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The Influence of the Current Systems and Lateral Mixing upon Antarctic Intermediate Water in the South Atlantic

by

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Director

Table of Contents

Introduction

A salinity minimum layer is observed at intermediate depths in the Atlantic Ocean in the region between the Antarctic Convergence and approximately 25°N. latitude. This layer is referred to as the Antarctic or sub-Antarctic Intermediate Water Mass, for it is assumed to be formed by the sinking of Antarctic and sub-Antarctic surface waters at the Antarctic Convergence[1].

German and British oceanographers have discussed its mechanism of formation, its flow pattern, and the distribution of its physical and chemical properties; but these studies were mostly concerned with the northward movement of this water mass as a mass movement rather than as transport due to the current systems of the region. If the surface current system of the South Atlantic is assumed to extend below the depth of this water mass, as the recent work of Riley (1951) suggests, the observed distributions of its temperature and salinity characteristics may be explained as a result of this pattern and the lateral mixing assumed to be associated with it.

The following sections attempt to show the influence of the current system of the southwestern South Atlantic and lateral mixing upon the distribution of the temperature-salinity characteristics of AAIW, and the data of previous investigations have been examined and shown to satisfy the above concept.

Resumé of previous investigations pertaining to AAIW

The source of AAIW has been located along the northern edge of the Antarctic Convergence, where the Antarctic and sub-Antarctic surface waters converge, mix, and sink. Sverdrup (1933) derived the north-south circulation pattern for the sub-Antarctic region and on the basis of a series of vertical sections across the convergence concluded that the source of this water mass lies along the northern edge of the convergence. Wüst (1936) obtained similar results from the "kernschicht"[2] technique. Depth contours of the kernschicht of this water mass were constructed for the South Atlantic, and the surface contour was assumed to represent the line along which the layer is formed and sinks (see figure 1a). This contour was found to coincide with the Polar Front, which is the German equivalent of the Antarctic Convergence, and so, from these results the northern edge of the convergence may be considered to be a source of AAIW.

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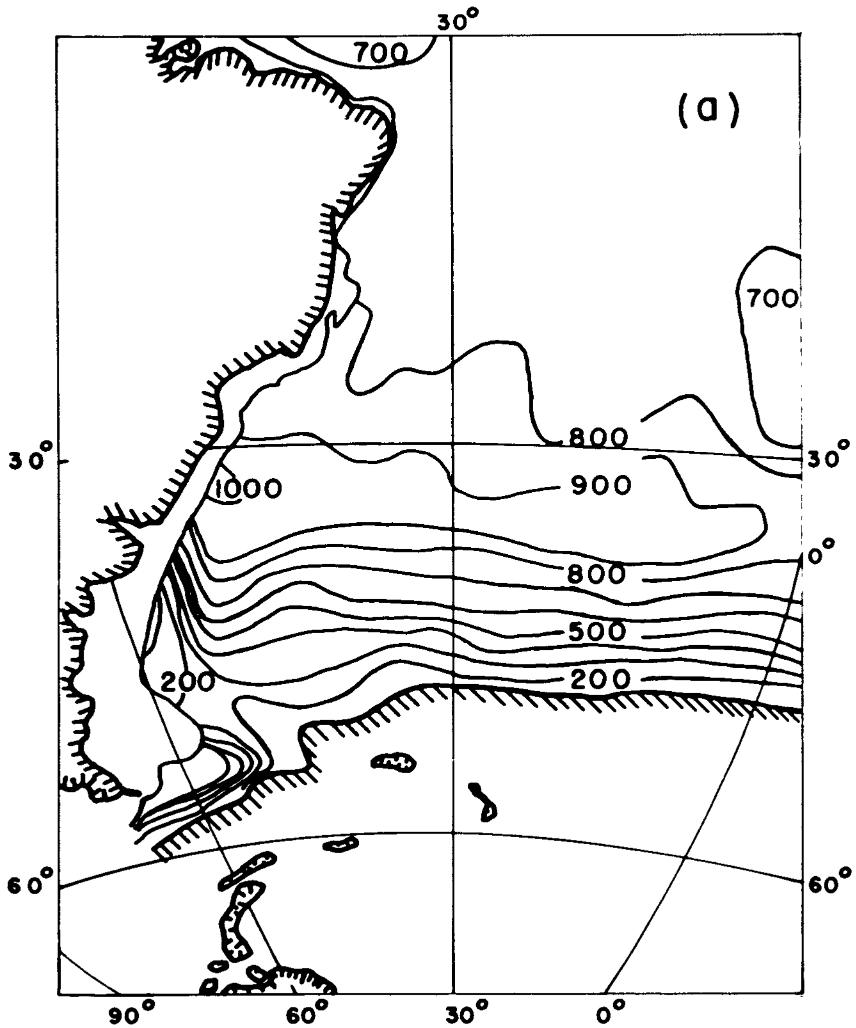
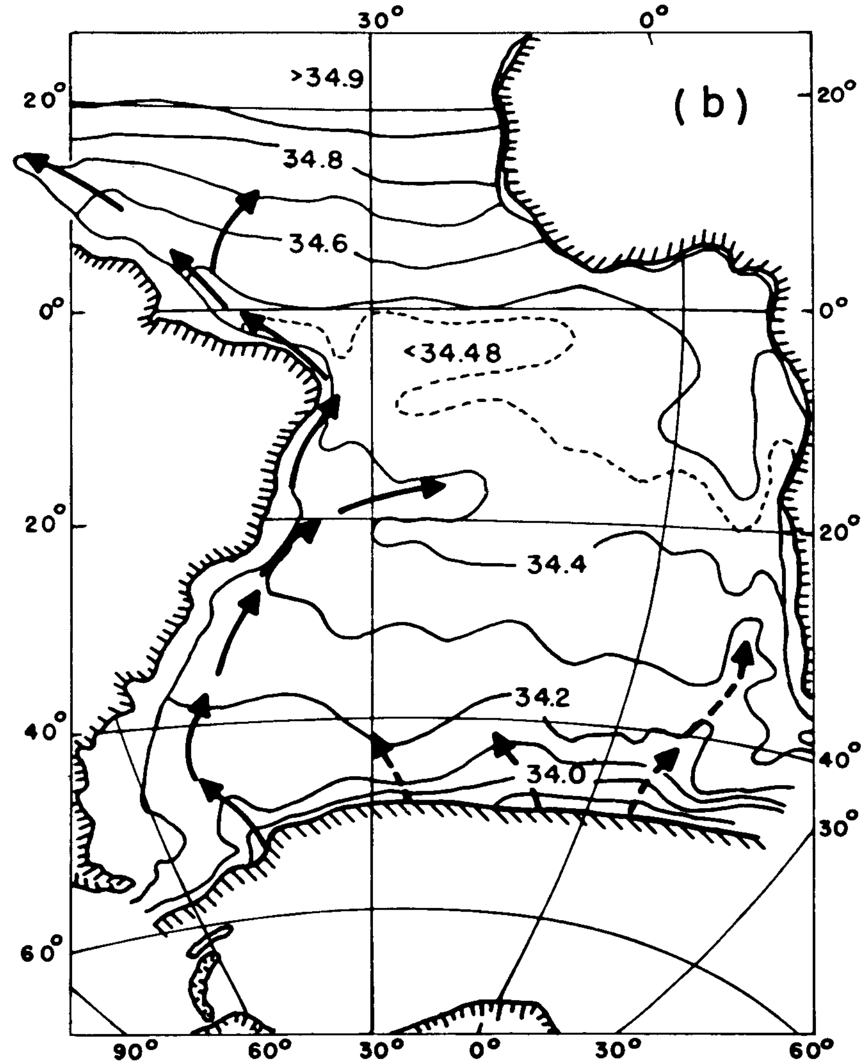
[1] Results of this paper show that the salinity minimum layer may also be formed by other surface waters, but the layer will continue to be referred to as Antarctic Intermediate Water and be abbreviated as AAIW.

