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On the areal division of the North Atlantic by temperature-salinity curves in connection with wind drift computations

by

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At present when studying sea and oceanic wind drifts the current velocity is normally expressed in the form of two components, i.e. pure drift and gradient flows (1,2,3,4,5,6,7).

Of these determinations of the gradient component of the current (1,2,6,7) presents greater difficulty from the viewpoint of utilization of the known methods of computation. In a deep heterogeneous sea or ocean this component of a steady wind drift can be determined with sufficient degree of accuracy by means of a dynamic method suggested by Bjerkenes and Sandström (1,2,3,4,5,6). Thus, for the northern hemisphere the horizontal components of the gradient flow along the X and Y co-ordinates (U_g and V_g), as estimated by the dynamic method, may be represented by the following expressions:-

$$U_g = \frac{g}{C\,\varrho_0} \int_0^z \frac{\delta \varrho(x,y,z)}{\delta y}\, dz$$

$$V_g = - \frac{g}{C\,\varrho_0} \int_0^z \frac{\delta \varrho(x,y,z)}{\delta x}\, dz \qquad (1)$$

where $\varrho\,(x,y,z)$ is the density of sea water and ϱ_0 its mean value, assumed as constant; g is the acceleration of gravity;

$C = 2\,\omega \cdot \sin \varphi$ is the Coriolis parameter, where ω is the angular velocity of the earth's rotation,

φ is the geographical latitude of the place,

(In this case the beginning of co-ordinates corresponds to the zero isobath surface, the axis Z being directed vertically upwards.

There are two ways of calculating the integrals in the right-hand sides of the expressions (1). The first method consists in application of density models with subsequent introduction of basic flow values (1,2,3,4,6,7) into the expressions of velocity. The second one concerns application of the equation of density diffusion (10). Current velocity values are then determined by direct integration of the available system of differential equations. However, in this case serious mathematical complications may arise which do not permit so far to create sufficiently convenient practical methods of calculation of wind drifts for the actual physico-geographical conditions.

Since application of density models permits to solve this task without unnecessary mathematical complications and, at the same time, with a degree of precision sufficient for practical purposes, many authors now give preference to the first method despite its lower accuracy from the viewpoint of pure hydrodynamics.

Let us consider an application of the density model suggested by V.B. Shtokman (3,4,6,8,9).

$$\varrho\,(x,y,z) - \varrho\,(0) = - \delta\,(z)\,.\,f(x,y) \qquad (2)$$

where $\varrho(x,y,z)$ is the density of sea water, and

$\varrho\,(0)$ its constant value at the lower border of the barocline layer within which the wind drift is developing;

$f\,(x,y)$ is a function characterizing the effect of wind circulation on the transformation of the density field as adapted to the wind-produced system of currents (this function is called the function of influence)

$\delta(z)$ is a function reflecting the vertical distribution of density within the area of water masses of homogeneous structure.

Two principles are involved in the basis of the density model (2): a constant character of density on the lower border of the baroclinе layer encompassed by the current, and the likeness of the curves of vertical distribution of density, within the whole area covered by the density model. Though these principles seem somewhat unnatural and do not follow directly the theory, the referred limitations with regard to density variations are not inconsistent with the real conditions observed in the seas and oceans. As shown by the observational data, similarity of the vertical distribution of sea water density within the whole areas is a typical feature of density distribution in the sea or ocean. On the other hand, such similarity of vertical density distribution is identical to the similarity of temperature-salinity curves which, in its turn, is equivalent to the similarity of vertical structure retained by the water masses within these areas.

Substitution of (2) into (1) gives the following expressions for the horizontal components of the gradient current:-

$$U_g = -\frac{g}{c\rho_o} \cdot \frac{\delta f\ (x,y)}{\delta y} \int_0^z \delta(z)\, dz$$

$$V_g = \frac{g}{c\rho_o} \quad \frac{f\delta(x,y)}{\delta x} \int_0^z \delta(z)\, dz \qquad (3)$$

If the function of influence $f\ (x,y)$ is expressed through the horizontal components of the basic flow S_x and S_y, then the expressions for U_g and V_g will obtain the following form:-

$$U_g = -\left(\frac{1}{\bar{\rho}} \cdot \frac{T_y}{c} - S_x\right) \cdot F\ (z)$$

$$V_g = \left(\frac{1}{\bar{\rho}} \cdot \frac{T_x}{c} + S_y\right) \cdot F\ (z) \qquad (4)$$

where

$$F(z) = \frac{\int_0^z \delta(z)dz}{\int_0^H dz \int_0^z \delta(z)dz} \qquad (5)$$

T_x and T_y are the horizontal components of the tangential wind stress, $\bar{\rho}$ is the mean value of density within the limits of the baroclinе layer, and H is the thickness of this layer.

