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The surface of no motion in the northern part of the Atlantic Ocean

by

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Abstract.

The evaluation of the decrease of wind currents involved with the secondary wind effect calls for the use of the vertical scale H (the depth of baroclinity) which provisionally characterizes the depth of penetration of the wind and the thermic disturbances into the ocean depths and can be viewed as a total baroclinic effect at sea. The dynamic oceanologypermits to estimate the values of H.

Some authors have accepted $e^{-\pi} \sim 0.043$ in regard to an analogous velocity at the surface (V_o) and have treated it as a most simple relative criterion of a disturbance decrease for the estimation of the lower barocline boundary layer at sea; others assumed $e^{-2} V_o \sim 0.135 V_o$ and lastly some authors determine the vertical scale as a thickness of a layer beyond which the velocities are rather negligible.

The author of this paper has determined the surface of no motion according to the formulas for the calculation of baroclinity depth developed in the paper of Dr. P.S. Lineykin "A simplified method for the estimation of the surface and deep layers at sea far away from the coastal area" (1961) and his work "The wind and the thermohaline circulation at sea" (1961). The first formula used in this investigation for calculation purposes is derived from the careful examination of the well established currents with the prevalence of the horizontal one, whereas the second formula is based upon the assumption of the predominance of a vertical exchange at sea. The basic parameters of the formulae are chosen from published sources. The coefficients for the horizontal and vertical exchange at sea are $\nu_x = 10^8 \frac{cm^2}{sec}$, $\nu_z = 10^2 \frac{cm^2}{sec}$. (L) is the distance viewed as a characteristic horizontal scale in the examined area, where the wind stress alters twicefold.

In the course of calculation the author has adopted various values of $\beta = \frac{df}{dy} = \frac{2\omega\cos\varphi}{R}$ for each belt, thus, it was possible to reach an approximation near to the solution observed on spheric land (f is the Coriolis parameter); the density gradient b is calculated in the 100-1000 m layer.

The calculation of the depth of the no motion layer in accordance with the formulae was carried out for various areas of the World Ocean: in the Gulf Stream, in the North Atlantic current, in the Kuroshio etc. and produced satisfactory results. For example, in the midpart of the Gulf Stream the zero level, according to synchronous surveys (VII-VIII, 1960) was situated at a depth of 1150 m.; as one moves eastwards along the flow the current velocity gradually weakens the flow is less strafied and it lowers. The inclination across the Gulf Stream in various areas ranged within 300-700 m, whereas along the direction of flow it proved to be 400 m.

The average position of the zero level during the winter (XII-II) and summer (VI-VIII) period was estimated for the aquatorium of the North Atlantic on the basis of the very same formulae. The results are almost similar to the previous ones.

There is a provisional character and likeness between the idea of the zero surface and the depth of baroclinity: for comparative purposes one can obtain equivalent figures for the depth of the no motion layer and for the depth of baroclinity at the very same point of the calculated depth of baroclinity and the depth of the no motion layer determined by employing one of the methods for the estimation of the latter (for the sake of comparison the author used A. Defant's method) by introducing an empirical coefficient into the formula of depth baroclinity.

The comparison of the calculatory results, accomplished with the formula which takes into account the horizontal turbulent exchange, and the average position of the surface of no motion according to A. Defant (1941) along the 30°W meridian and its comparative examination with the position of the zero level for single hydrological sections have led to the establishment of empirical coefficients attached to the formula for the calculation of H which alters in regard to latitude (k (φ)) :-

φ : 10°-20° $k \sim 1.8\pi$

φ : 20°-40° $k \sim \pi$

φ : 40-60° $k \sim 0.5\pi$

This range of variations of empirical coefficients has appeared, most probably, at the cost of insufficient consideration of the geographical latitude

$\left(H \sim \frac{\sin\varphi}{\cos\varphi}\right)$ in the theoretical formulae; the comparative study of the calculatory results carried out in agreement with the formula with a due consideration of turbulent exchange $H \sim \sin\varphi$ led to the empirical coefficient which amounts to 2.4.

The calculated depth of the no motion layer almost does not change along the parallel and it follows the planetary pattern observed in Defant's paper, i.e. it descends as one moves towards the higher latitudes and is situated between the intermediate Antarqtic and the abyssal water masses. The Gulf Stream area is characterized by the drop of the latter in the cross-current direction.

The seasonal variations of the depth of the no motion layer basically develop owing to the seasonal changes of density in the surface waters. During the year the situation of the zero level throughout large basins of the tropical and equatorial latitudes is almost of stationary character (near 25 N. ~ 1000 m, near 10 N. ~ 700 m).

In the northern areas, particularly in the areas of the Polar front which is highly mobile and exhibits a strongly pronounced difference of water properties, one observes changes in the position of the zero level ranging from the summer period (1000-1300 m) to the winter period (1500-1800 m); these changes are sometimes rather great, amounting to 500 m and even more.

The amplitude of seasonal variations of the depth of the no motion layer in the area of escape of Mediterranean waters and in the upwelling area near the African coast amounts to 200 m.

Transient variations in the position of the zero level are rather great; even in such a stabilized flow as the Gulf Stream the fluctuations of H run beyond 200 m. (calculations were carried out at a 3 hour interval).

The calculated values in regard to the surface of no motion fully coincide with the data obtained in the course of instrumental observations devoted to current studies.

The advantageous aspects of the method employed by the author lie in its simplicity, easy handling of the formulae which provide definite results and give a possibility to determine the zero level at sea on the basis of only one series of observations collected at a single hydrological station.

The determination of the position of the surface of no motion in the ocean is a matter of substantial significanse for the study of currents with the aid of the dynamic method.

The efforts of many foreign investigators (G. Dietrich, 1936; A. Parr, 1938, A. Defant, 1941; Riley, 1951, Sverdrup, 1942; H. Stommel, 1956; K. Hidaka, 1949; and Soviet oceanographers: O.I. Mamaev, 1955; Fomin, 1961 have been directed towards the development of methods for the estimation of the zero level which resulted in the establishment of several methods for the determination of the zero layer at sea.

Each of the mentioned methods has several drawbacks and cannot be regarded as a universal one.

Dynamic oceanology provides some means for the determination of the characteristic scale for the penetration of wind and thermic disturbances into the sea depth.

Referring to an analogy with the drift currents Ekman adopted a vertical scale D (depth friction) for the evaluation of the decrease of wind currents connected with the secondary wind effect; in this case a vertical scale H (depth of baroclinity) is applied.

The depth of baroclinity provisionally stands for the total baroclinic effect under conditions of wind currents at sea. This phenomenon is dealt with in the works of V.B. Shtokman (8), P.S. Lineykin (2,3,4), Kamenkovich (1), Stommel and Veronis (6).