[2] This may be translated as the "core" technique, and the "core" of a layer is considered to be the part of the layer within which the salinity or temperature reach extreme values.



DEPTH OF AAIW "Kernschicht" IN METERS. (AFTER Wüst)



FLOW PATTERN AND SALINITY DISTRIBUTION AT DEPTH OF AAIW "Kernschicht" (AFTER Wüst)

Though the British and German oceanographers agree upon this region of formation of the water mass, the nature of their respective observations has led to different approaches for studying its behavior as it spreads northward from the source. The British north-south sections offer excellent physical and chemical profile, but the German results more completely describe the water mass with respect to horizontal and vertical flow and modification by turbulence.

Wüst (1936) has discussed the flow pattern of the Antarctic Intermediate Water by considering the salinity minimum to represent its "kernschicht" The distributions of depth, temperature, salinity and oxygen as observed at the depth of the salinity minimum associated with this water mass were used to trace its flow throughout the Atlantic Oceans. Figure 1b is a reproduction of the depth, salinity, and flow patterns derived from the "kernschicht" technique. According to Wüst the main flow is along the east coast of South America. Upon sinking at the Antarctic Convergence, the water mass moves north and westward towards South America, and the water entering the Northern Hemisphere is assumed to have flowed along the coast of South America from latitudes south of 40° South.

A series of hydrographic stations with positions closely approximating the main flow derived by wüst were used to study the modification of this water mass by turbulence. Defant (1936) attributed the northward salinity increase of the water mass to the effects of horizontal advection and vertical turbulence with the over- and underlying waters. The ratio of the vertical austauch coefficient to the horizontal velocity was computed and the resulting profile of this ration used to determine the lower boundary of the water mass as well as its extension into the Northern Hemisphere. Since one of the terms of the ratio must be assumed in order to evaluate the other, this profile does not present an accurate method for determining the velocities at which this water mass progresses northward.

The only direct estimate of the current velocity for this water mass was made by Deacon (1931). A profile of the velocity at the depth of the salinity minimum was constructed from the oxygen observations made along the 30th meridian. The secondary oxygen maxima, which were observed along this meridian, were attributed to the seasonal formation of the water mass and the distance between successive maxima was assumed to represent the distance of travel in one year. While this method offers a means for computing the north-south component of a velocity along a given meridian, it does not account for the east-west component which in some areas may be larger than the north-south one.

The combined studies of Wüst and Defant suggest (1) that the salinity minimum layer is formed near the northern edge of the Antarctic Convergence; (2) from its source it sinks north and westward until it flows parallel and offshore of the continental shelf of South America; (3) the main flow parallels the continental shelf well into the Northern Hemisphere; and (4) along the direction of flow the temperature and salinity are being modified by horizontal advection and vertical mixing.

This concept has mostly been based on interpretations of the Meteor Expedition data. In view of the more recent studies of the currents in the southwestern South Atlantic and of the discussions of lateral mixing in preference to vertical (Montgomery, 1941) a re-examination of the temperature, salinity, and depth distributions given by Wüst suggests that these distributions may be explained by an entirely different flow pattern and turbulent process.

Influence of the current system of the southwestern South Atlantic upon the formation and distribution of AAIW

The major currents of the southwestern South Atlantic are the Circumpolar, the Falkland and the Brazilian Currents. The general features of their flow pattern are shown in figure 2. These features have been derived from the mean 200 meter temperature and salinity distributions of this region and the current pattern of the Patagonian Shelf as given by Hart (1946). As the West Wind Drift and Circumpolar Current clear Drake Passage part of it separates and becomes the Falkland Current, which flows northward along the coast of South America. Since the Falkland Current originated from waters with properties similar to those of the Circumpolar Current, the temperatures and salinities of these two currents are similar. They are colder and less saline than the southward flowing Brazilian Current, which flows parallel and opposite to the Falkland Current north of latitude 45°S.

Sverdrup (1946) has shown the Circumpolar Current is related to the Antarctic Convergence. This Circumpolar Current must be related to the processes by which the water mass is formed and sinks, even though the mechanism of AAIW formation is not completely understood. Upon sinking AAIW flows towards the central South Atlantic, but the currents of the West Wind Drift region, between the Antarctic and sub-Tropical Convergences, move it towards the east at a faster rate than it sinks northward. As a result the trajectory of the water mass is more easterly than northerly and is in agreement with the general transport pattern of the southern part of the South Atlantic as derived by Riley (1951).

Previous studies have concluded that a mass movement at mid-depths, which is opposite to the surface system in some areas, transports AAIW away from the source at the Antarctic Convergence; but if the surface current system is assumed to extend to depths below the AAIW water mass, the flow pattern of AAIW will approximate that shown in figure 3. The importance of this pattern is that the water mass reaches the Northern Hemisphere without moving