$F(z)$ is called the function of stratification (3,4) since it reflects the effect of the vertical stratification of sea water on the gradiental component of current velocity. This function is assumed as being constant for each layer within the whole area with homogeneous structure of water masses.

In this connection it is important for the appraisal of precision of current velocity estimates to know whether the stratification function $F\ (z)$ is really constant in the horizontal direction, and if not, what errors in determination of current velocity may result from the changes of the function $F(z)$. This problem was dealt with by L.M. Fomin (3,4) who came to the conclusion that numerical values of the function $F(z)$, as estimated for different stations within any one area, are close to each other. The differences do not exceed a few units of the second place, so the corresponding maximum error in determination of the gradient flow would make about 4% of its real value. In as much as the drift component of the current velocity does not depend on the structure of the density field the error in the definition of the total flow will tend to diminish.

Consequently, for application of the density model (2) it is enough to know the vertical distribution of density in any one point within the area of water masses of homogeneous structure, the initial vertical line being chosen at random.

Besides, for application of the considered density model it is necessary preliminary to divide the areas of the sea (or ocean) by the similarity of T-S curves, having defined the areas of a homogeneous vertical structure of water masses and the borders between them.

However, such areal division has not been done so far for all seas and oceans. In the North Atlantic such division was given by Jacobsen in his work published in 1929 (11). It was based on the hydrological data collected in the Atlantic Ocean during the expedition of "Dana" in 1921-22. In view of the scanty character of these data, some other expeditionary observations performed in different years, were also used, in particular those obtained on the "Planet" (1906-07), "Michael Sars" (1910), "Möwe" (1911), "Scotia" and "Margrethe" (1913) and some others. The area covered by these observations extends from the equator to 50°-60°N.

Using the T-S curves Jacobsen, as a result of the analysis, has described both the main water masses and those that are formed as a result of their mixing. On the basis of typification of the T-S curves Jacobsen divided the investigated part of the Atlantic Ocean into 24 areas in accordance with the types of water (fig.1). Each one of these areas is characterized by a homogeneous structure of water masses. Jacobsen presents a detailed description of all these areas and respective water masses.

Evaluating the importance of this work to-day one should note some drawbacks related exclusively to the selection of background hydrological data. When marking out the areas Jacobsen could make use of only a very limited number of observations, very unevenly distributed in space. Some areas included as little as 2 or 3 hydrological stations. Furthermore, the analysis comprised observations performed during different seasons in different years. Consequently, the condition of simultaneity of observations, which even now is not so strict and permits to use observations extended in time for 1-2 months, has not been observed.

Similar work on the areal division of the Northern Atlantic Ocean, and within the same limits as in the Jacobsen's work, was performed in 1957 in the diploma thesis by N. Ivanova, Chair of Oceanography, the Leningrad University, under the guidance of A.P. Belyshev. All observational data were used that were collected during the period of 1914-1957, 20 areas were marked out, but the results of this work have not been published.

One more work should be mentioned here which deals with the definition of regions of homogeneous water masses in the central part of the North Atlantic. In 1960 O.J. Mamaev (12) analysed the water masses on the basis of the hydrological observations obtained during the fourth cruise of the R/V "Mikhail Lomonosov" (1 October - 10 December, 1958). Mamaev marks out four main water masses in the area within the limits from 40°N to 50°-55°N., in full accordance with the generalized data by Sverdrup (13), and establishes the borders between them. He points out 5 regions with homogeneous structure of water masses: four for the marked out water masses, and one transition zone associated with the horizontal transformation between the Gulf Stream waters and the Labrador Current waters. It must be noted, however, that the comparatively small area covered by the hydrological observations on the R/V "M.Lomonosov" did not allow the author of the referred work to clearly fix the regions with identical structure of water masses. The borders were drawn by him only partially: they divide water masses only within the area of survey. Furthermore, the area occupied by the North Atlantic water mass is merely outlined without an account of the zonal transformation which is analysed by Mamaev in detail and, if taken into consideration would have led to a division of this area into two regions.