In some works the decrease of disturbances $e^{-\pi} \sim 0.043$ in regard to an analogous velocity at the surface (V_0) is adopted as the most simple relative criterion for the determination of the lower baroclinic layer. In other studies the vertical scale is defined as a thickness of a layer which exhibits considerable velocities.

There is a provisional character and likeness between the idea of the zero surface and the depth of baroclinity: for comparative purposes one can obtain equivalent figures for the depth of the no motion layer and for the depth of baroclinity at the very same point of the calculated depth of baroclinity and the depth of the no motion layer determined by employing one of the methods for the estimation of the latter (for the sake of comparison the author used A. Defant's method) by introducing an empirical coefficient into the formula of depth baroclinity.

The author has made an attempt to apply the formulae for the calculation of the depth of baroclinity developed in the papers of P.S. Lineykin (2,3,4) in the immediate physico-geographical areas (hydrological sections running through the Gulf Stream, the North Atlantic current, the Kuroshio and along 40° l. in the Indian Ocean)

$$H = \sqrt{\frac{f^2 \rho_o \nu_x}{g . \beta . L . b}} \qquad (1)$$

$$H = \sqrt[4]{\frac{\varepsilon \nu_z . L . \rho_o f^2}{b . g . \beta}} \qquad (2)$$

ν_x and ν_z stands for the kinematic coefficients of eddy viscosity at sea in the horizontal and vertical directions, ε stands for the ratio of the eddy diffusion coefficient of density (in the vertical direction) to the corresponding coefficient of eddy viscosity, ρ_o is the characteristic value for the sea water density, f the Coriolis parameter, L the characteristic horizontal scale in the examined area, the parameter $\beta = \frac{df}{dy}$ characterizes the variation of rate in f along the meridian, b the density gradient of sea water.

Formula (1) is derived in the course of the solution of a plane problem; the examination of the steady wind currents in an ocean of infinite depth where the horizontal dimensions do not exceed 500 km. permits to assume that the Coriolis' parameter value f alters in the linear direction in accordance with the latitude $\beta = \frac{df}{dy} = \text{Const} \neq 0$ $f = f_0 + \beta y$. It is supposed that these currents are of geostrophic nature and that at sea the horizontal eddy diffusion prevails. Formula (2) is derived on the basis of solving a problem on spheric land for the planetary circulation in cases when the vertical turbulent exchange plays a predominant role at sea.

The selection of the basic parameters has been made in accordance with the literary sources. It is accepted that $\nu_x = 10^8 \frac{cm^2}{sec}$ and $\nu_z = 10^2 \frac{cm^2}{sec}$

The horizontal scale (L) in the open sea is adopted in agreement with the characteristic dimensions of the wind field: L is the distance and throughout its stretch the stress of the wind changes twice; for the North Atlantic area this figure amounts to about 1000 km.

In the course of deriving formulae it was assumed that $\beta = \frac{df}{dy} = \text{Const} \neq 0$
The calculation for each belt was based on the varied value of $\beta = \frac{df}{dy} = \frac{2\omega \cos\varphi}{R}$

(R earth's radius, f latitude of the examined area); a similar approach helped to solve the problem on a spheric area. The density gradient b was figured out in regard to the 100-1000 m layer. Its role in the surface layer has not been taken into account, for density variation in this layer is frequently of accidental nature. The lower horizon for the calculation of b has been provisionally ascribed to the 1000 m horizon. Value b which is incorporated into the calculatory formulae depends on H. successive multiplying operations help to make the choice of the lower density horizon depth more precise.

The depth of baroclinity was calculated in accordance with formula (1) aboard the expeditionary ship "M.Lomonosov" (VI-IX, 1960) for two hydrological sections running through the Gulf Stream (fig.1 and 2). Its value agrees fairly well with the depth of the no motion layer examined in the very same section sites which were established (for the sake of comparison) with the use of A. Defant's method.

Up to late there were no hydrologic investigations elucidating the midpart of the Gulf Stream and, hence the analysis of the calculated material dealing with the depth of the no motion layer is certainly of great interest.

The curve reveals two elevations; the first one refers to the Gulf Stream; the water in the latter is strongly stratified (materials pertaining to stations 654-655) and the maximum rise corresponds to the depth of the no motion layer (1150 m) in the midpart of the current. There is a decline on both parts of the curve's maximum rise; on the right side of the curve the fall extends to the Sargasso Sea and amounts to 1850 m and the left part amounts to 1750 m. The stretch of the Gulf Stream in the area (approximately) is believed to be 45-50 miles.

The zero surface which depends upon the intensity of circulation and basically upon the value of the water's vertical stratification cannot have the very same position in the ocean for it is understood that the mentioned factors experience strong alterations and vary in regard to the ocean area.

The second elevation of the curve is observed at a 300 km. distance, and probably, refers to the waters of the Atlantic current. In the area between the two sections the Gulf Stream turns eastwards and is noticed in the second section, in the area of stations 671-672. Here the waters are less stratified than in the first area, the flow is weakened and dispersed and the penetration depth of the wind currents is situated in the midpart of the flow below 1550 m, in the right hand part away from the mean the depth is 1750 m and in the left hand part it is 2300 m; however, the curve reveals only one elevation. In the area between the sections the waters of the Antilla current have partly mixed with the waters of the Gulf Stream. According to the materials of GEK surveys the maximum currents at the first section were observed at station 655, the stretch of the Gulf Stream was estimated as 40-50 miles; in the second section the maximum velocities were noted at station 671 and fully coincide with the calculated values. According to our calculations the inclination of the zero surface in a crosswise direction towards the flow $(\frac{\delta H}{\delta x})$ in the first section is 700 m; at the second section 300 m; these observations agree with the published data (Neumann 1956). Some authors claim that the depth of the no motion layer along the flow is a constant characteristic; our calculations revealed that there is an inclination in the Gulf Stream and in the direction of the main flow which equals $\frac{\delta H}{\delta y} \sim 400$ m.

Fig. 3 represents a chart of the surface of no motion in the Gulf Stream area (based upon the materials of six synchronous hydrologic sections, VI-VII, 1960).

The position of the zero surface in the area of the Gulf Stream current system strongly varies.

The maximum rise corresponds to the midpart of the Gulf Stream (1150 m). The second elevation seems to correspond to the midpart of the Antilla current. In the north-eastern direction one notices a descent of the zero surface and at 38°N the diffused waters of the Antilla current merge with the waters of the Gulf Stream.

The position of the zero surface in a definite area changes in regard to the variation of the water structure. As an example of the transient change in the position of the zero surface the author cites the calculations performed at the buoy station in the Gulf Strem (4-6 VIII,196o); even in such a steady flow as observed in the Gulf Stream, the transient variations develop beyond 2oo m (during 3 hours) though the average diurnal situation alters negligibly.

The calculations dealing with the depth penetration of the gradient-convective currents in the North Atlantic current (expeditionary ship "Lomonosov" 11/10-10/12, 1958) produced an interesting picture.