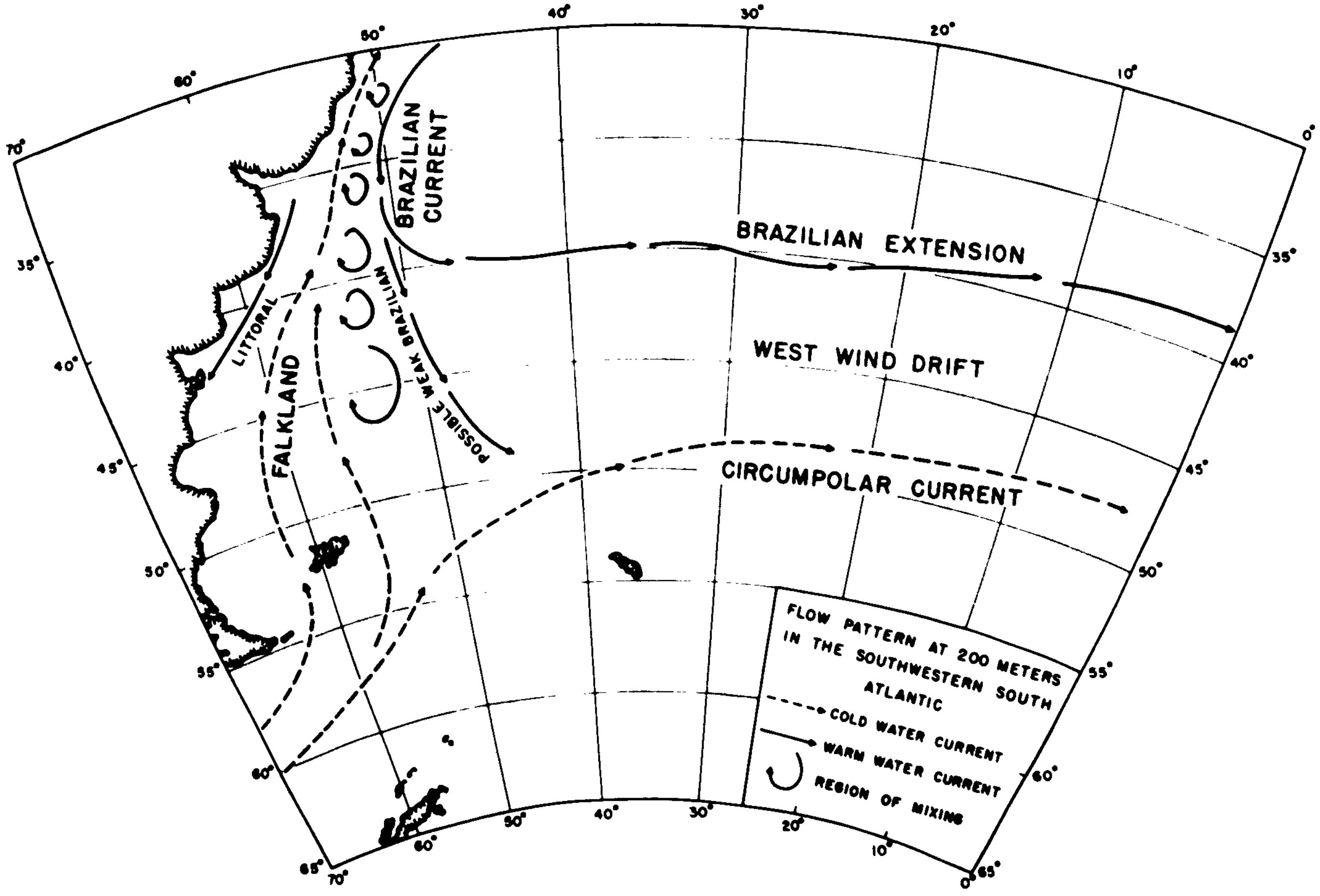
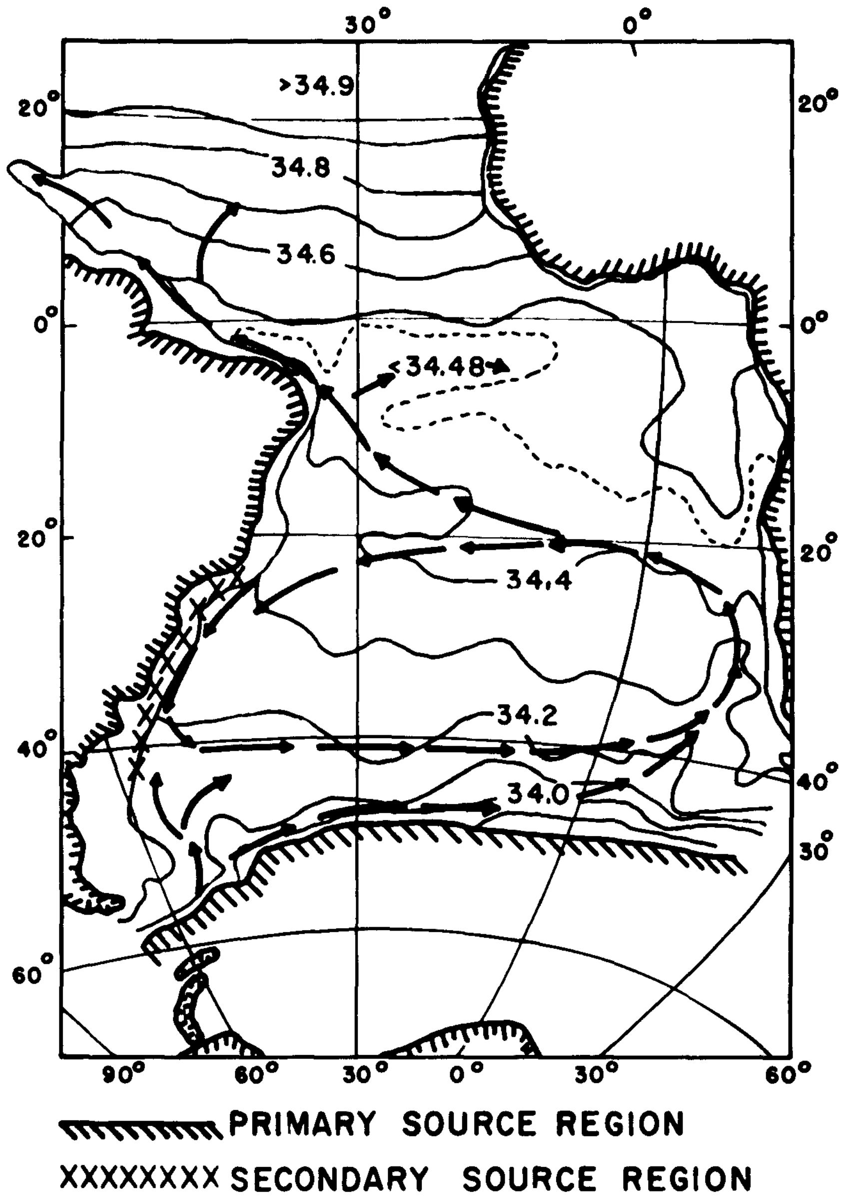

BRAZILIAN CURRENT
BRAZILIAN EXTENSION
WEST WIND DRIFT
CIRCUMPOLAR CURRENT
LITTORAL
FALKLAND
POSSIBLE WEAK BRAZILIAN
FLOW PATTERN AT 200 METERS IN THE SOUTHWESTERN SOUTH ATLANTIC
COLD WATER CURRENT
WARM WATER CURRENT
REGION OF MIXING

FIG. 2



SOURCE REGIONS AND ASSUMED
CIRCULATION OF AAIW.
(SALINITY DISTRIBUTION AFTER Wüst)

FIG. 3

in a direction opposite to the under- and overlying waters, and also the salinity distribution of the AAIW kernschicht observed by Wüst may be explained. This salinity distribution is shown with the flow pattern in the figure.

According to this pattern the main source of the water mass is along the Antarctic Convergence, but a secondary source may exist along the coast of South America as a result of mixing between the Falkland and Brazilian Currents. The proximity of these currents suggests that their surface layers may mix in a transition zone between them and the resulting mixture sink into the intermediate layer of the Brazilian Current. It is possible for the surface waters of the two currents to produce a heavier water by cabeling[3], and this water will sink until it reaches water of its own density. If low stability conditions exist, the density gradient is small and the heavier mixed water will have to sink well below the depth at which mixing occurs in order to reach water of equal density, and this means it will be removed from the zone of mixing.

This mechanism has been observed around the edge of the Labrador Sea where the intermediate water of the basin is formed (Smith et al, 1937). Along the coast of Labrador the Labrador Current flows southward between the coast and the remainder of the Irminger Current. Sections across these currents indicate that they produce a mixture which sinks in the transition zone between them and then spreads towards the center of the basin. Soule (1938) constructed stability profiles across these currents and the tongue of mixed water may be shown to correspond to a layer of low stability.

If the intermediate water off the coast of South America is assumed to be formed under similar conditions, a layer of low stability should be present. From the transition zone between the Falkland and Brazilian Currents such a layer is found to extend seaward beneath the Brazilian Current. The salinity and stability profiles in figure 4 suggest the layer is formed by the above mechanism. These profiles were constructed from the observations at Meteor stations 1, 3, 4, and 5. Although these stations are widely spaced, the section shows the general hydrographic features of the two currents and the transition zone and indicates the necessary movement for the mixing and sinking process described above.