As seen from the referred works the areal division of the North Atlantic into regions of homogeneous water masses was performed only within the space from the equator to 50°-55°N. At the same time the wind drift computations which are presently being made at the Chair of Oceanology of the Leningrad Hydrometeorological Institute cover more northward latitudes including those of the Norwegian and Greenland Seas. This necessitates the areal division on the basis of homogeneity of the structure of water masses over the whole northern part of the North Atlantic.

The present paper gives the results of such division for the area extending from 35°-40°N to 75°-80°N. The work comprises the results of deep water observations collected in the North Atlantic during the International Geophysical Year. The hydrological surveys were used that were performed by the Soviet and foreign (American, British, Danish, etc.) vessels in March-April, July-August, and September-October 1958, i.e., in different seasons of one and the same year. This enabled us to make an appraisal of the seasonal changes of the borders of the established regions. A short summary of the expeditional observations that were used in this work, is given in Table 1.

The method of T-S curves was adopted as a basic one, as it is now considered the most valid and convenient for identification of water masses. So, the method used in this work is quite similar to the one applied by Jacobsen.

Altogether 520 curves T-S were constructed. The main water masses were determined by means of these curves and their thermohaline indices were compared with the values given by Sverdrup (13), Mamaev (12) and other authors. Then, in accordance with the identified water masses, the typification of the T-S curves was made after which it was relatively easy to establish the water masses.

The limited size of the present paper does not allow the author to dwell on the typification of the T-S curves itself within the established water masses. An analysis of the typification performed with samples of the typical T-S curves for each area, as well as the characteristics of the water masses of each area, will be given in another paper which is to be published in the Proceedings of the Leningrad Hydrometeorological Institute.

In the present paper we confine ourselves to determination of the borders of the areas having a homogeneous structure of water masses because this part of the work is greatly needed for wind drift computations.

The results of the work on the areal division of the North Atlantic are given in three charts (figures 2,3,4) constructed for the spring, summer and autumn of 1958. Sixteen regions were mapped altogether, including 5 in the Norwegian and Greenland Seas. It must be noted that in summer 1958 almost no hydrological observations were registered in the Norwegian and Greenland Seas, and in spring and autumn almost no observations were carried out in the extreme north-western part of the North Atlantic. In view of this, the borders between the identified areas were not marked on the summer charts of the Norwegian and Greenland Seas (they were merely outlined in the southern parts of these seas); neither were they marked on the spring and autumn charts of the Labrador Sea and Davis Strait. The entire central and northern parts of the North Atlantic were well covered by observations in 1958, therefore the borders between the regions with a homogeneous structure of the water masses were lined on all three seasonal charts.

A comparison of all these charts permits to draw a conclusion on the seasonal variability of the established borders. The seasonal changes are, on the whole, rather small and the borders between separate areas undergo only insignificant alterations. More noticeable changes are observed from spring to summer and from summer to autumn on the borders between the areas 6 and 7, as well as between the areas 1, and 3, 2 and 3, i.e., in the zone of transformation of the Mediterranean water and in the transitional zone of transformation between the waters of the Gulf Stream and the Labrador Current. In this case the spring and autumn charts have the closest similarity; in comparison with them the summer chart is characterized by more pronounced alterations of the borders, especially in the referred zones of transformation. However, all three charts pretty well repeat one another and are indicative of a seasonal stability of space distribution of the areas occupied by homogeneous water masses.

A comparison of the constructed charts with the chart produced by Jacobsen shows good agreement in the places where those charts overlap, especially in the eastern part of the North Atlantic where such overlapping is greatest. Similar correspondence is observed when the constructed charts are compared with the borders established by Mamaev.

In conclusion the following inferences can be drawn:-

1. As a result of the work done the areal division was performed on the basis of similarity of vertical structure of water masses of a vast area of the North Atlantic extending from 35°-40°N to 75°N.

2. Seasonal alterations of the borders between the marked out areas are not great and can practically be ignored for the most part of the North Atlantic with the exception of the transformation zones of the Mediterranean waters and those of the Gulf Stream and the Labrador Current.

3. Together with the areas defined by Jacobsen the areas established in the present work cover the whole space of the North Atlantic from the equator to 70°-80°N.

4. Taking into consideration the scanty character and different time of the hydrological observations used in the work of Jacobsen, it seems advisable to repeat the areal division of the North Atlantic from the equator to 40°-45°N. taking advantage of the new data, first of all those collected during the International Geophysical Year.

