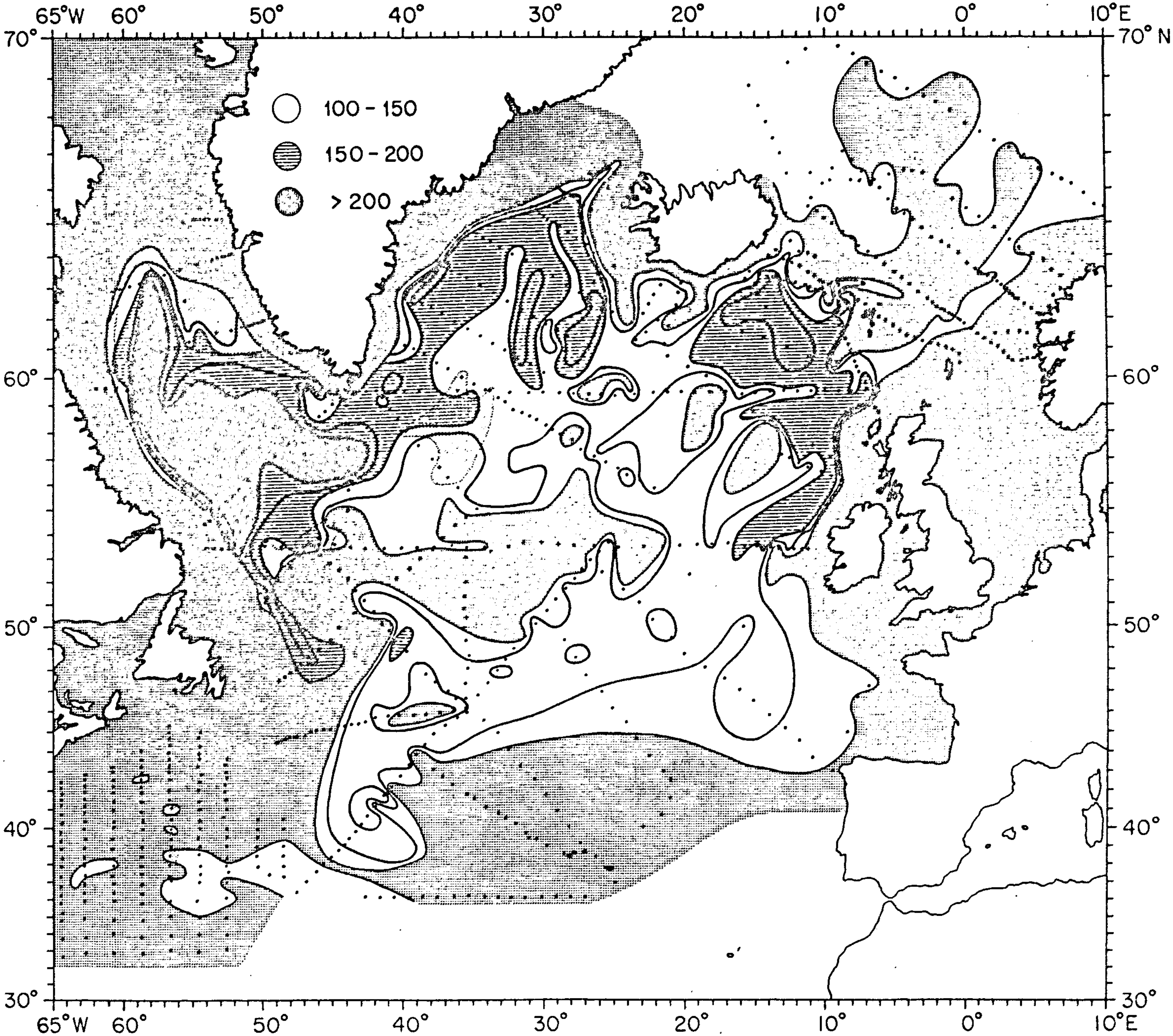
Figure 6. Potential vorticity at the Labrador Sea Water potential vorticity minimum.