In fig. 4 one can observe a fair agreement in the course of the curves produced according to the formula (1) and by the method of A. Defant. The strong variation of the depth of the no motion layer is conditioned by a complex picture of currents. The geostrophic currents of the area do not appear as a mighty uniform flow, the current has a multistream character and it is split up into separate brances with countercurrents.

The seasonal variation in regard to the position of the zero surface in some sections runs up to 500 m.

According to formula (1) the depth of the site should exceed the depth of baroclinity.

Besides, formula (1) is derived with a due account of the influence of horizontal viscosity and hence it was of interest to carry out calculations for all the above mentioned areas following formula (2)

$$\omega = 7.29 \cdot 10^{-5} \frac{1}{sec}, \quad \varepsilon = 0.1 \quad \nu_z = 10^2 \frac{cm^2}{sec}$$

$$H = 880 \sqrt[4]{\frac{\cos^2 \theta}{b}} \qquad (2a)$$

The depth of baroclinity directly depends upon the latitude of the site ($H \quad \sin\varphi$, $\theta^\circ = 90^\circ - \varphi^\circ$) and reciprocally depends on the water stratification.

Formula (2) reveals the very same regularity which was produced by A. Defant in a somewhat screened form when he was plotting the chart of the zero surface in the Atlantic Ocean.

The calculations according to formula (2) produced a somewhat weak relation regarding the depth of the no motion layer values following A. Defant's method.

The calculations based on the use of formula (1) in the Gulf Stream area, the Kuroshio and the 40° section in the Indian Ocean led to the discovery of an empirical coefficient close to the π value, which decreases with latitude.

According to the formula (2) the average empirical coefficient is approximately 2.4.

Bearing in mind the factthat many problems involved with the seasonal variation in the position of the surface of no motion are still not quite clear, the author has calculated the mean position of the latter during the summer (VI-VIII) and winter (XII-II) seasons for the Northern Atlantic.

The analysis of the data related to the depth of baroclinity (fig.5) and its comparison with the mean position of the zero surface according to A. Defant (1941) along the 30°W meridian (for each 5° belt) permitted to verify the empirical coefficients. The empirical coefficients K (φ) produced by calculations based on formula (1) for single hydrologic sections (for example, the Gulf Stream, the North Atlantic Current etc.) which were found somewhat earlier are in agreement with similar coefficients in the very same latitudes produced for the average multiannual values.

Three areas may be roughly singled out with the following empirical coefficients attached to them:

φ : 10°-20° $\quad k \sim 1.8\,\pi$

φ : 20°-40° $\quad k \sim \pi$

φ : 40°-60° $\quad k \sim 0.5\,\pi$

This range of variations of empirical coefficients has appeared, probably, at the cost of insufficient consideration of geographical latitude in the formula

(i.e. $H \sim \frac{\sin\varphi}{\cos\varphi}$)

The examination of the charts with the depth of the no motion layer throughout the summer and winter (fig.6) and the application of formula (1) proves that the order of values in the mid section of the Northern Atlantic is very close to A. Defant's data; substantial differences are observed only in the north-eastern, north-western and equatorial areas.

The zero surface reveals almost a zonal character throughout the greater equatorial part of the ocean. The Gulf Stream is characterized by an abrupt decrease of depth of the zero surface crosswise to the current.

The zero surface is in conformity with the very same planetary regularity observed by A. Defant, i.e. it descends towards high latitudes.

Owing to its low depths the zero surface does not experience the influence of the bottom relief and is situated basically between the Antarctic (intermediate) and the abyssal water masses.

The chart of seasonal variations of the depth of the no motion layer is of definite interest (fig.7).

As a rule the seasonal fluctuations in regard to the zero surface develop owing to the seasonal variations of density in the surface waters. In summer the position of the zero layer is somewhat higher, in winter on the contrary. Throughout vast basins of the tropical latitudes (south of 35°N) the seasonal variation in the density fluctuations is insufficient, and hence, the position of the surface of no motion during the year is almost of constant character. Various changes (at times up to 500 m) in the position of the zero surface ranging from the summer indices (1000-1300 m) to the winter characteristics (1500-1800 m) are observed in the northern areas, especially in the convergence area of the cold waters of Labrador and the warm waters of the Gulf Stream. In other words, these alterations are observed in the subpolar hydrological front which reveals high dynamic features and strongly pronounced difference in the properties of water and sharply distinguished seasonal change of its situation. The area north of the discharge of the Mediterranean waters exhibits a lesser (200 m) seasonal change. This area is under the influence of the somewhat colder waters inflowing from the North Atlantic current; the temperature of the waters becomes still lower near the north-western coast of Africa owing to the rise of the cold waters from the depths to the surface area.

The position of the subtropical line of convergence reveals a seasonal variation, but this line is pronounced neither in temperature nor in water salinity and, hence, it does not affect the position of the zero surface.

Throughout the vast water basin of the equatorial and tropical latitudes the position of the zero surface during the year is almost steady (for example, at 10°N. ∼ 700 m and at 25°N. ∼ 1000 m).

The results of calculations in accordance with formula (1) require specification in the position of the zero surface in regard to several areas. This can be achived under the condition that our knowledge of the spatial distribution of field density is more precise.

The order of values and the regularities involved with the spatial position of the zero surface produced with the use of formula (2) (fig.8) are approximately similar to those obtained with formula (1); the amplitude of seasonal variability in the latter case is somewhat larger.

Analogous results originated from the very same ocean aquatorium and produced on the basis of various physical premises give grounds to regard them as reliable. An observation of striking interest was made. It was learned that the position of the surface of no motion (fig.9) calculated according to formula (1) for the summer months of the North Pacific and with the use of the very same empirical coefficients, proved to be very much alike the picture noted in the North Atlantic: the depth of the no motion layer for the vast basin of the northern section of the ocean is almost unchangeable along the parallel, there are two exceptions - the Kuroshia area and the Californian current - which reveal severe changes of the zero surface. The significance of the zero surface increases with the latitude ranging from 400-1300 m.

In several areas the role of density was not fully grounded and this fact conditioned the lack of reliability in some values concerned with the zero surface in the near-coastal areas.

The calculated values involved with the zero surface were compared with the results of current observations.

The author's calculation have shown that the utilization of a uniform average value in regard to the depth of no motion layer throughout various seasons (in the course of current calculations by applying the dynamic method) is possible in vast ocean spaces ranging from the equator to 35°N.

In northern areas especially in the area of the Polar hydrologic front and near the African coast the knowledge of the depth of the no motion layer during separate seasons of the year is a matter of immediate necessity, otherwise the average chart of A. Defant or the assumption concerning the average uniform zero surface throughout the year may lead to serious errors and distort the current pattern.

The knowledge of but the average position of the zero surface for hydrological sections in the areas of complex current systems (the Gulf Stream, the Kuroshio) with stratified waters in various parts of its course results in grave faults during the calculation of the geostrophic currents.