Literature

1. Felsenbaum, A.I.: On the theory of sea currents - Trudy GOIN, No.29, 1955.

2. Felsenbaum, A.I.: Theoretical foundations and methods of computations of steady currents - USSR Academy of Science publication. (Moscow, 1960).

3. Felsenbaum, A.I. and Fomin, L.M., and Shtokman, V.B.: A method of computation of deep sea currents by means of the surface flow and atmospheric pressure gradient - Trudy Instituta Okeanologii, USSR Academy of Sciences, Vol. 25, (1957).

4. Fomin, L.M.: Theoretical foundations of the dynamic method and its application in oceanology - Publishing House of the Academy of Sciences of the USSR, (Moscow, 1961).

5. Lineikin, P.S.: A modified method of determination of oceanic currents - Trudy GOIN, No. 67, (1962).

6. Tyurjakov, B.I.: An approximate method of computation of sea wind drifts - Papers of the Conference on the problem of "Interaction of atmosphere and hydrosphere in the northern part of the Atlantic Ocean", No. 3-4, Leningrad, Gidrometeoizdat, 1961.

7. Tyurjakov, B.I.: An attempt to apply calculation in the study of variability of wind drifts in the deep sea - Trudy LGMI, No.16, Leningrad, 1962.

8. Shtokman, V.B.: Determination of current velocities and distribution of density in the cross-section of an infinite channel-Doklady Akademii Nauk SSSR, Vol. 71, No. 1, 1950.

9. Shtokman, V.B.: Determination of stationary currents and the field of water masses caused by wind in a barocline sea - Trudy Institute Okeanologii, Vol. 6, 1951.

10. Lineikin, P.S.: Main problems of the dynamic theory of the barocline sea layer - Gidrometeoizdat, 1957.

11. Jacobsen, J.P.: Contribution to the hydrography of the North Atlantic - The "Dana" Exped. 1921-1922, Oceanographic Reports edited by the "Dana" Committee, No. 3, Copenhagen, 1929.

12. Mamaev, O.I.: On the water masses of the North Atlantic and their interaction - Trudy Morskogo Gidrofizicheskogo Instituta, Vol. XIX, Moscow, 1960.

13. Sverdrup, H.U., Johnson, M.W., and Fleming, R.H.: The Oceans, their physics, chemistry and general biology - N.Y. Prentice Hall, Inc. 1942.

SUMMARY

1. When applying the calculation methods to the study of steady sea and oceanic wind drifts the basic difficulty is encountered in connexion with determination of the gradient flow. It can be determined with sufficient precision by means of the dynamic method suggested by Bjerknes and Sandström. There are two ways of doing this: one is connected with utilization of density models, and the other with application of density diffusion equations. In many works preference is given to the first method because of the mathematical complications involved in utilization of the equations of density diffusion.

2. In this paper a density model by V.B. Shtokman is considered. Its application is based on two assumptions:

   1) on the constant density on the lower border of the barocline layer, and
   2) on similarity of the curves of vertical distribution of density within the whole area covered by the density model. The latter condition is equivalent to the similarity of the T-S curves which means that within these areas the water masses retain the similarity of vertical structure.

3. To use the density model of Shtokman it is first necessary to divide the areas of the sea or ocean by the similarity of the T-S curves by marking out the regions with homogeneous vertical structure of water masses and establishing the borders between them.

4. Such areal division for the Northern Atlantic Ocean was performed by Jacobsen in 1929, however, it was confined to the space from the equator to 50°N-55°N and based on the scanty and very dissimilar hydrological observations.

5. In the present work the results of such areal division are given for a vast area extending from 35°-40°N to 75°-80°N. The data are used that had been collected in the North Atlantic during the International Geophysical Year. The results of the work on the areal division of the North Atlantic are given in three charts constructed for the spring, summer and autumn seasons of 1958. Sixteen regions were mapped altogether, five of them for the Norwegian and Greenland Seas. It was found that seasonal alterations of the borders between the marked out regions are not great, so one may speak about the seasonal stability of the space distribution of the areas occupied by homogeneous water masses.