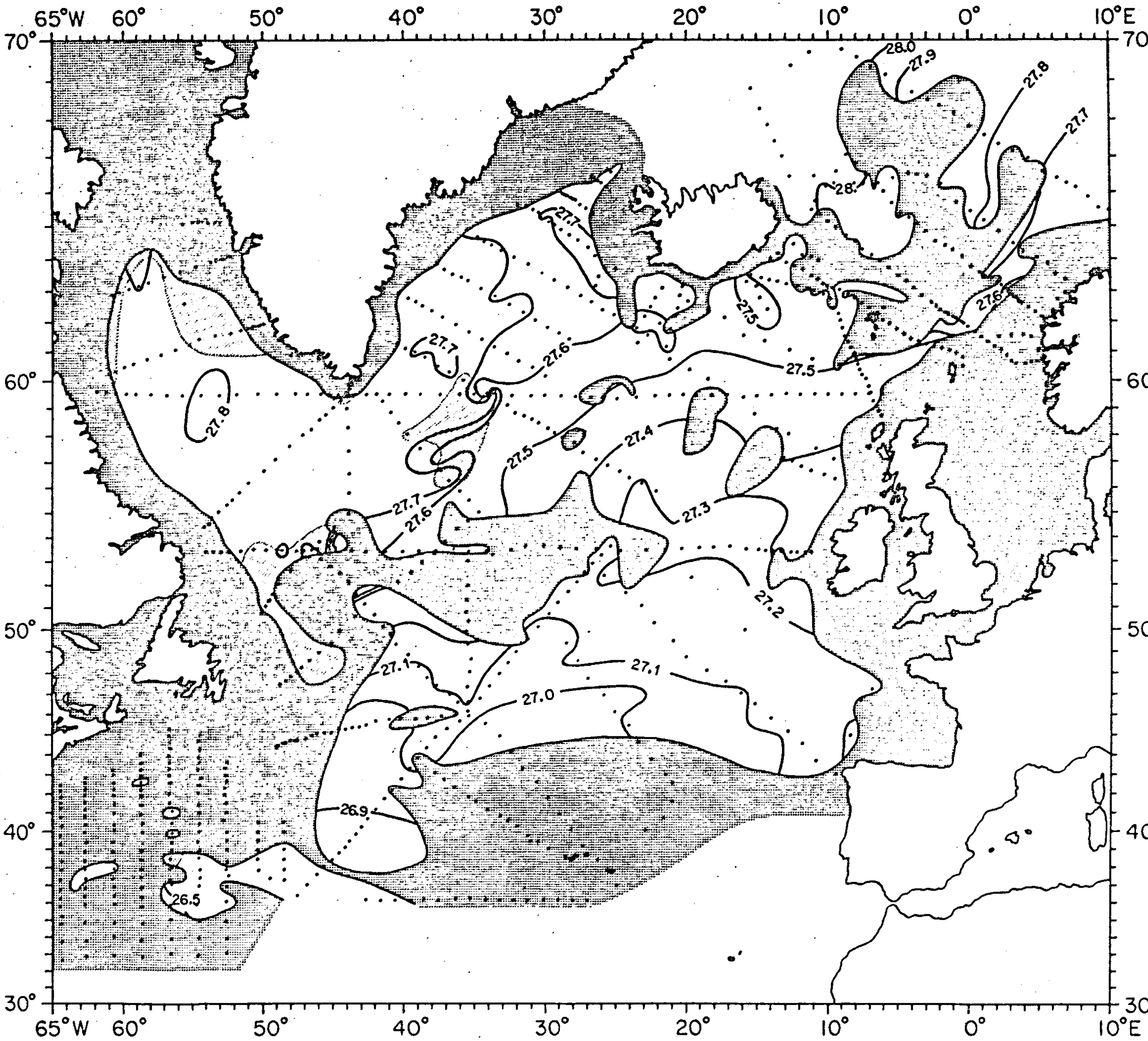
Figure 7. Salinity at the Labrador Sea Water vorticity minimum.

Figure 8. A simplified representation of Worthington's (1976) vertical box model, and a modification consistent with our estimate of warm water to cold water conversion.