The formation of AAIW along the coast of South America may be expected to occur as far north as the two currents are observed

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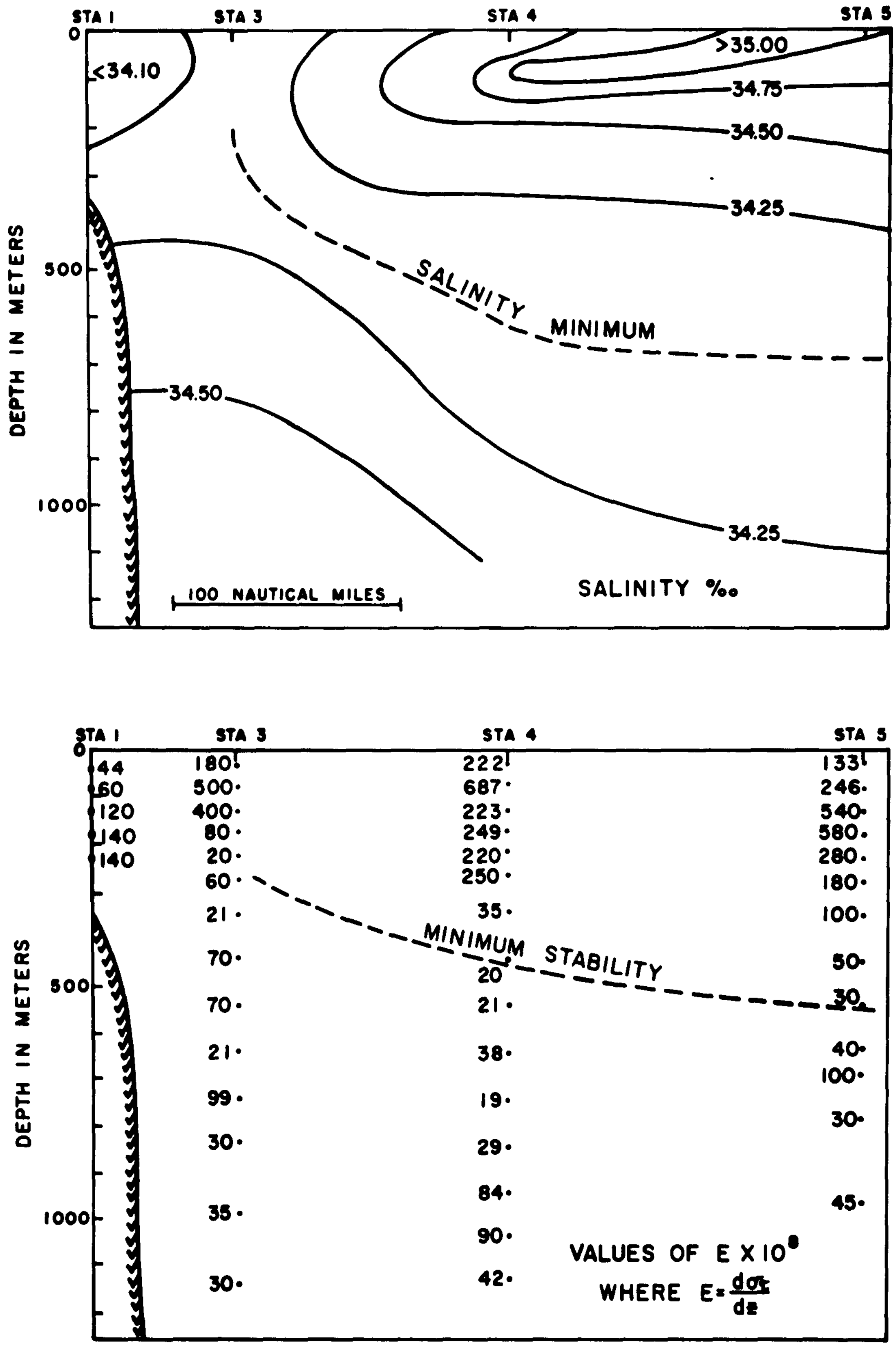
[3] Smith et al. (1937) state that because of the nonlinear relationship between temperature and density an adiabatic mixture of two waters of equal density but of different temperatures and salinities will have a greater density than that of the original two waters.



SALINITY AND STABILITY SECTIONS
ACROSS THE FALKLAND AND BRAZILIAN CURRENTS

FIG. 4

to run parallel and opposite to each other. Surface current data for the area indicate that these currents migrate seasonally and during the Southern Hemisphere winter months the Falkland Current is observed as far north as Cape Frio (23°S.). This enables AAIW to be formed along the coast between Cape Frio and latitude 45°S., where the Brazilian Current veers eastward from the coast.

From this source and the one along the northern edge of the Antarctic Convergence, AAIW sinks and in doing so is moved downstream by the prevailing currents. The circulation system described in figure 3 is the principle means by which this low salinity water is distributed, but there is also lateral mixing taking place along the edge of these currents. This lateral mixing is responsible for the observed AAIW in such regions as the central South Atlantic, where the currents are either absent or weak.

Influence of lateral mixing upon the temperature and salinity characteristics of AAIW

Previous papers concerning the movement and modification of AAIW have considered a mass movement northward from the Antarctic Convergence accompanied by a modification due to vertical mixing with the under- and overlying waters. The last section has shown that the movement may be considered to follow the general circulation of the South Atlantic rather than a northward flow of mass; and from the papers by Sverdrup (1939), Montgomery (1940), and Iselin (1939) it is suggested that the principle turbulence mechanism which modifies this water mass is lateral rather than vertical mixing.

Defant (1936) attributed the northward salinity and temperature increases in the AAIW and AABW[4] masses to vertical mixing, but a later paper by Sverdrup refuted this assumption and showed that the temperature and salinity distributions for the AABW could best be accounted for by the processes of lateral mixing and currents directed along isopycnic surfaces. The results of Sverdrup and others (Montgomery, 1940) indicate rather than prove that lateral mixing and mass advection along isopycnic surfaces are the important processes by which the temperature and salinity characteristics of the intermediate waters of the Atlantic are modified. These results suggest that the temperature and salinity distributions of AAIW might be explained by lateral rather than vertical mixing.

A study of the influences of vertical and lateral turbulence on the characteristics of the waters found at mid-depths in the North Atlantic has shown that for certain regions lateral mixing can be considered to be the predominant mechanism for producing the observed temperature and salinity distributions. Iselin (1939)

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[4] AABW is the conventional abbreviation for Antarctic Bottom water.

found the temperature-salinity correlation for the intermediate water in the Sargasso region to be representative of the winter surface temperature and salinity conditions for the region in which the water mass sinks; and for this condition to exist it is necessary for the water mass to sink along isopycnic surfaces and be mostly modified by lateral mixing.

This process has been adapted to the southwestern South Atlantic in order to determine whether or not lateral mixing and mass advection along isopycnic surfaces can account for the temperature-salinity characteristics of AAIW as observed in the central South Atlantic. Method: A method similar to the one employed by Iselin for the North Atlantic has been used to relate the observed temperature-salinity correlation of AAIW in the central South Atlantic to the surface layer conditions in the regions of its origin. In the case of the North Atlantic the observed temperature-salinity characteristics at mid-depths were extrapolated along isopycnic surfaces until these surfaces intersected the actual sea surface. The characteristics of the sea surface in the region of intersection were then found to be comparable to the original mid-depth properties, and the changes in salinity and temperature between the surface and mid-depths were attributed to lateral mixing.

Analogous to this method, the difference between the AAIW temperature-salinity characteristics of its source region and those observed in the central South Atlantic has been attributed to the effects of lateral mixing as the water mass flows along isopycnic surfaces. This assumption has been used to determine the surface conditions of the source region that would be required to produce the observed conditions in the central South Atlantic. If it were possible to determine the area of the South Atlantic whose surface layer conditions are comparable to these required values, this area would coincide with the region of the Antarctic Convergence, which has previously been shown to be a source of AAIW.