Table 1

Spring (III-IV)			Summer (VII-VIII)			Autumn (X-XI)		
R/V	Area	Nos.of stations	R/V	Area	Nos.of stations	R/V	Area	Nos,of stations
"Polyarnik"	Norwegian and Greenland Seas	29-56 102-130	"M.Lomonosov" 3rd cruise	NE part of the North Atlantic	198-213	"Polyarnik"	Norwegian and Greenland Seas	29-57 102-130
"Sevastopol" 8th cruise	Norwegian and Greenland Seas	1356-1461	"Sackville"	W.and NW parts of the North Atlantic	1-51	"Sevastopol" 10th cruise	Norwegian and Greenland Seas	1695-1810
"Equator"	NE part of the North Atlantic	52-77	"Discovery II"	E.and NE parts of the North Atlantic	3823-3911	"Equator"	NE part of the North Atlantic	133-184
"M.Lomonosov" 2nd cruise	Central and northern parts of the North Atlantic	56-152 171-196	"Dana"	Northern part of the North Atlantic (off Iceland and Greenland)	93-192	"M.Lomonosov" 4th cruise	Central part of the North Atlantic	215-316
"Le Verrier"	Northern part of the North Atlantic	Point A 5	"Explorer"	Icelandic area	1-11, VII 1-32, VII-VIII	Ocean Weather Station "I"	NE part of the North Atlantic	-
"Amiral Mouchez"	W approaches to the Strait of Gibraltar	1,2,3,4	"Aegir"	Southern Greenland Sea (off Iceland)	7,34,35			
			"Le Verrier"	Eastern part of the North Atlantic	Point K	"Mermoz"	Eastern part of the North Atlantic	Point K
"Panulirus"	The Bermudas	-	"Panulirus"	The Bermudas	-	"Panulirus"	The Bermudas	-
			Ocean Weather Station "M"	Norwegian Sea	-			
T-S curves constructed for 184 st.			T-S curves constructed for 156 st.			T-S curves constructed for 180 st.		