CENTRAL WATER
BRUNT VÄISÄLÄ PERIOD minutes
0 20 40 60 80 100 120 140 160 180 200
POTENTIAL DENSITY GM/L
26.0 27.0 28.0
O_2 maximum
Salinity minimum
O_2 maximum
DEPTH (m)
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000


65°W 60° 50° 40° 30° 20° 10° 0° 10°E
70° 70° N
60° 60°
50° 50°
40° 40°
30° 30°
100 - 150
150 - 200
> 200



65°W
60°
50°
40°
30°
20°
10°
0°
10°E
70°
70° N
60°
50°
40°
30°
28.0
27.9
27.8
27.7
28.
27.1
27.5
27.6
27.7
27.6
27.5
27.8
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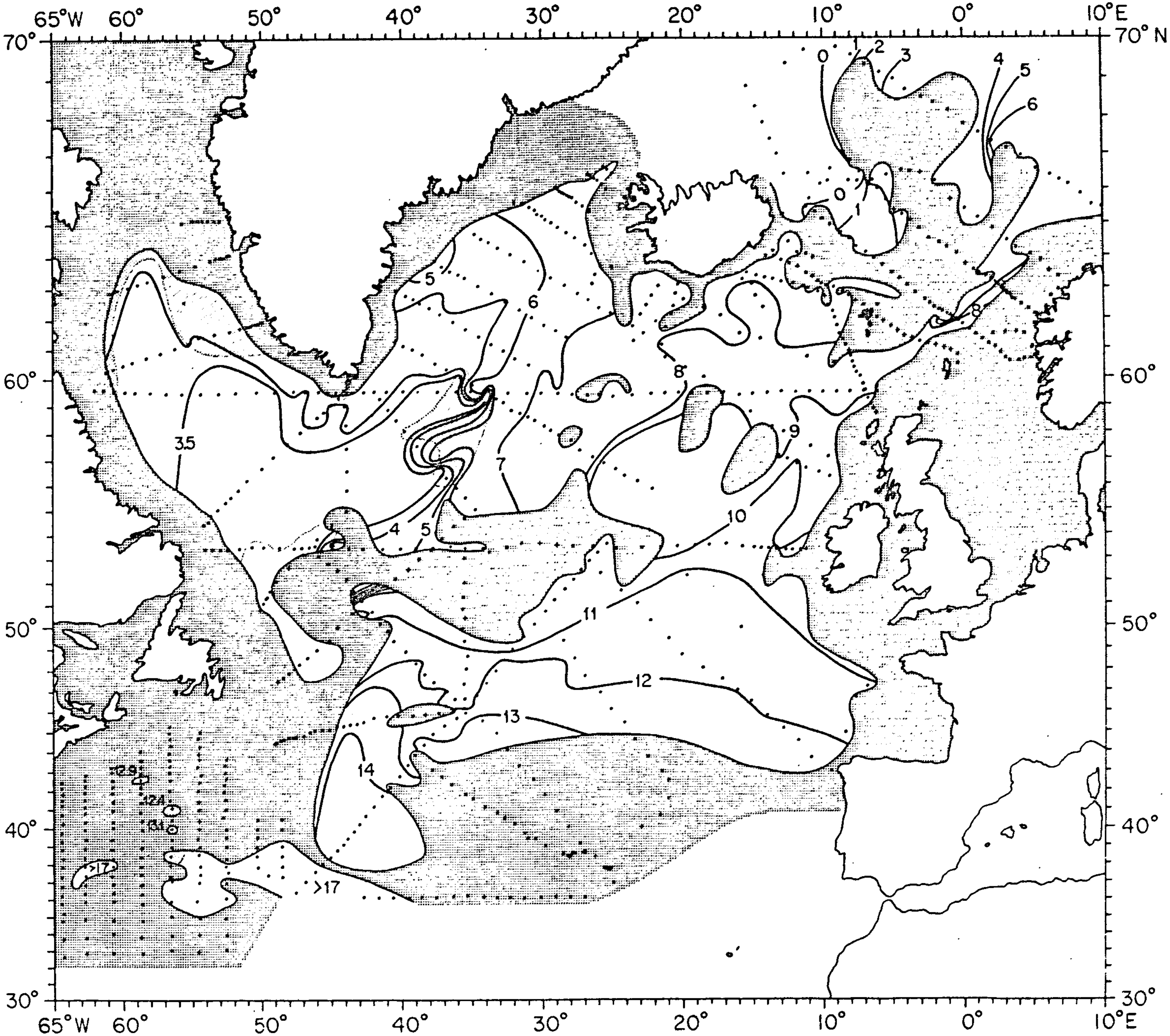
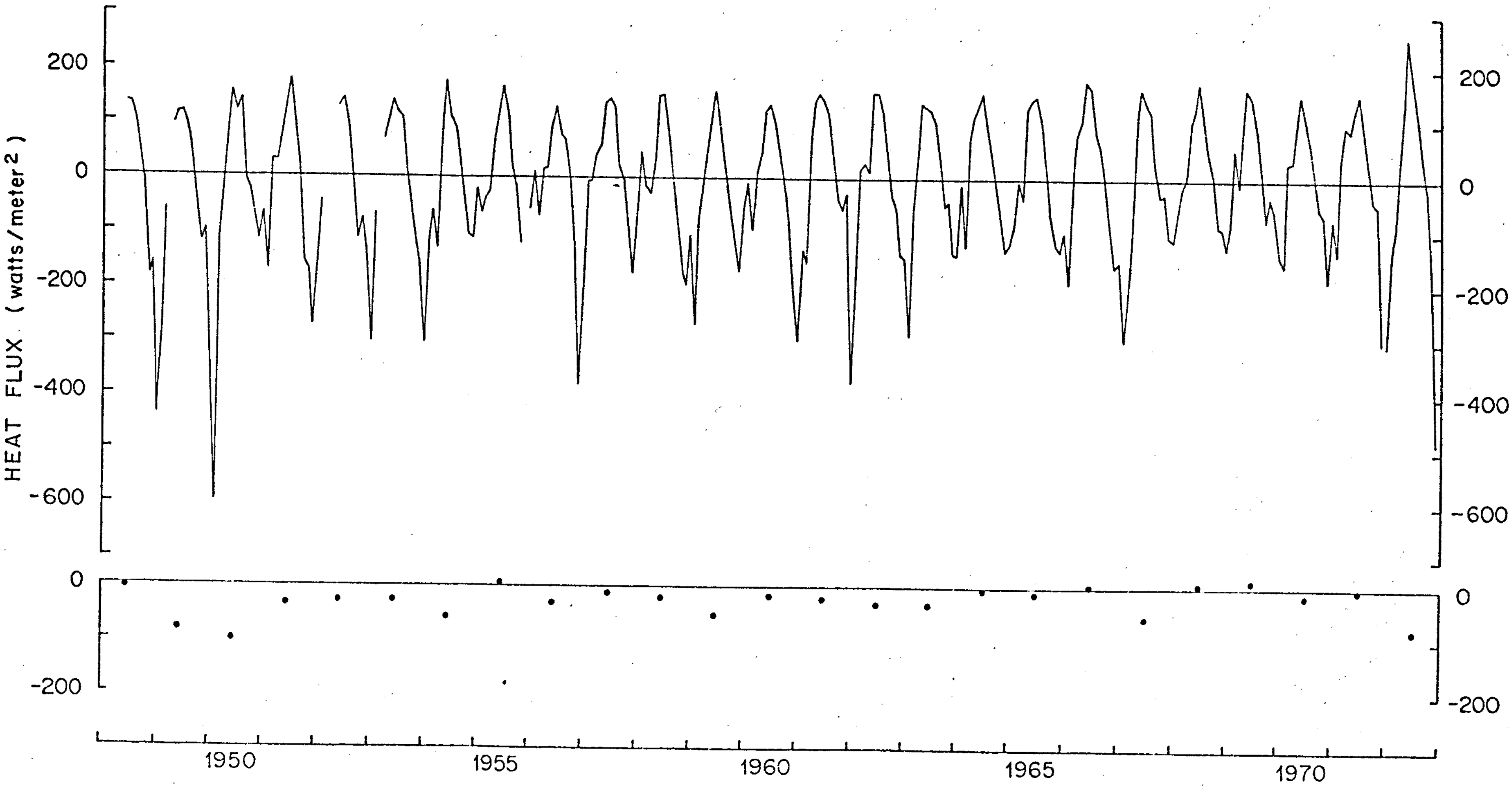
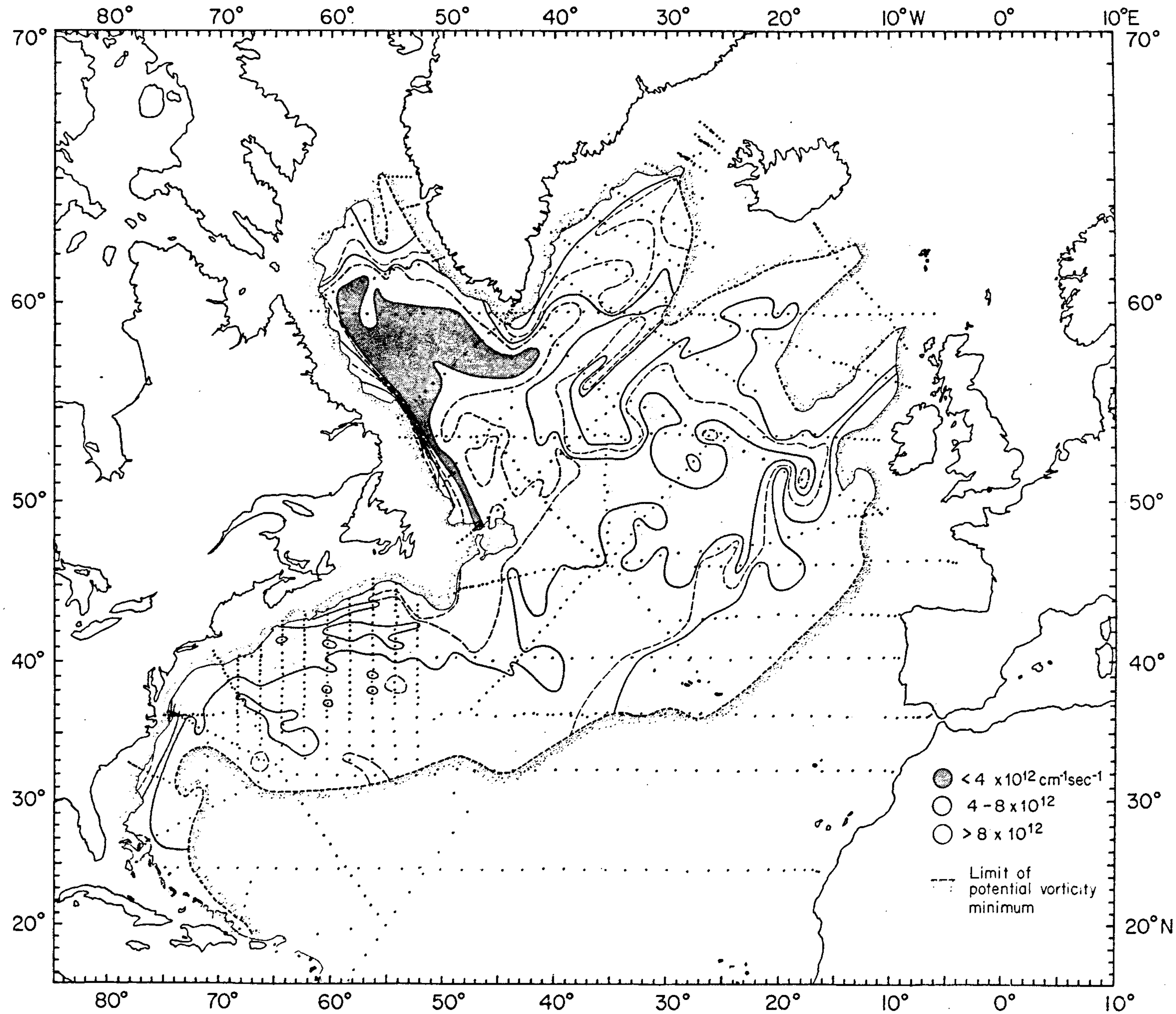
27.1
27.1
27.0
26.9
26.5