The results of the calculations are quite satisfactory. It is worth to mark the simplicity of calculations based on the mentioned formulae, the definiteness of values, the possibility to determine the zero surface in the open sea areas on the basis of the very first series of observations obtained during the hydrological station.

The calculations of depth (H) based on the formulae of the theory of baroclinic layer are quite promising.

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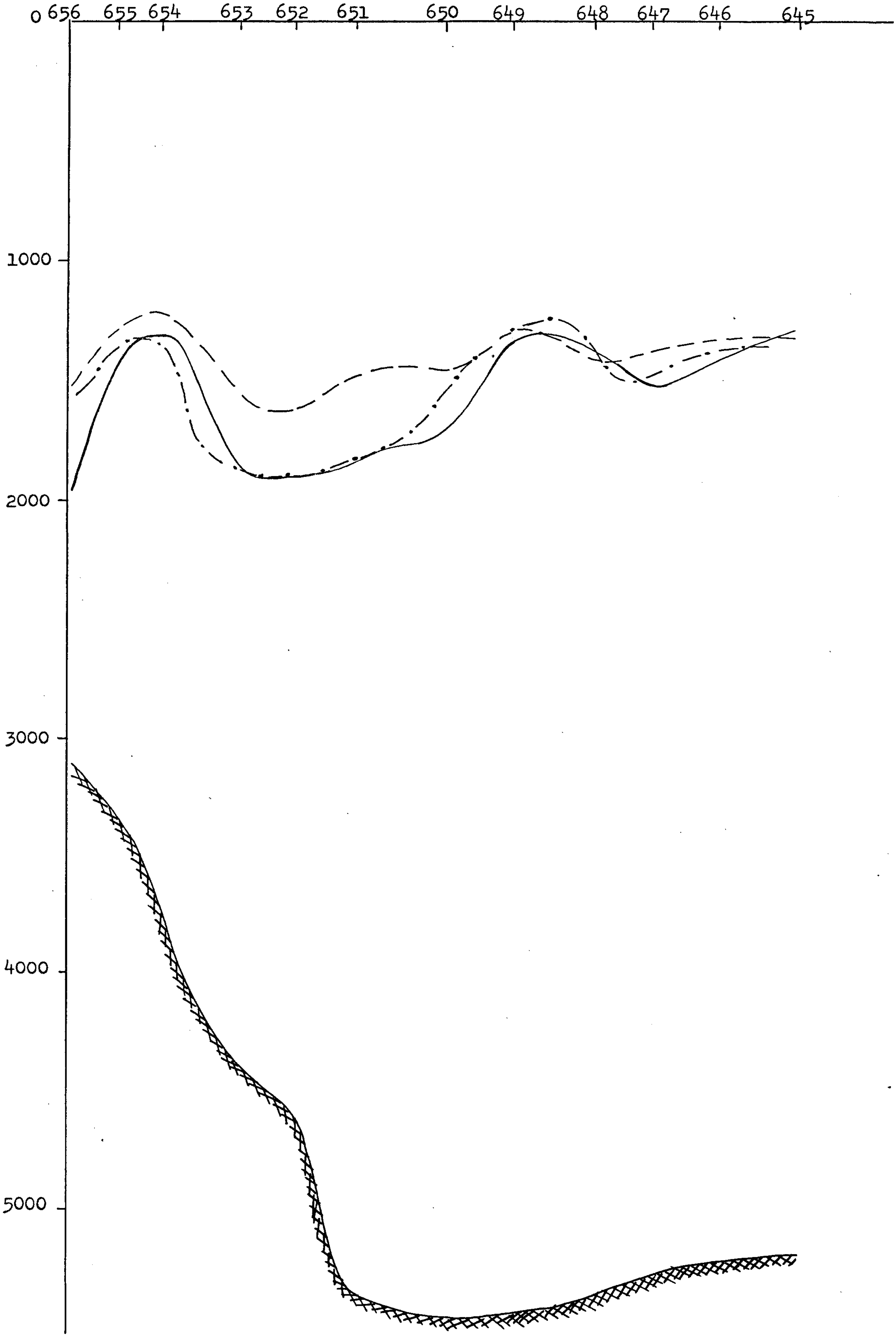

Figure 1. The depth of the no motion layer at sections running through the Gulf Stream calculated according to formula (1) and formula (2) by applying A. Defant's method.