Since it is difficult to determine such an area from the existing data, it has been assumed that the required temperature-salinity correlation for the surface layer in the source region may be interpreted as representing the characteristics of the southern boundary for the region of AAIW formation. This assumption requires that the coldest and least saline water on each isopycnic surface be found at the intersection of the isopycnal with the surface layers and that the intersection be the most southerly point along the isopycnal. These conditions are found to exist in the South Atlantic.

With this interpretation of the required surface layer temperature-salinity correlation, the southern boundary for the area in the southwestern South Atlantic, whose surface layer conditions are warmer and more saline than those described by the correlation curve, has been compared with the position of the Antarctic Convergence to determine the validity of the assumptions upon which this method is based.

In order to apply this method, a series of Meteor and Discovery hydrographic stations made in the central South Atlantic were selected to obtain a representative temperature-salinity correlation for the water mass in this region. The insert in figure 5 shows the distribution of these stations, and curve A presents the mean correlation obtained from them. As stated above, these values have been assumed to be the results of lateral mixing upon the original surface layer conditions as the water mass moved along constant density surfaces. The required surface layer conditions in the region of AAIW formation which could produce the temperature-salinity properties of the central South Atlantic are described by the temperature-salinity correlation of curve B. This curve has partially been constructed from the reported temperature-salinity properties of the AAIW kernschicht for depths equal to or less than 200 meters. The mean correlation of these values is represented by the segment of curve B between isopycnals 26.9 and 27.2.

Sverdrup (1946) states that the lower boundary of AAIW corresponds to the 27.4 isopycnal and so curve B has been extrapolated for the segment beyond 27.2. The extrapolation was based on the temperature difference between curves A and B corresponding to a given isopycnal. This temperature difference was assumed to represent the magnitude of temperature modification due to lateral mixing and the advection of a particle from the source to the central South Atlantic. The magnitude of temperature modification along isopycnic surfaces within the range from 26.9 to 27.2 were plotted in figure 6 and the magnitude of modification corresponding to the range of isopycnic surfaces between the values 27.2 and 27.45 were obtained by extrapolation. These extrapolated values were applied to the segment of curve B beyond the 27.2 isopycnal.

The temperature-salinity characteristics of correlation curve B have been interpreted as representing the characteristics of the surface layer for the southern boundary to the region of AAIW formation. In order to establish this boundary, the mean surface layer temperature and salinity properties for the southwestern South Atlantic were obtained and compared with those described by curve B. The region of the southwestern South Atlantic from 35°S. to 60°S. and from the Greenwich meridian to Drake Passage was considered. A complete list of the source of data from which the mean surface layer temperature and salinity values for this region were obtained may be found at the end of this report.

The mean properties have been used in preference to the individual observations in order to minimize the seasonal variation in the magnitudes of the salinity and temperature. Furthermore, Deacon (1931) has considered this water mass to be mainly formed during the winter months, as is the intermediate water of the North Atlantic (Iselin, 1939). On the basis of this seasonal formation, a subsurface level with year 'round properties similar to the winter conditions was selected. Of the standard depths for which data were reported the 200 meter level best suited this requirement. The homogeneous surface layer should extend below

MEAN TEMPERATURE—SALINITY CORRELATION FOR THE CENTRAL SOUTH ATLANTIC, CURVE A, AND ASSUMED CORRELATION FOR THE 200 METER LEVEL OF THE SOURCE REGION, CURVE B.

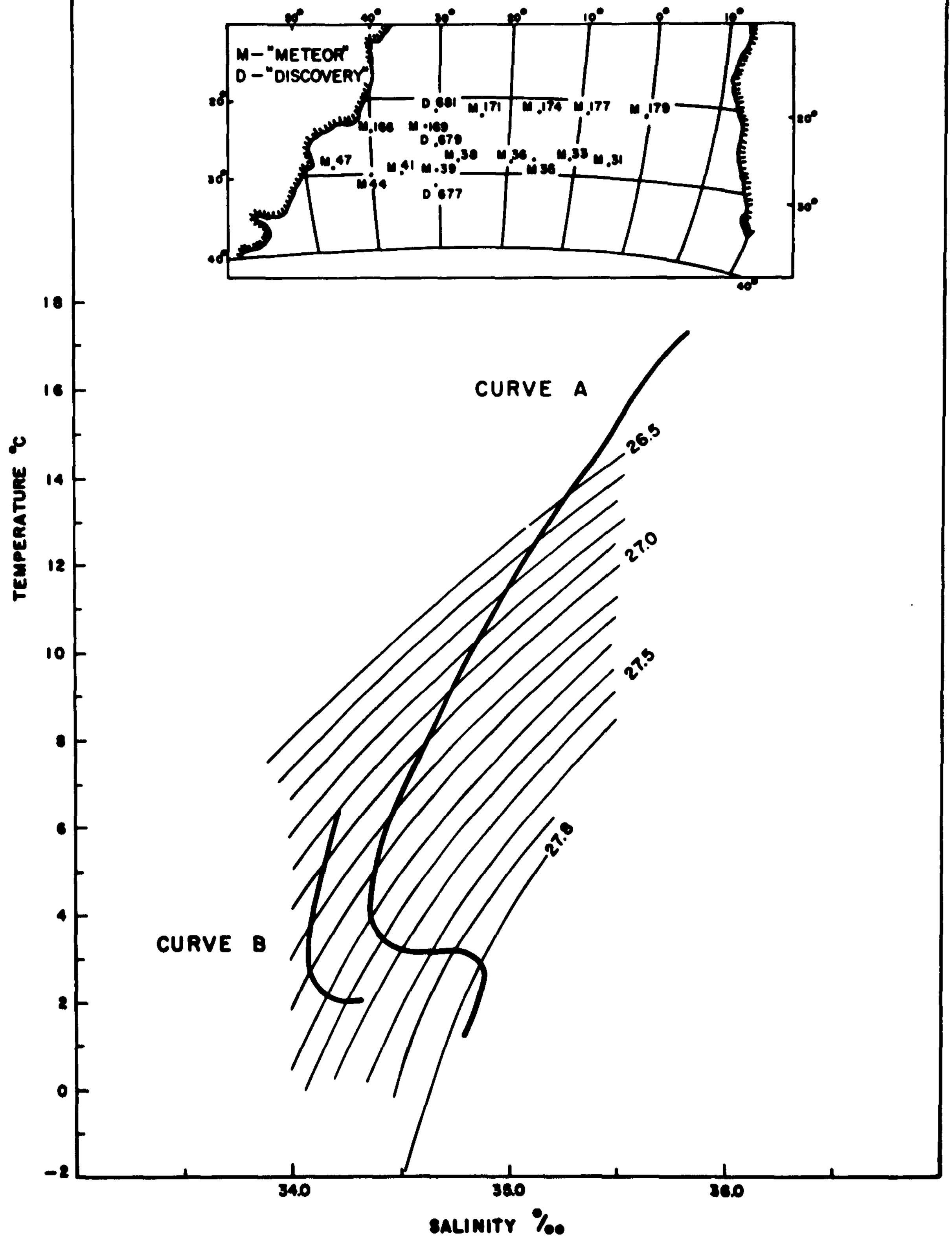
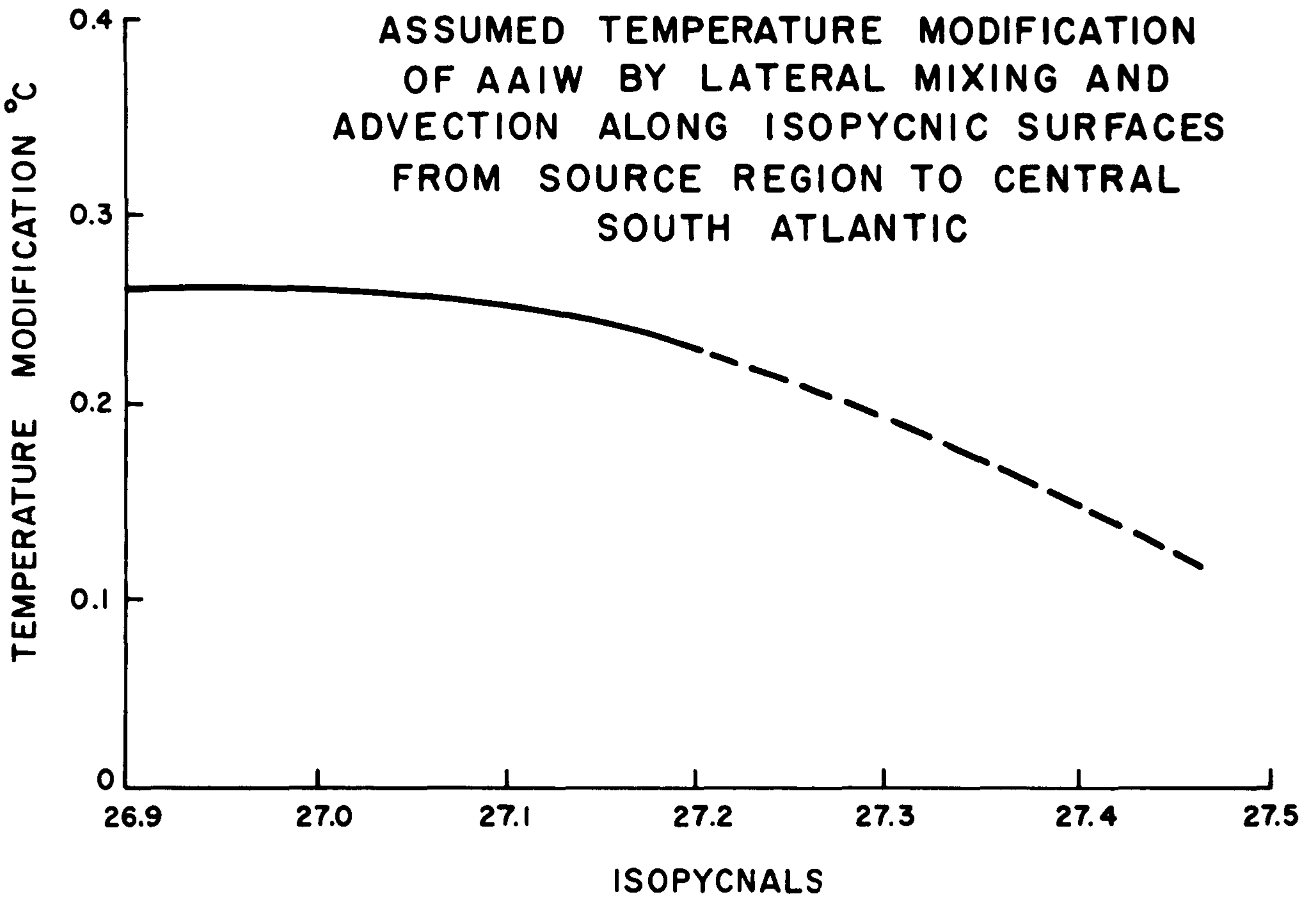