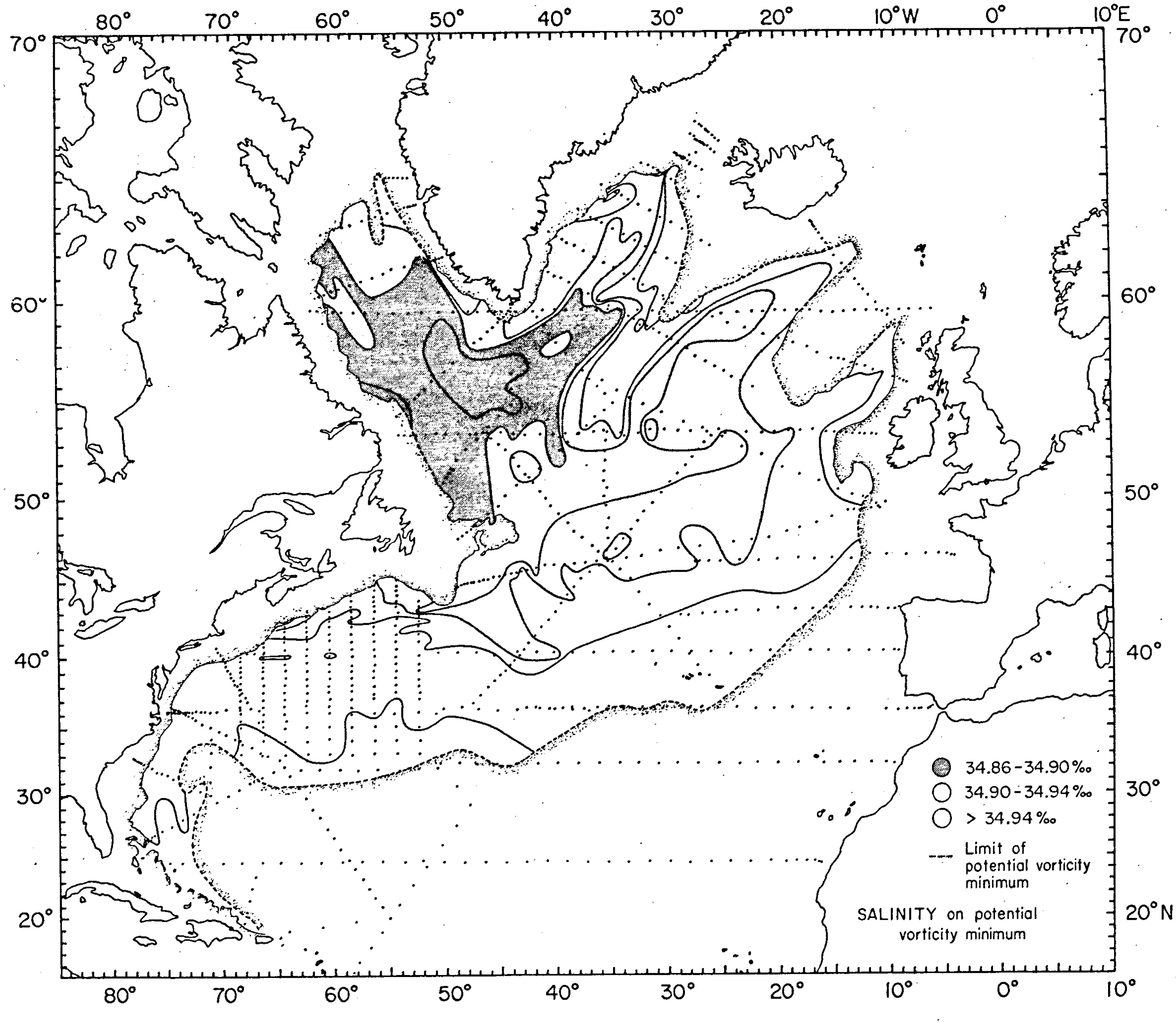

65°W
60°
50°
40°
30°
20°
10°
0°
10°E
70°
70° N
60°
50°
40°
30°
0
1
2
3
4
5
6
8
9
10
11
12
13
14
3.5
7
>17
12.9
12.4
13.1



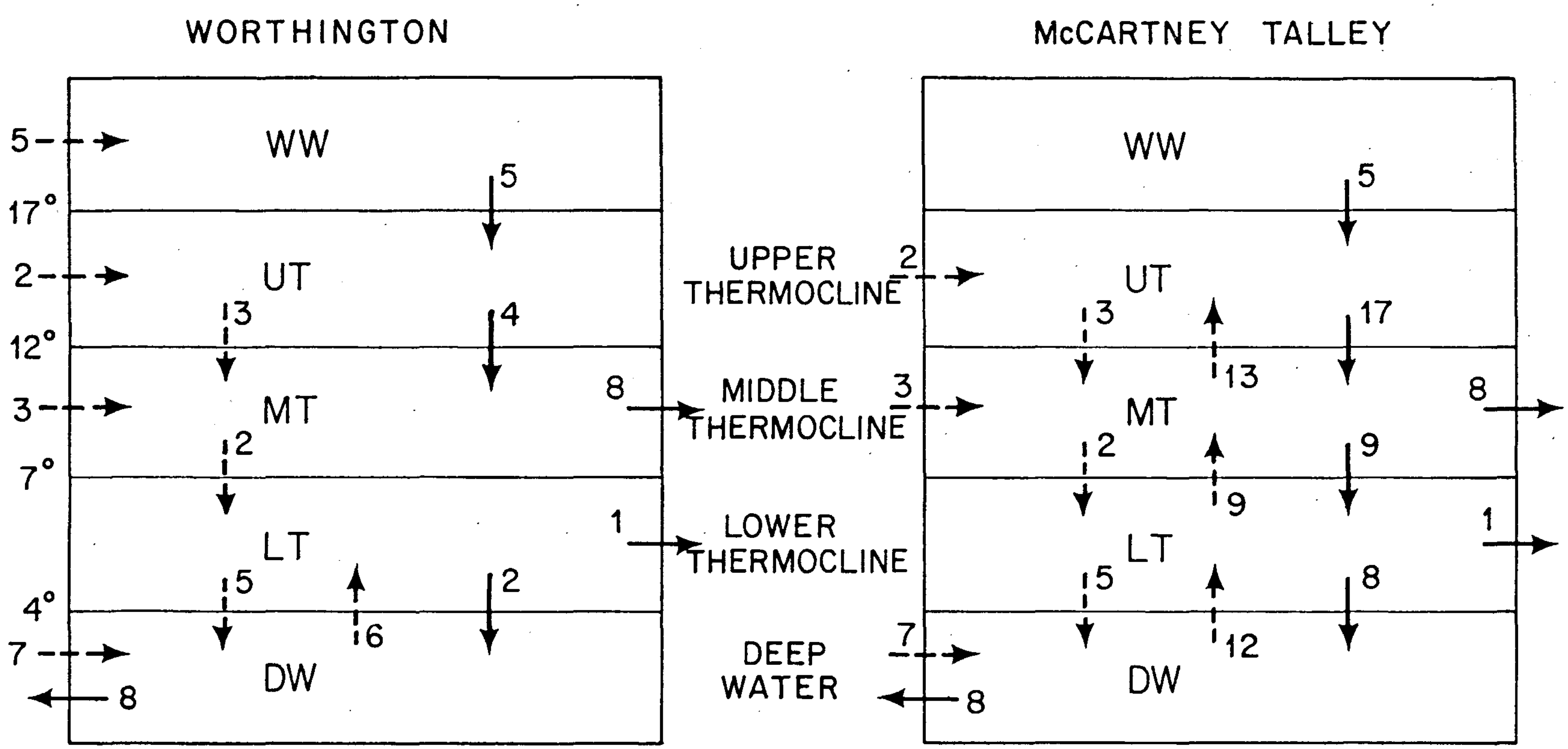
HEAT FLUX (watts/meter²)
200
0
-200
-400
-600
0
-200
1950
1955
1960
1965
1970



80°
70°
60°
50°
40°
30°
20°
10°W
0°
10°E
70°
60°
50°
40°
30°
20°N
20°
10°
< 4 x 10^12 cm^-1 sec^-1
4 - 8 x 10^12
> 8 x 10^12
Limit of potential vorticity minimum



34.86-34.90‰
34.90-34.94‰
> 34.94‰
Limit of potential vorticity minimum
SALINITY on potential vorticity minimum
80°
70°
60°
50°
40°
30°
20°
10°W
0°
10°E
70°
60°
50°
40°
30°
20°N



Entrainment at overflows — Mediterranean & Norwegian Sea

Pycnostad conversions

Upwelling

Flows into the Norwegian Sea

Flows into the layer from adjacent seas and oceans: South Atlantic and Polar Seas

Outflow to South Atlantic