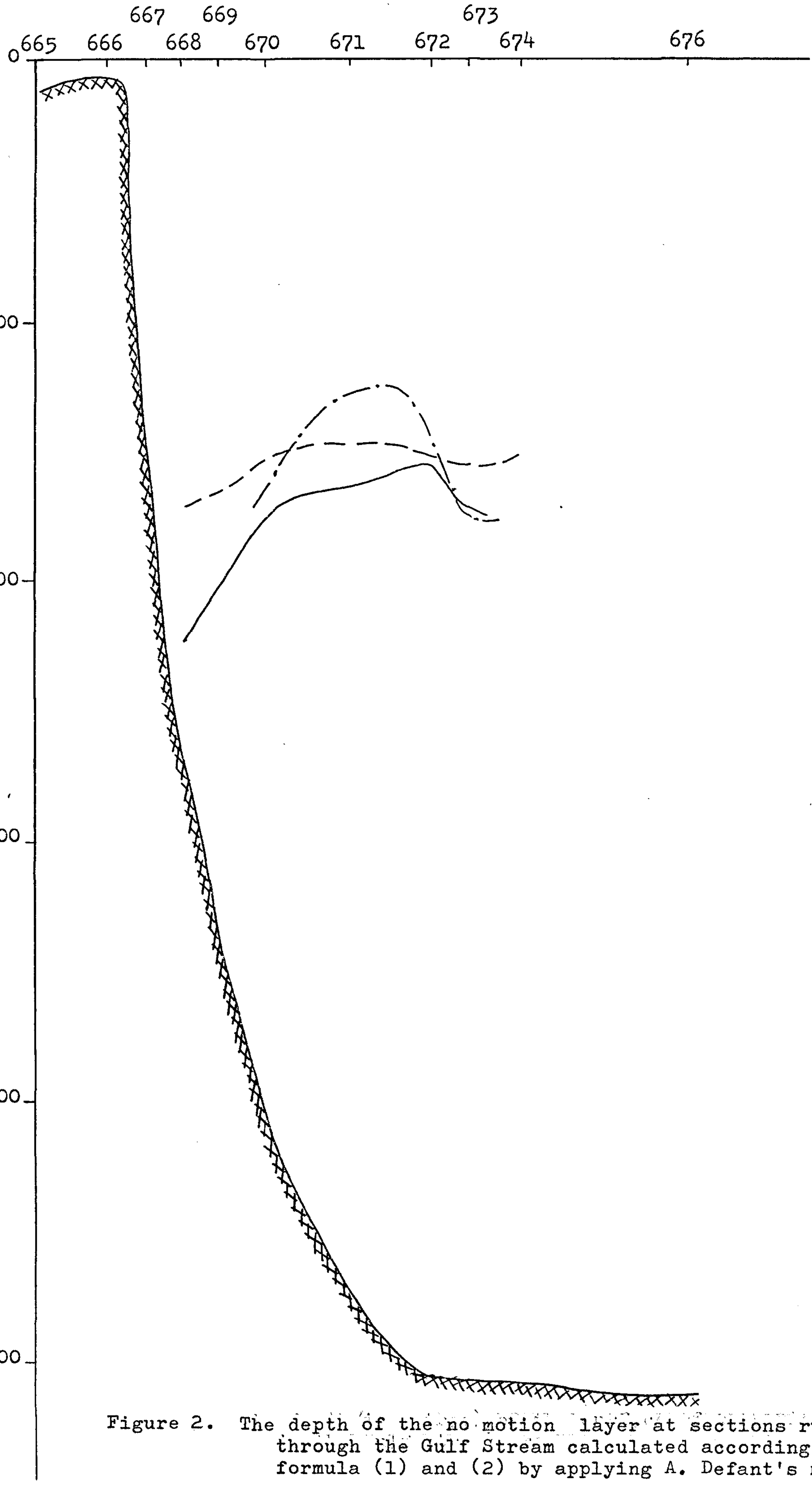

Figure 2. The depth of the no motion layer at sections running through the Gulf Stream calculated according to formula (1) and (2) by applying A. Defant's method.

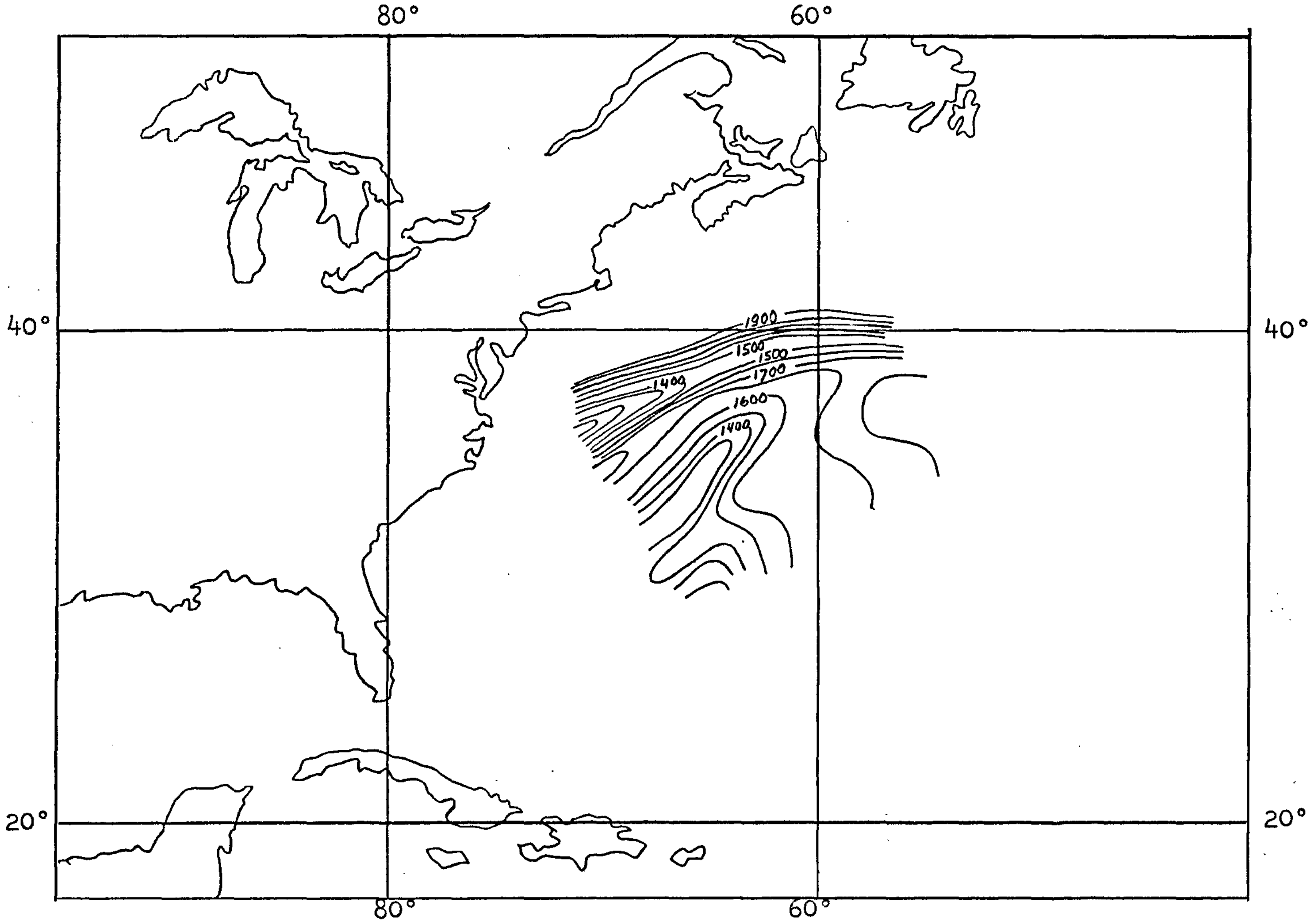

Figure 3. The depth (in metres) of the surface of no motion in the Gulf Stream area.