FIG. 5



ASSUMED TEMPERATURE MODIFICATION OF AAIW BY LATERAL MIXING AND ADVECTION ALONG ISOPYCNIC SURFACES FROM SOURCE REGION TO CENTRAL SOUTH ATLANTIC
TEMPERATURE MODIFICATION °C
0.4
0.3
0.2
0.1
0
26.9
27.0
27.1
27.2
27.3
27.4
27.5
ISOPYCNALS

FIG. 6

this level in winter; and with a smaller annual range of temperature and salinity at this level than at the sea surface, a mean 200 meter temperature and salinity obtained from data for all seasons should better represent the winter surface layer conditions than a set of mean surface values.

For each one-degree field of latitude and longitude within the described above area and for which data were available, an arithmetic mean 200 meter temperature and salinity was computed. This mean 200 meter temperature and salinity for a given one-degree field constitutes a temperature-salinity point, and these points have been plotted in figure 7. Curve C of this figure has been constructed so that nearly all these points lie to its left. Since the 200 meter temperature-salinity points for the source region of AAIW are included among the points in figure 7, they too must lie to the left of curve C.

Since curve B has been assumed to represent the coldest and least saline temperature-salinity values of the source region and curve C has been constructed to include nearly all the mean 200 meter temperature-salinity points of the southwestern South Atlantic, the southern boundary of an area with mean 200 meter properties corresponding to those included between the two curves should correspond to the southern boundary for the AAIW source region. If the assumptions upon which this method has been based are to be satisfied, these boundaries should coincide.

Verification of assumptions: All one-degree fields of latitudes and longitude with temperature-salinity properties within the hashed area of figure 8 were determined, and the southern boundary of such fields constructed and shown as curve I in figure 9. A comparison between this southern limit and the one derived by Wüst shows the two to be in agreement. In most regions the one by Wüst lies to the north of the other as should be expected since the curve by Wüst refers to the "core" of the water mass and the other one refers to its lower boundary which extends further towards Antarctica. The similarity of the two curves derived from different methods seems to substantiate the basic assumptions of the method.

An additional verification of these assumptions may be found in the value of the isopycnic surface which approximates the boundary between the AAIW and NADW[5]. It should be noted that the curves in figure 8 cross at the 27.4 isopycnals. The crossing at this isopycnal is considered to coincide with the boundary between the two water masses. It is not possible for AAIW to be found beyond the 27.4 isopycnic surface and still satisfy the condition that the mean 200 meter temperature-salinity points in the source region must lie to the left of curve C in figure 7 and be bounded

[5] NADW is the conventional abbreviation for North Atlantic Deep Water.

