Average Temperature and Salinity at a Depth of 200 Meters in the North Atlantic[1]

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Abstract

New charts are presented showing the average temperature and average salinity at a depth of 200 meters in the North Atlantic. These are compared with charts published by WÜST and DEFANT in 1936 and it is shown that, over most of the ocean, conditions are nearly constant at this depth. Attention is focused on the areas of changing temperature where the major ocean currents exist. It is shown that important details are obscured by the averaging process. The range of observed temperature is charted and supplements the information given by the average charts. The standard deviation from the mean temperature, calculated for two portions of the Gulf Stream System, indicates that when more observations are available such calculations may be of use in studying the major ocean current systems. Temperature anomalies from the mean for each degree of latitude are plotted and compared with data published by WÜST in 1937.

Introduction

The best source of information on the subsurface temperature, salinity and density distribution in the North and South Atlantic is the atlas to volume six of the Deutsche Atlantische Expedition Meteor (WÜST and DEFANT, 1936). The atlas contains charts of average conditions for various standard depths from 200 meters to 5,000 meters. These charts represent the mean state or yearly normal and were based on all available data regardless of date. The charts are printed in colors and are large, clear and easy to read. Because virtually all studies of the general circulation of the oceans are based on what is known of the temperature, salinity and density distribution and also because of its exceptional quality this atlas should be a standard reference on the subject.

Since the date of publication of the Meteor Atlas many observations, especially of subsurface temperatures, have been made in the North Atlantic. The files of the Woods Hole Oceanographic Institution contain 210,000 records of subsurface temperatures obtained with the bathythermograph and 37,000 serial observations of subsurface temperature and salinity obtained by the Nansen bottle method. All of the bathythermograph and approximately 50 % of the serial observations were made after 1934. With these new data on hand the question arises as to whether or not that part of the Meteor Atlas that deals with the North Atlantic is obsolete.

The task of producing a new atlas in any way comparable to the German one would

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be an expensive and large undertaking. If it should prove desirable at this time, then the U.S. Navy Hydrographic Office with its punch card system and complete file of data would be best able to do this work. This paper is intended as an investigation of the problem of whether or not a part of the Meteor Atlas is obsolete and it may serve as a supplement to that atlas. Only the 200 meter depth is considered, partly because there are more new data for this than for any other depth represented in the German Atlas and partly because the temperature conditions at this depth have been of special interest in various studies of the Gulf Stream System, (Wüst, 1937) (FUGLISTER, 1951). Problems that arose in the averaging process will be discussed and the need for other than average charts examined.

Chart Construction

Of the available temperature observations, 40,000 reached to a depth of 200 meters and were used in constructing the accompanying 200 meter average temperature chart (chart 2); 14,000 salinity observations were available for the 200 meter average salinity chart (chart 4). This is approximately 10 times as many temperature observations and 4 times as many salinity observations as were available for the construction of the German Atlas Charts (here copied as charts 1 and 3). Lest it is felt that the saturation point of observations in the North Atlantic is being approached, chart number 5 has been drawn up to show the large portions of this ocean for which our files contain no data for the 200 meter depth.

In the process of averaging, the unit of area used was the one degree field. All observations from one month, regardless of year, were averaged and then these monthly values were in turn averaged to obtain a yearly normal. This system tended to decrease the weight of numerous observations made by one ship at one time in a unit area as it increased the weight of scattered "off season" observations. The temperature and salinity values from serial observations were, in many cases, interpolated values. The tabulations for each unit area included, besides the average temperature and salinity, the total number of observations, the months represented, the maximum and minimum observed values and the range. In order to compare the 200 meter temperature data with some results published by WÜST (1937), the average temperature for each degree of latitude was calculated and the temperature anomalies for each one degree field were tabulated. In these computations the Mediterranean data were excluded.

After the various tabulated values were plotted on the charts an important decision had to be made. Should the isopleths be drawn to follow the plotted values exactly or should some smoothing of the resulting irregular curves be done? Once a smoothing process of this sort is started it is difficult to know where to stop. Rather than risk misinterpreting the data, the decision was made to make every effort to follow the data exactly. An exception was made in a few cases where separate isopleths would have been required to represent a single value unsupported by the values in adjacent one degree fields. Some interpretation and interpolation of the data was, of course, necessary in order to make the isopleths continuous over the areas devoid of data.