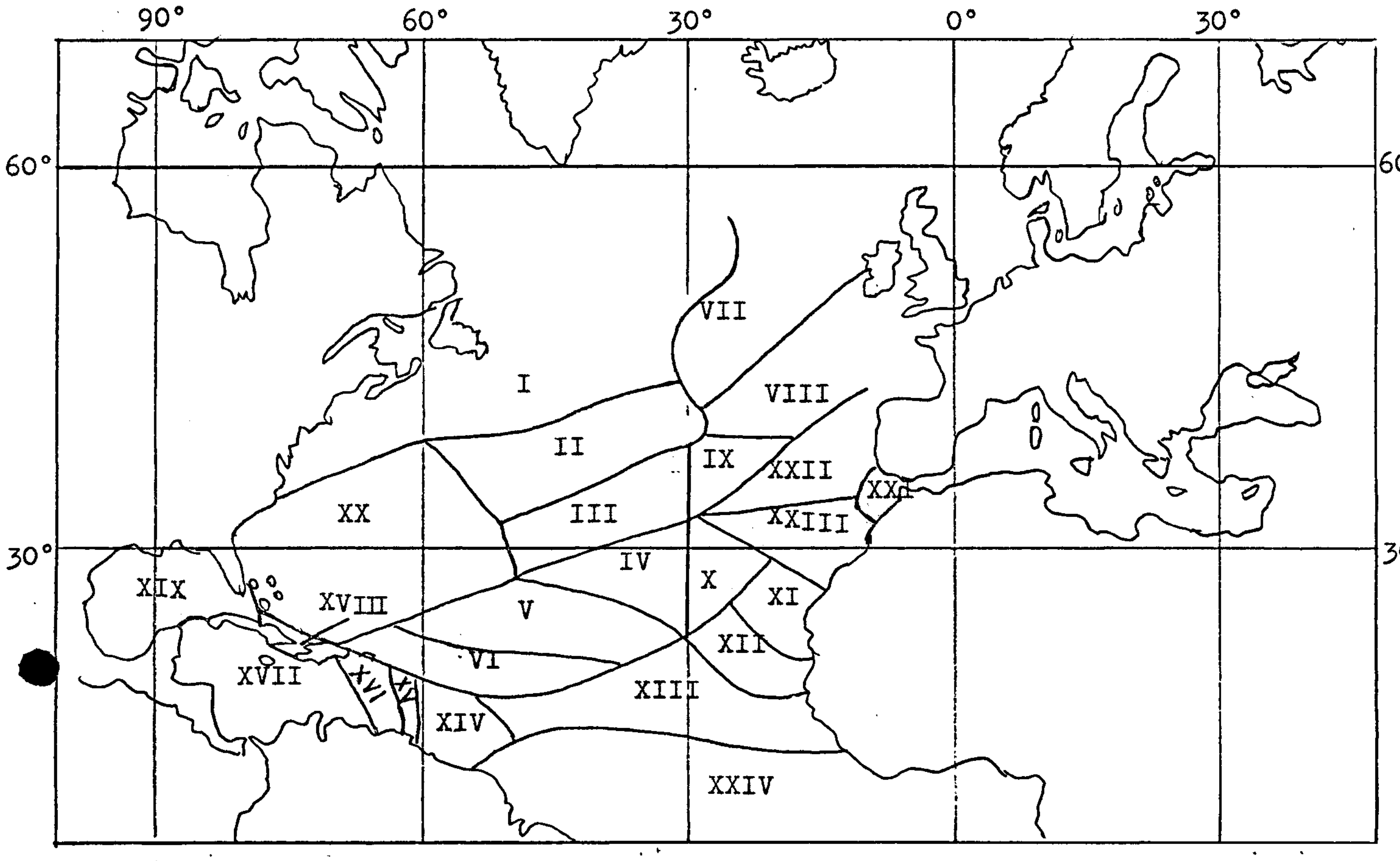

Figure 1. Areas of the North Atlantic having the homogeneous vertical structure of water masses according to Jacobsen.