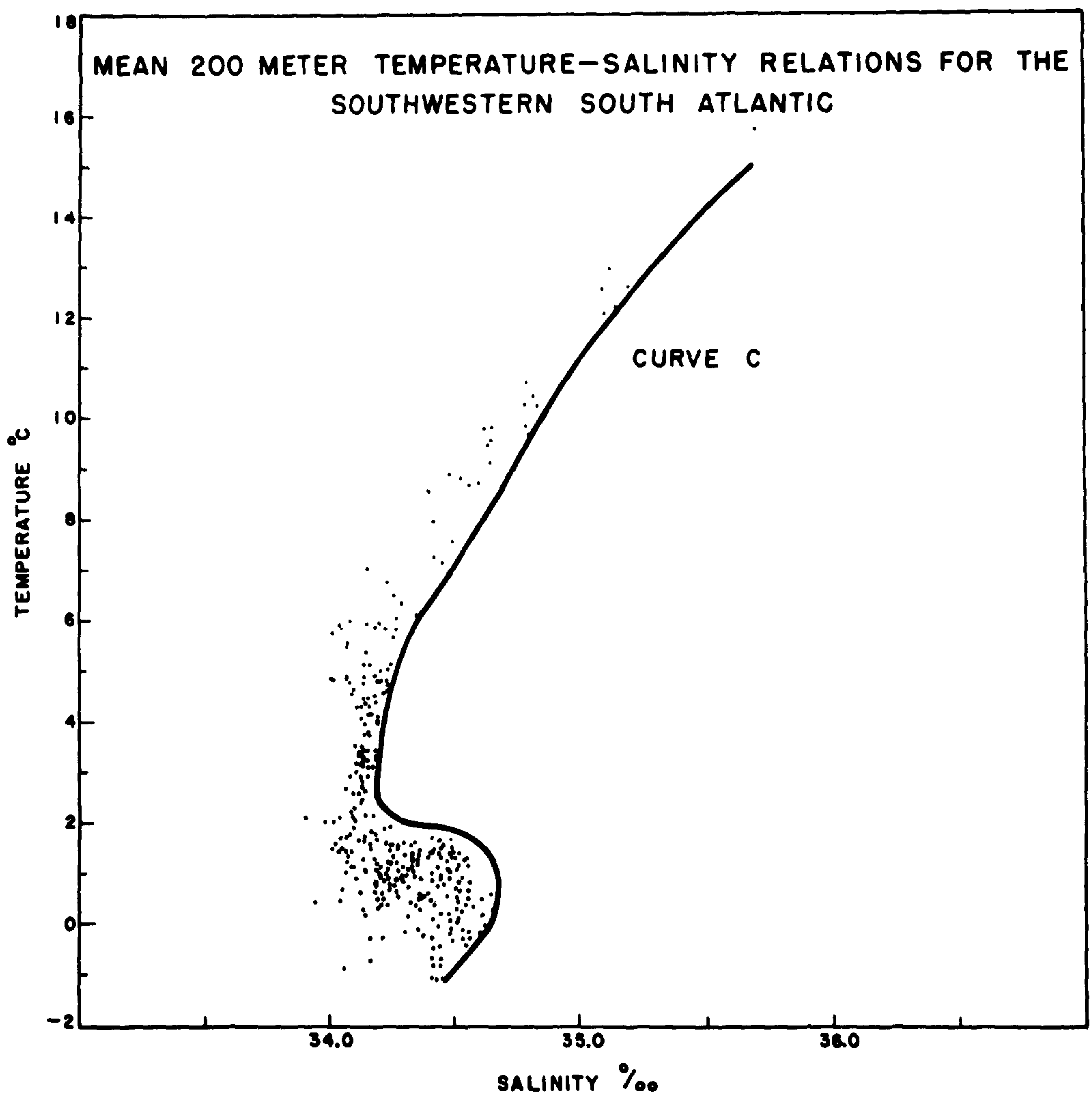

MEAN 200 METER TEMPERATURE—SALINITY RELATIONS FOR THE SOUTHWESTERN SOUTH ATLANTIC
CURVE C
TEMPERATURE °C
SALINITY ‰
18
16
14
12
10
8
6
4
2
0
-2
34.0
35.0
36.0

FIG. 7

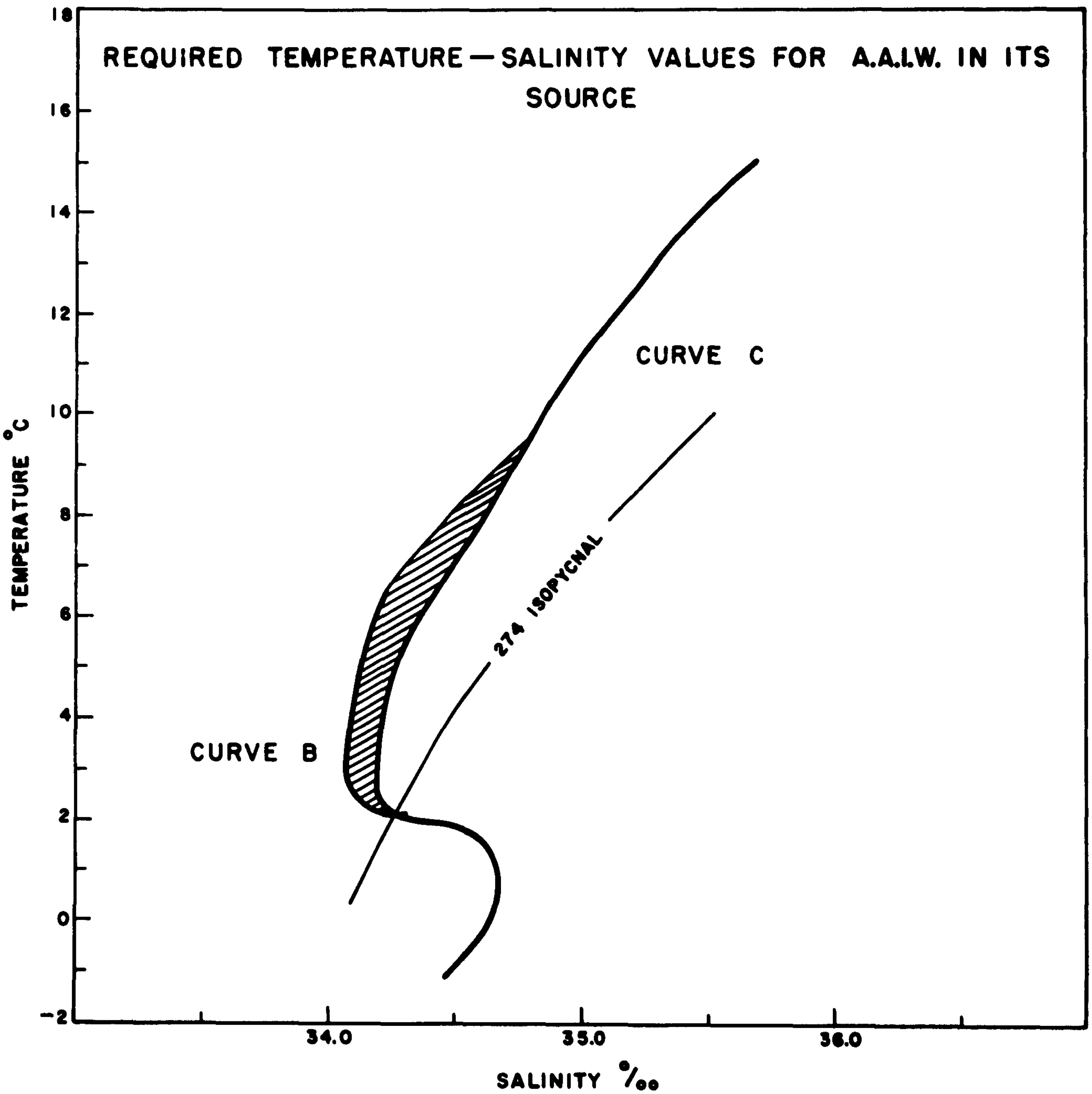
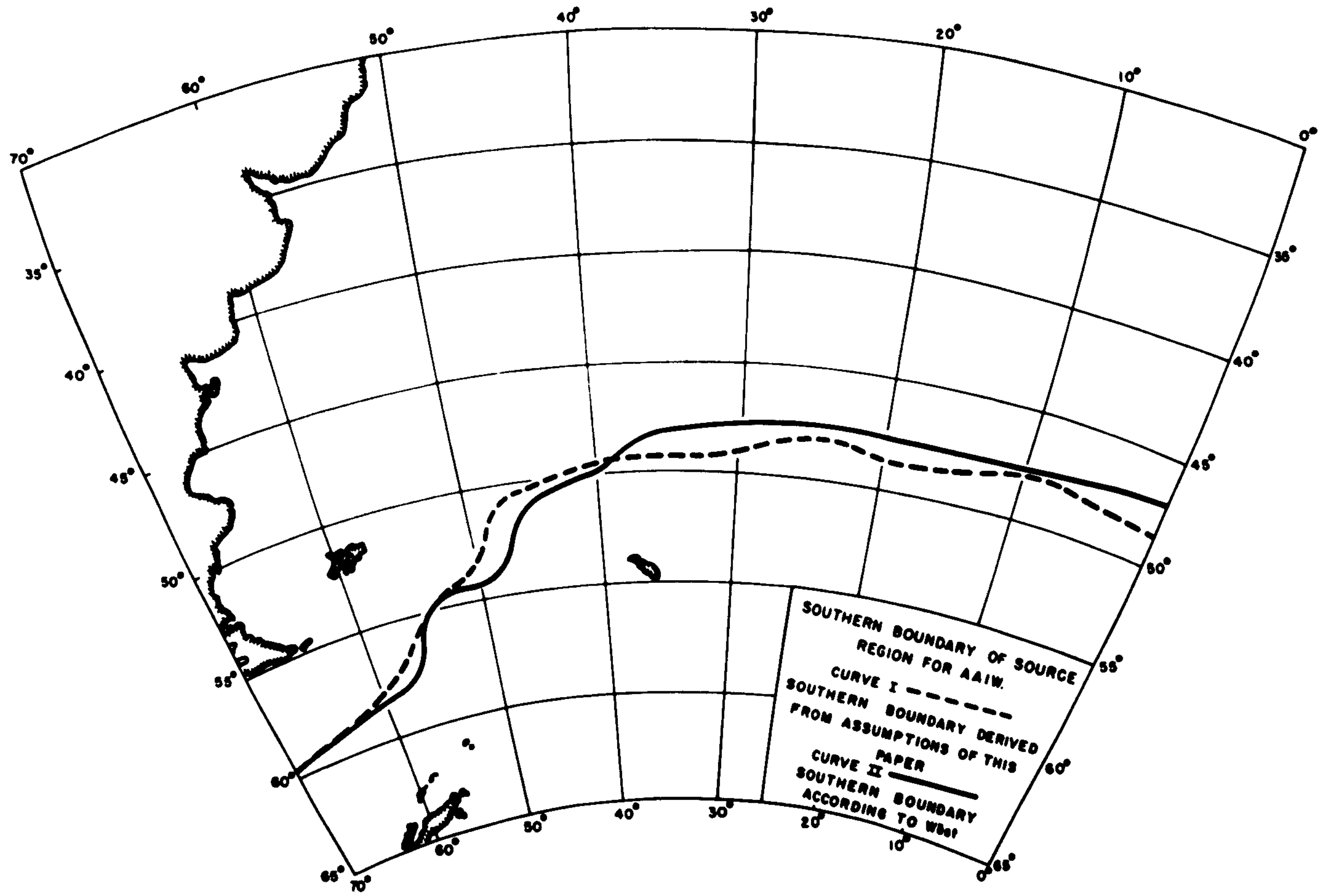