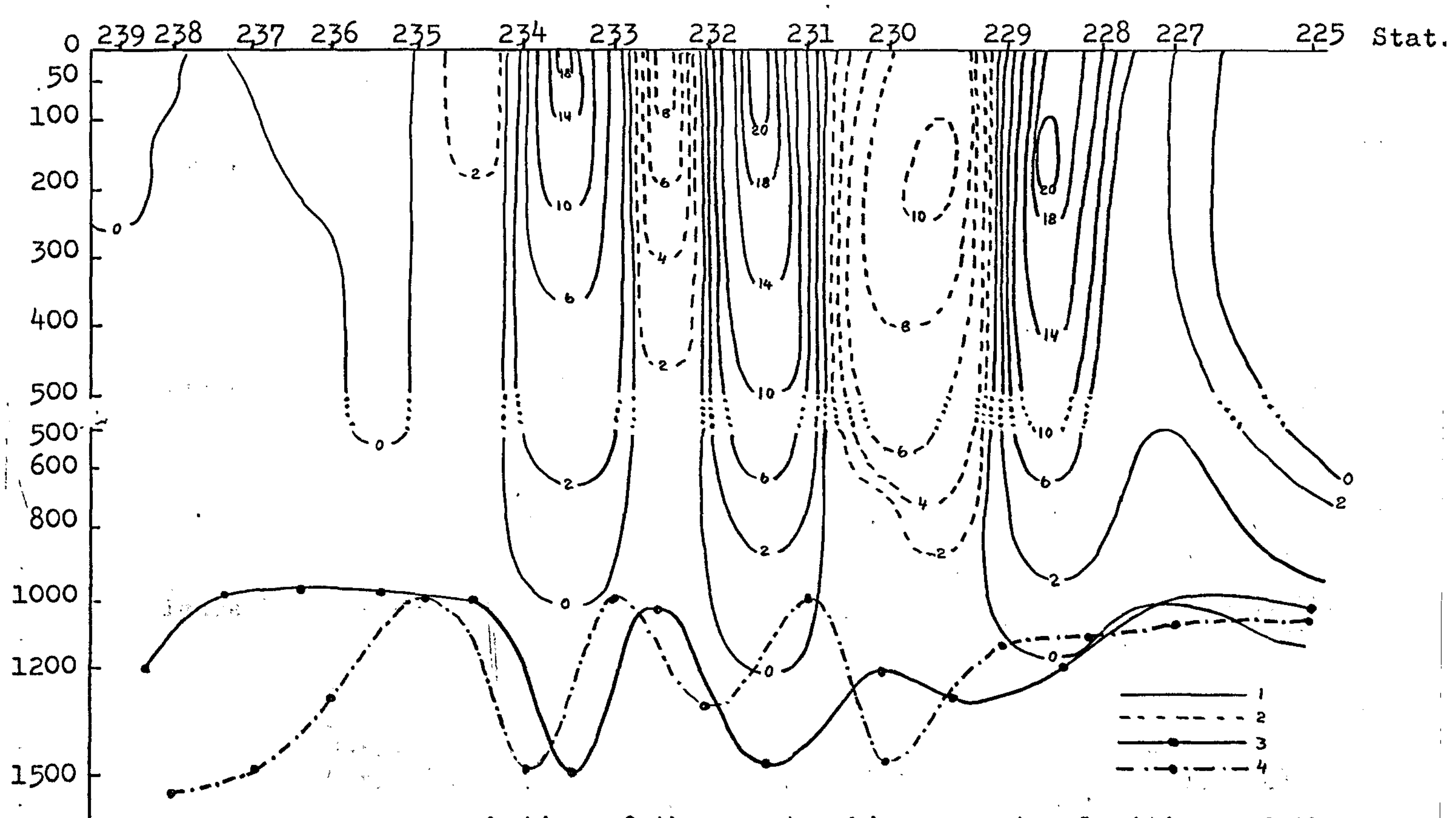

Figure 4. The distribution of the geostrophic current velocities and the depth of the no motion layer at a section running through the North Atlantic current:

1-current velocity in the northward direction.
2- " " " " southward " .
3-the depth of the zero surface according to A.Defant.
4-the estimation of the same depth according to formula (2).

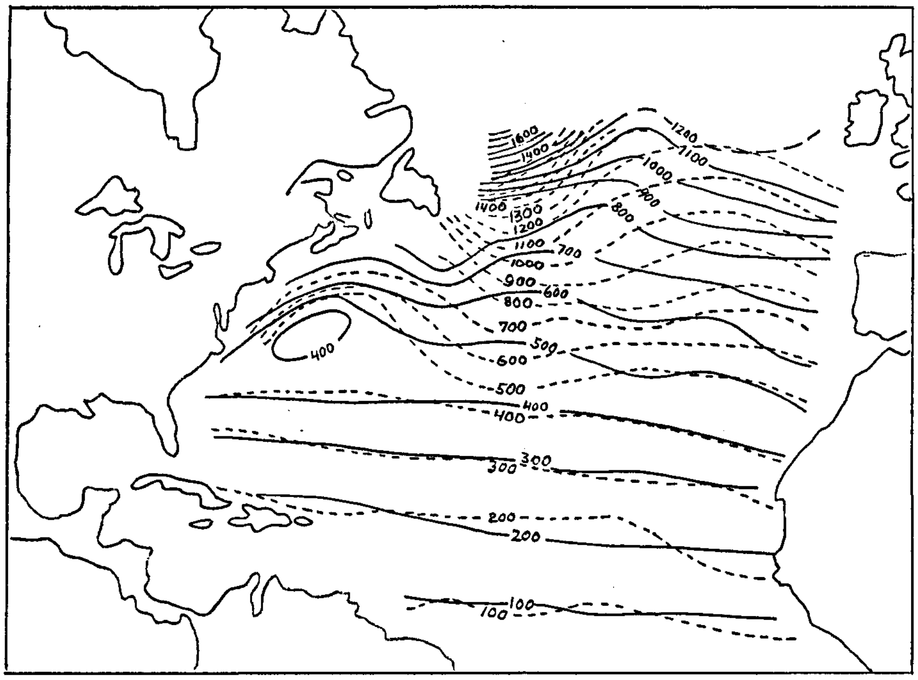

Figure 5. The depth of baroclinity (in metres), calculated according to formula (1); The unbroken line stands for the summer season, the dotted line represents the winter period.