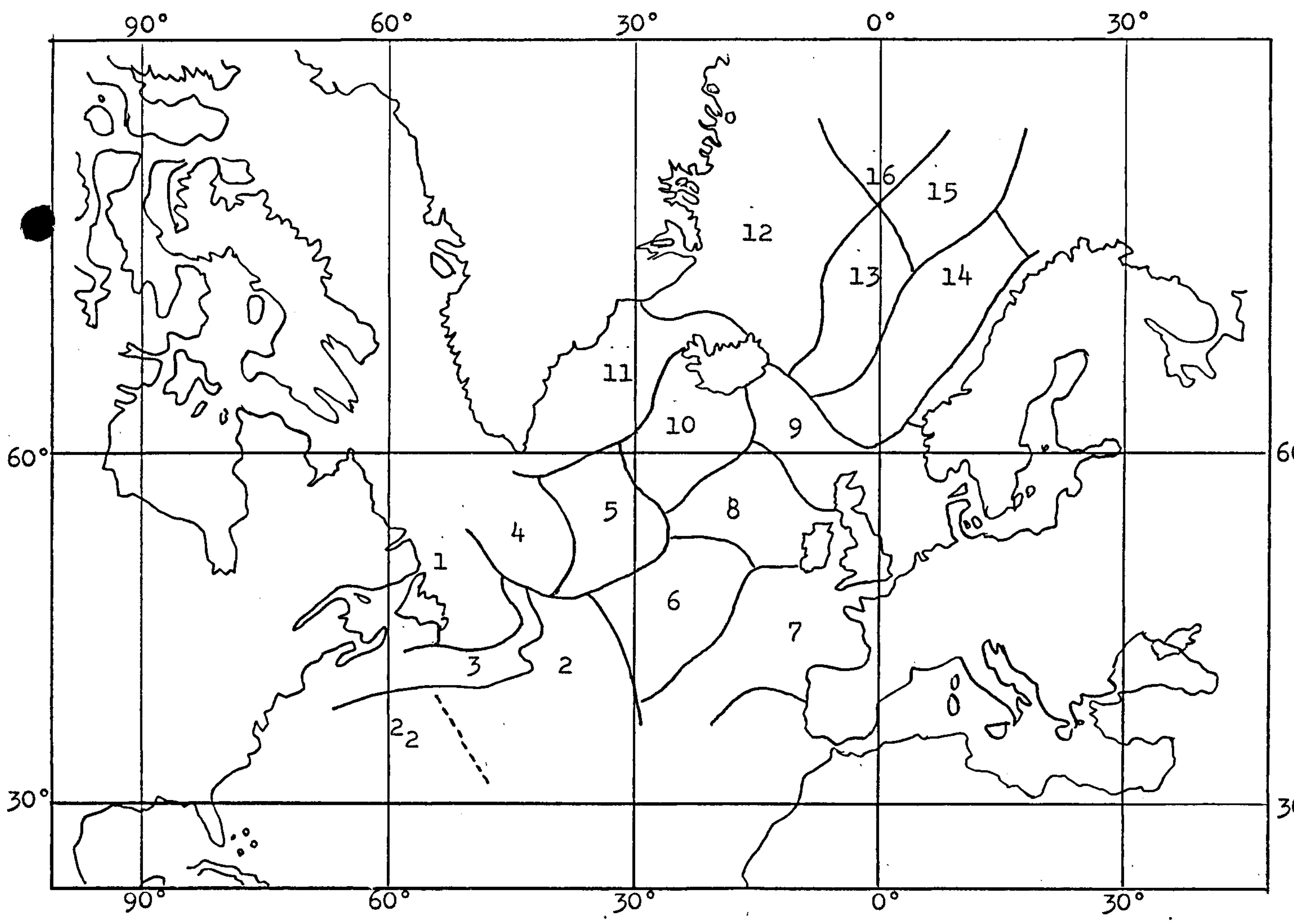

Figure 2. Areas of the North Atlantic having the homogeneous vertical structure of water masses (according to the observational

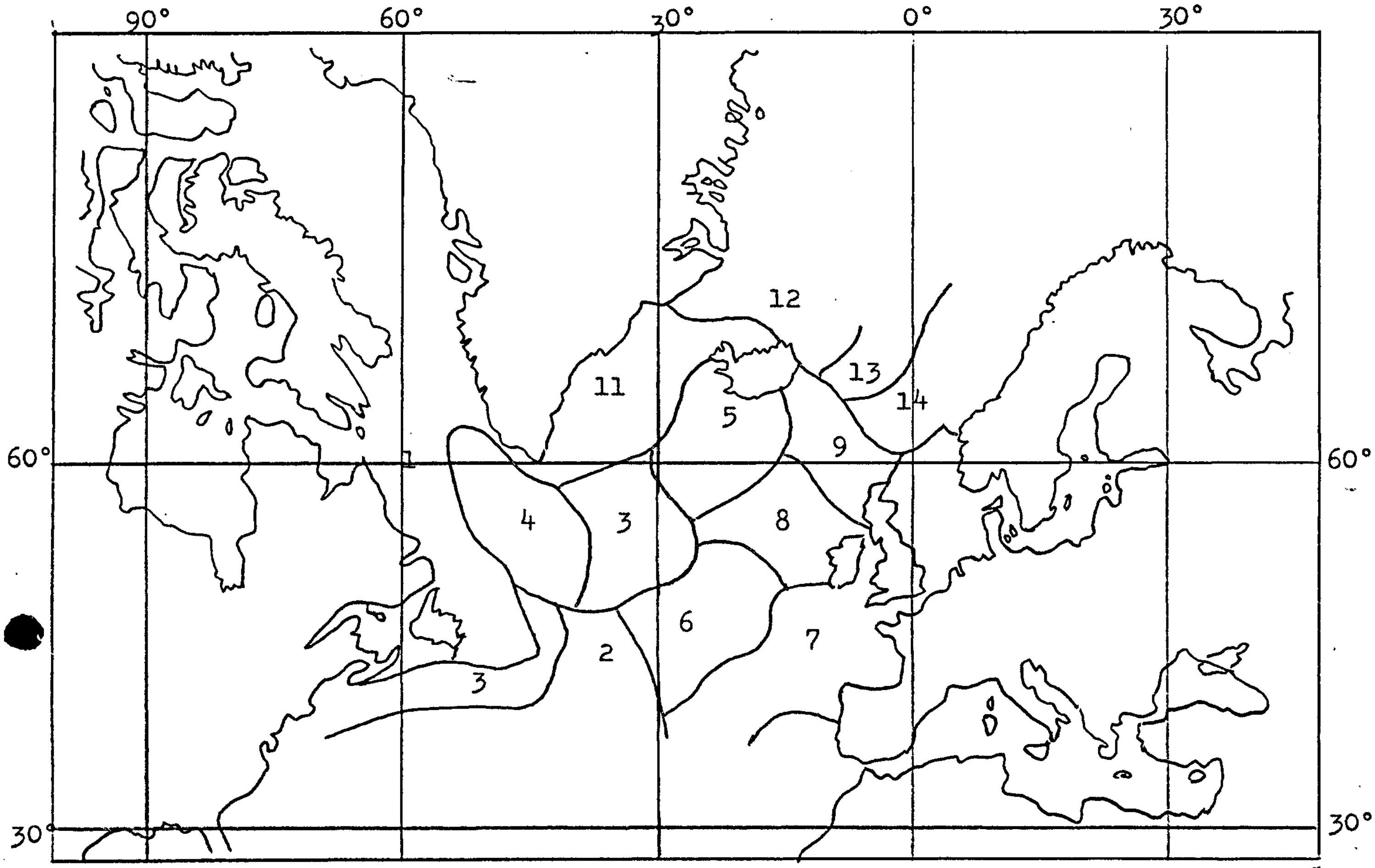

Figure 3. Areas of the North Atlantic having the homogeneous vertical structure of water masses (according to the observational data collected in July-August 1958).