REQUIRED TEMPERATURE—SALINITY VALUES FOR A.A.I.W. IN ITS SOURCE
CURVE C
CURVE B
274 ISOPYCNAL
TEMPERATURE °C
18
16
14
12
10
8
6
4
2
0
-2
34.0
35.0
36.0
SALINITY ‰

FIG.8



SOUTHERN BOUNDARY OF SOURCE REGION FOR AAIW.
CURVE I
SOUTHERN BOUNDARY DERIVED FROM ASSUMPTIONS OF THIS PAPER
CURVE II
SOUTHERN BOUNDARY ACCORDING TO Wüst
70°
60°
50°
40°
30°
20°
10°
0°
35°
40°
45°
50°
55°
60°
65°

FIG. 9

by curve B in figure 5 on the left. For this reason, the 27.4 isopycnic surface has been considered to represent the lower boundary of the intermediate water. This value agrees with the 27.4 value report by Sverdrup (1946) as representing the lower boundary of the water mass as it spreads northward. The agreement between the two values suggests that the assumed magnitude of modification upon which curve B in figure 5 is based is valid.

Results and Conclusions

The recent study by Riley (1951) of the mass transport and the distributions of salinity, oxygen, phosphate, and nitrate along sigma-t surfaces in the Atlantic Ocean has suggested that the flow of AAIW in the South Atlantic conforms to the surface current pattern and may not constitute a mass movement northward, particularly along the coast of South America, as Wüst (1936) and others have advocated. By considering the surface current system of the South Atlantic to extend to depths below those at which the AAIW is found, it has been attempted here to show that the distribution of salinity associated with the core of this water mass can be explained by this flow pattern.

It has been concluded that AAIW is mainly formed along the northern edge of the Antarctic Convergence and a secondary source is located along the coast of South America. From these sources the water sinks and is transported by the major currents of the South Atlantic. Eventually part of the water mass is transported into the Northern Hemisphere by a branch of the Southern Equatorial Current. Such a flow pattern could produce a latitudinal velocity distribution similar to the one given by Deacon (1931). According to the latter, the northward component of velocity for AAIW along the thirtieth meridian increases north of latitude 20°S. Since this is approximately the latitude from which the branch of the Southern Equatorial Current flows northward, the increase in velocity may be explained by the northward transport of AAIW by the current.

Further consideration of the surface current system for the southwestern South Atlantic indicates that the presence of AAIW along the coast of South America may be the result of mixing between the Falkland and Brazilian Currents. A _Meteor_ section across these two currents suggests that the mechanism of formation in the transition zone between them is similar to the one by which the intermediate water of the Labrador Basin is formed. It is believed that the local winds are also important in the formation of this layer and may account for the absence of such a source region along the southwestern coast of Africa (Currie, 1953). A detailed study of the wind field and currents along the coast of South America should determine the dependence of this source region upon the local wind conditions.

In addition to describing the flow pattern for AAIW and also its secondary source region along the coast of South America, it has been attempted to show that the observed temperature-salinity characteristics of AAIW in the South Atlantic are produced by the modification of the initial temperaturesand salinities of the source region and that this modification is mainly produced by lateral mixing as the water mass described in the flow pattern shown in figure 3. An assumed amount of modification was prescribed for the portion of the water mass on each isopycnic surface. The combination of this prescribed amount of modification and the observed temperature-salinity properties of AAIW in the central South Atlantic have been used to describe the required temperature-salinity properties of the source region. The region in the South Atlantic with surface layer conditions comparable to the required ones was found to coincide with the source region of AAIW as previously determined by Wüst (1936).

The lower boundary of this water mass was also determined and found to coincide with the 27.4 isopycnic surface. This value is in agreement with the value reported by Sverdrup (1946).

The results of this paper suggest that an isentropic analysis of the flow of AAIW along isopycnic surfaces within the range of values between 26.9 and 27.4 would substantiate the assumed flow pattern. Riley's transport patterns were computed from average values which were representative of large areas. They indicate the major characteristics of the pattern, but a finer scale study, particularly for the region along the coast of South America, is in order. Future field work in the South Atlantic should emphasize the hydrography of the region along the coast of South America between the Falkland Islands and Cape Frio. The British Discovery Committee has examined the region about the Antarctic Convergence and along the coast of Africa, and now the coast of South America should be considered. Since the current patterns for this region have seasonal variations, a Southern Hemisphere winter survey is suggested. With the aid of additional data from sections across the Falkland and Brazilian Currents, it should be possible to study further the vertical movement within the transition zone between these currents.

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