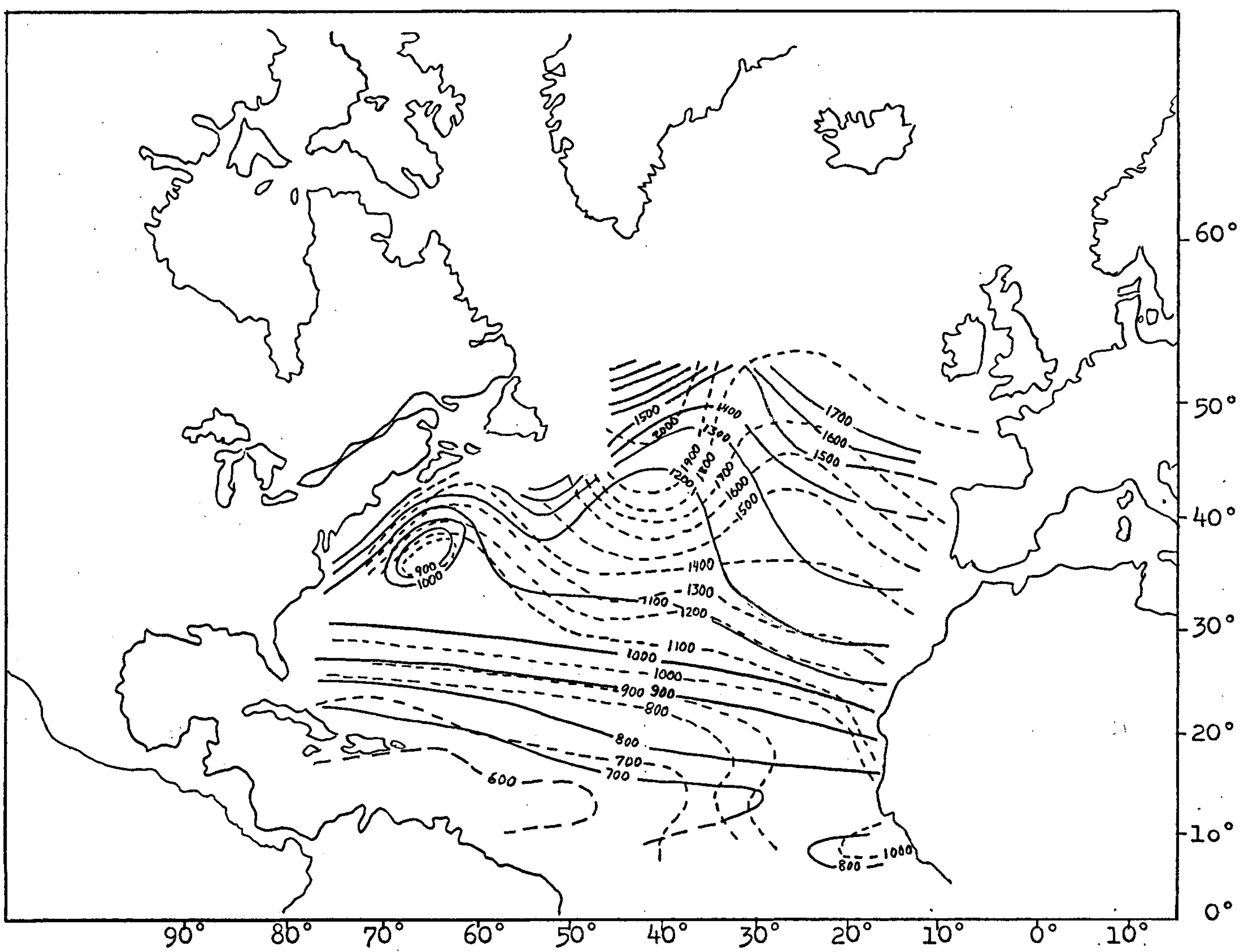

Figure 6. The depth (in metres) of the surface of no motion, calculated according to formula (1). The unbroken line stands for the summer season, the dotted line represents the winter period.

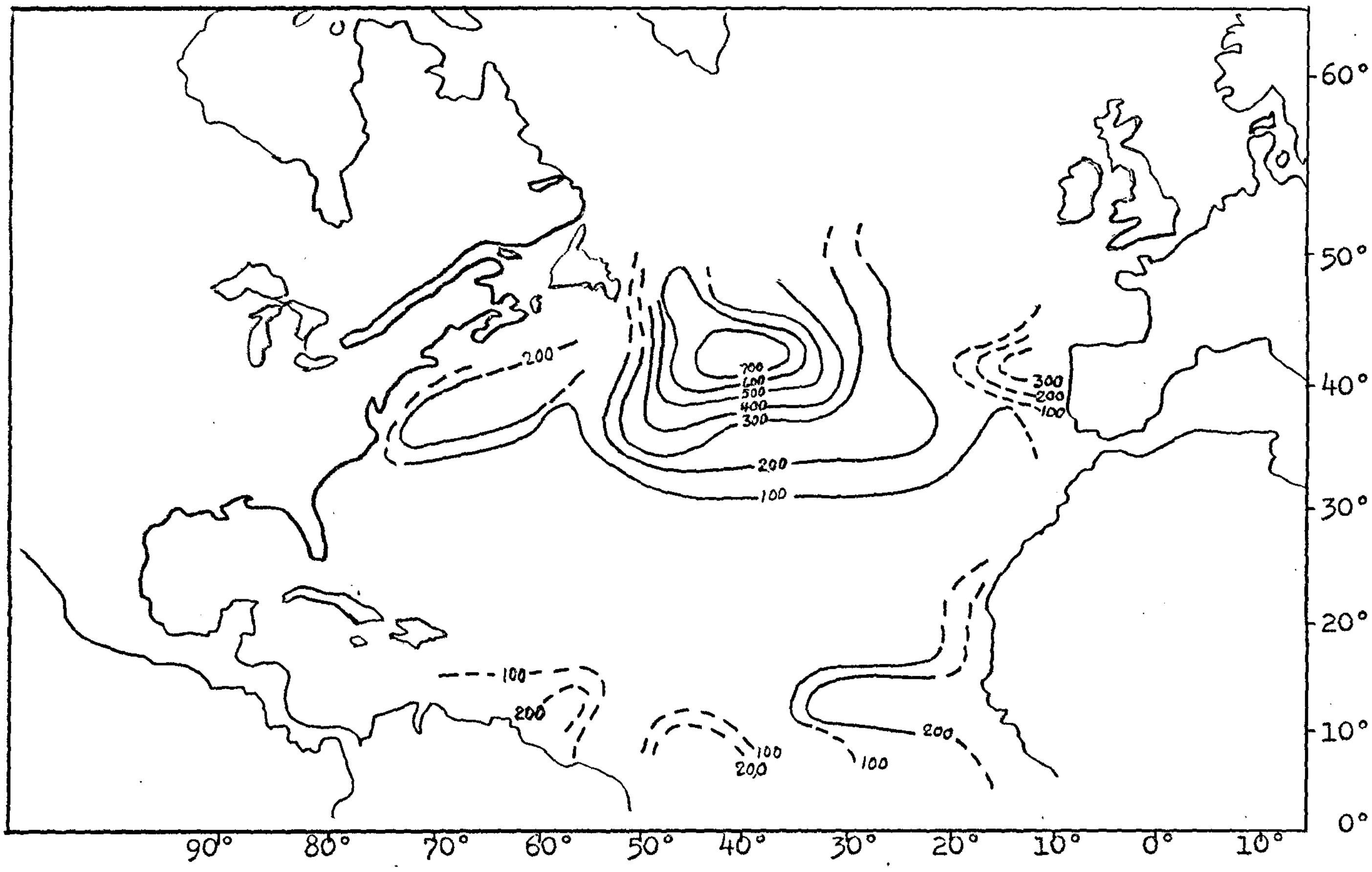

Figure 7. The amplitude (in metres) of seasonal variations of the depth of the surface of no motion according to formula (1).