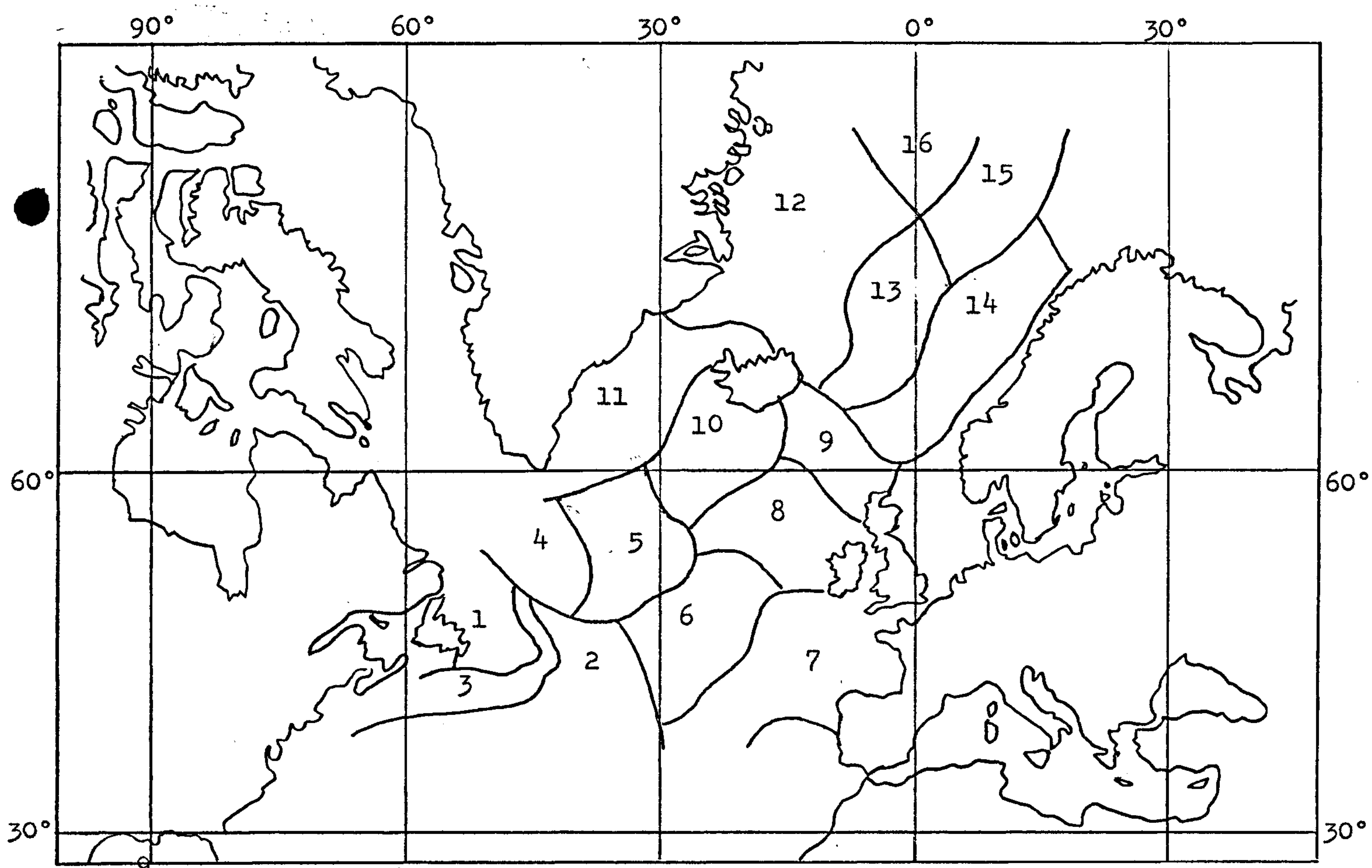

Figure 4. Areas of the North Atlantic having the homogeneous vertical structure of water masses (according to the observational data collected in October-November 1958).