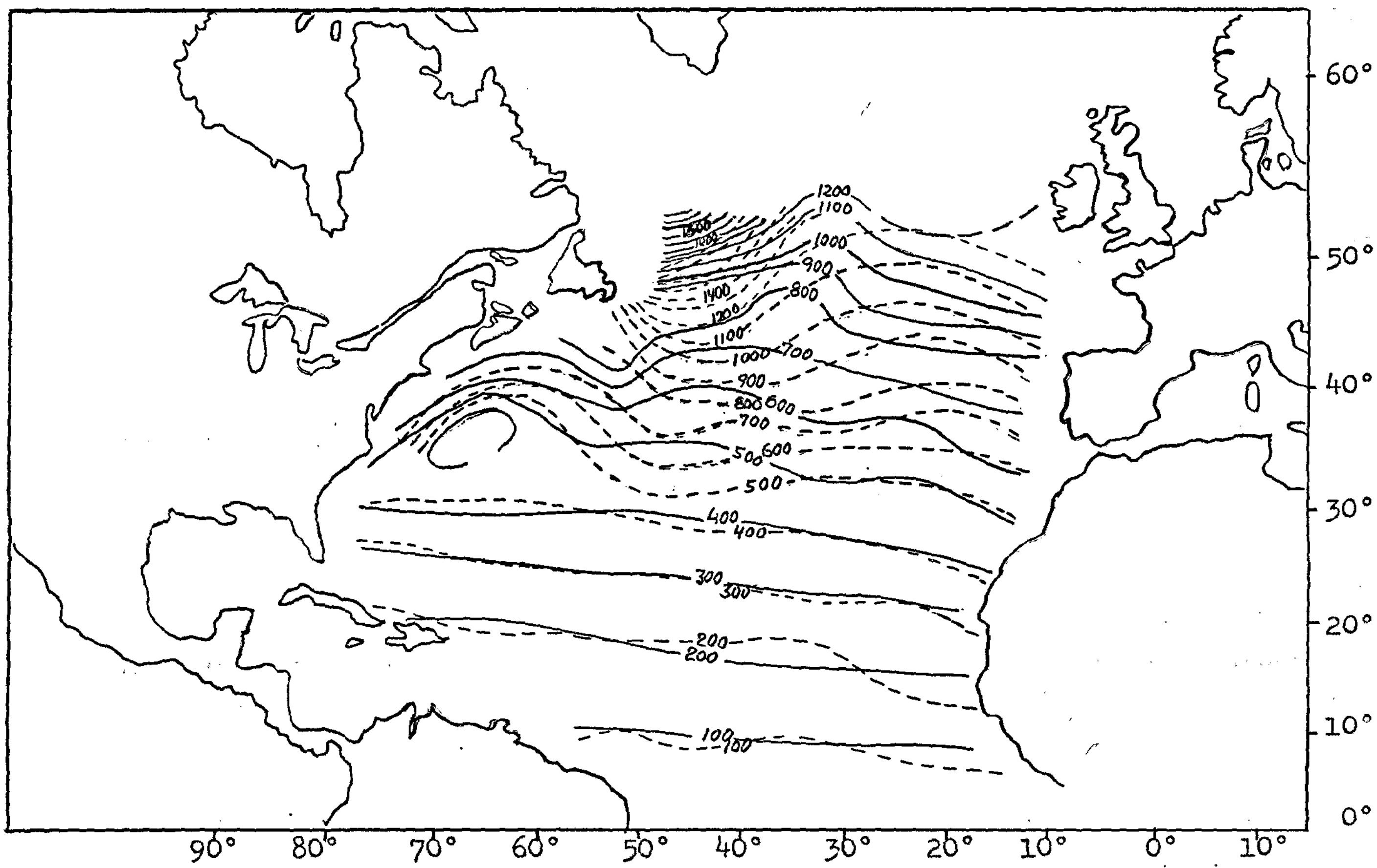

Figure 8. The depth (in metres) of the surface of no motion calculated according to formula (2). The unbroken line stands for the summer season, the dotted line represents the winter period.

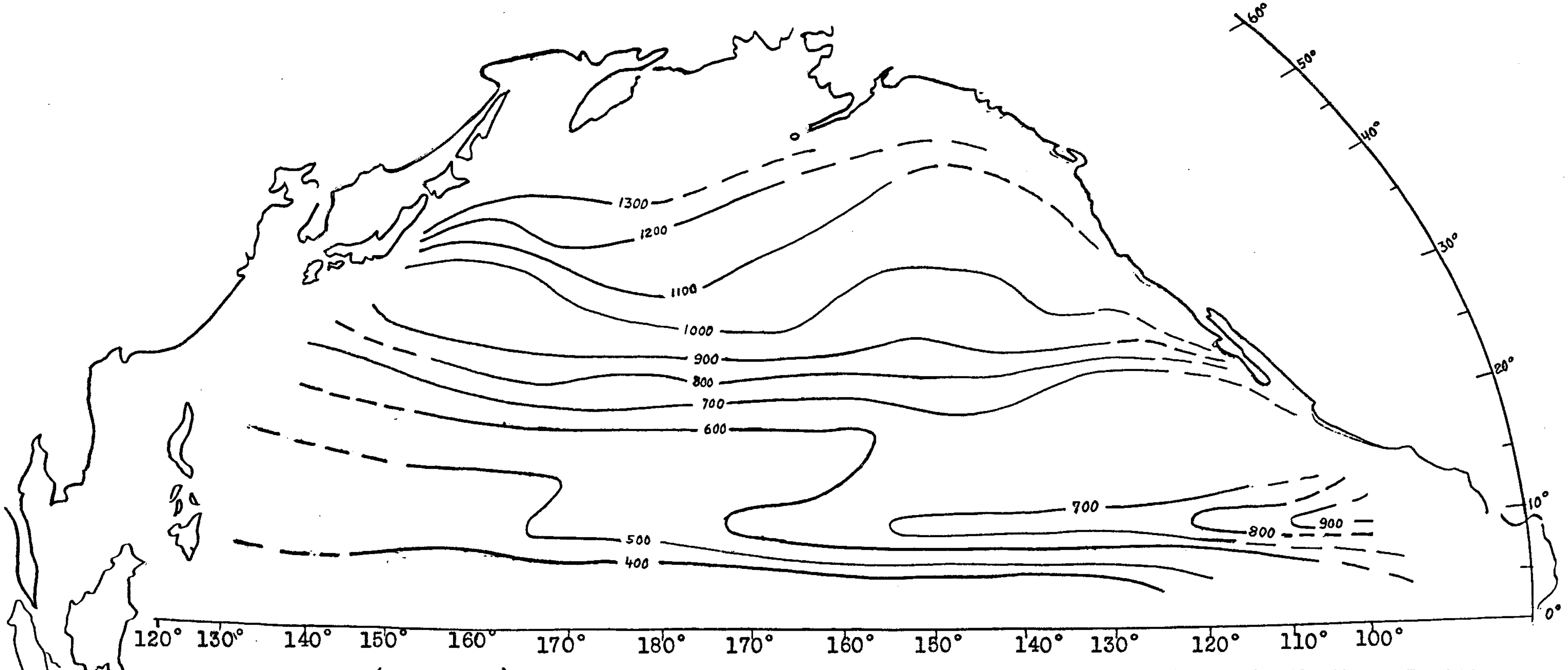

Figure 9. The depth (in metres) of the surface of no motion during the summer period for the Northern Pacific.