A Comparison with the Meteor Atlas Charts

A superficial comparison of the new and older charts will give the impression that they are radically different. However, a closer study shows that, except for the addition of new areas and the introduction of numerous irregular lines instead of long smooth curves, there is remarkably little difference in the two sets of charts. In many instances the isotherms and isohalines of the German Charts are a smooth or average representation of the more complicated curves of the new charts. This suggests that the Meteor Charts, although based on far fewer observations, are in fact more nearly correct representations of the average conditions in the North Atlantic than are the new charts. It suggests that the method of drawing the isopleths on the new charts tends to confuse the average picture and the curves should have been smoothed, that is, an averaging process should have been employed in drawing the isopleths. Although it is quite possible that the German Charts

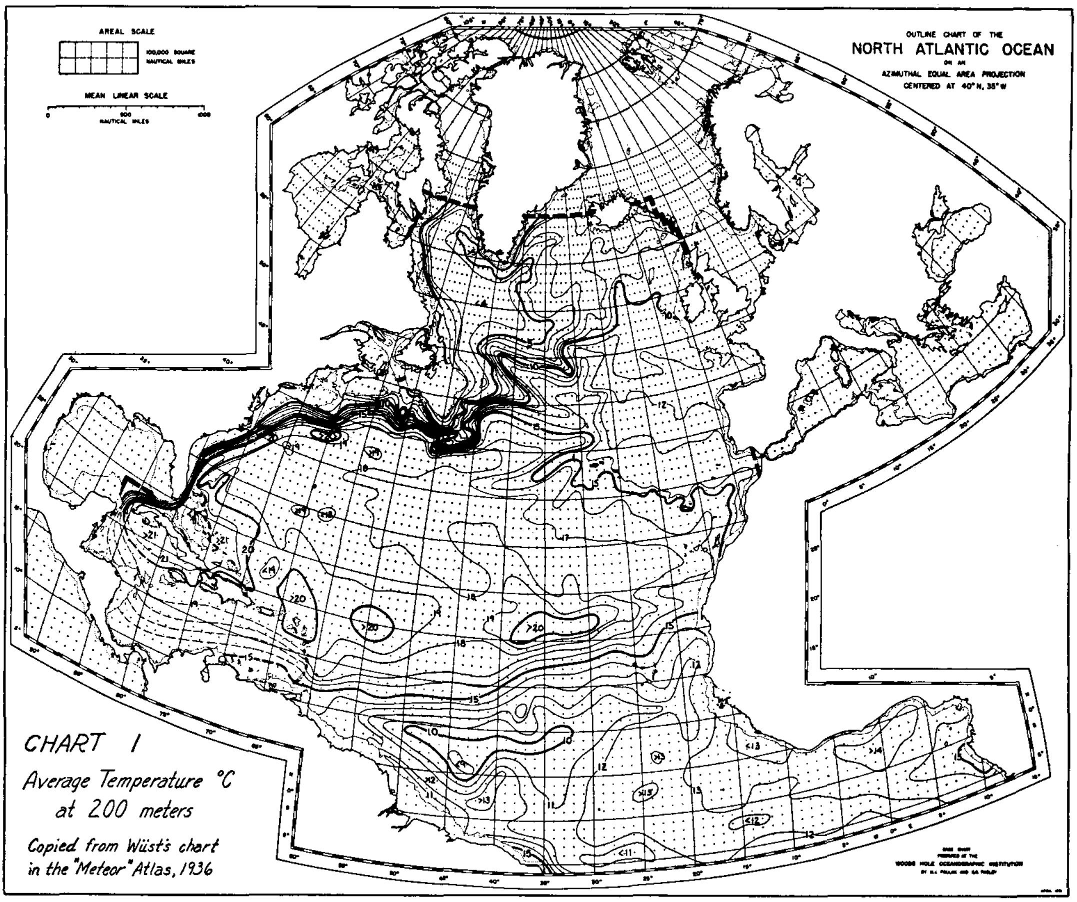

Chart 1. Average Temperature (after Wüst).

approximate the true average condition, the new charts have the advantage of showing some of the complexities and details (which may or may not be significant) and of allowing the reader to interpret and smooth the results for himself.

A comparison of these charts brings out the important fact, that over most of the vast extent of the North Atlantic conditions at 200 meters must be very nearly constant. The complex areas on all the charts are confined to certain portions of the ocean and it is evident that in these areas the major ocean currents exist. Most of what follows will be a discussion of the details in these complex areas and, because of the better distribution of temperature data, attention will be focused on the new 200 meter average temperature chart.

The 200 Meter Average Temperature Charts

The new 200 meter temperature chart shows many interesting details not appearing on the German Chart. Since it is almost impossible to discuss these details without referring to currents, the general assumption will be made here that the positions of the major ocean currents coincide with the positions of the pronounced horizontal gradients of temperature at 200 meters. Also, the assumption is made that the current directions are such that the warm water is to the right facing downstream. Because of the fresher water in the following areas the direction of flow is reversed with warm water to the left: in a narrow belt just off the continental shelf from the tail of the Grand Banks northward to Baffin Bay, and similarly from Cape Farewell

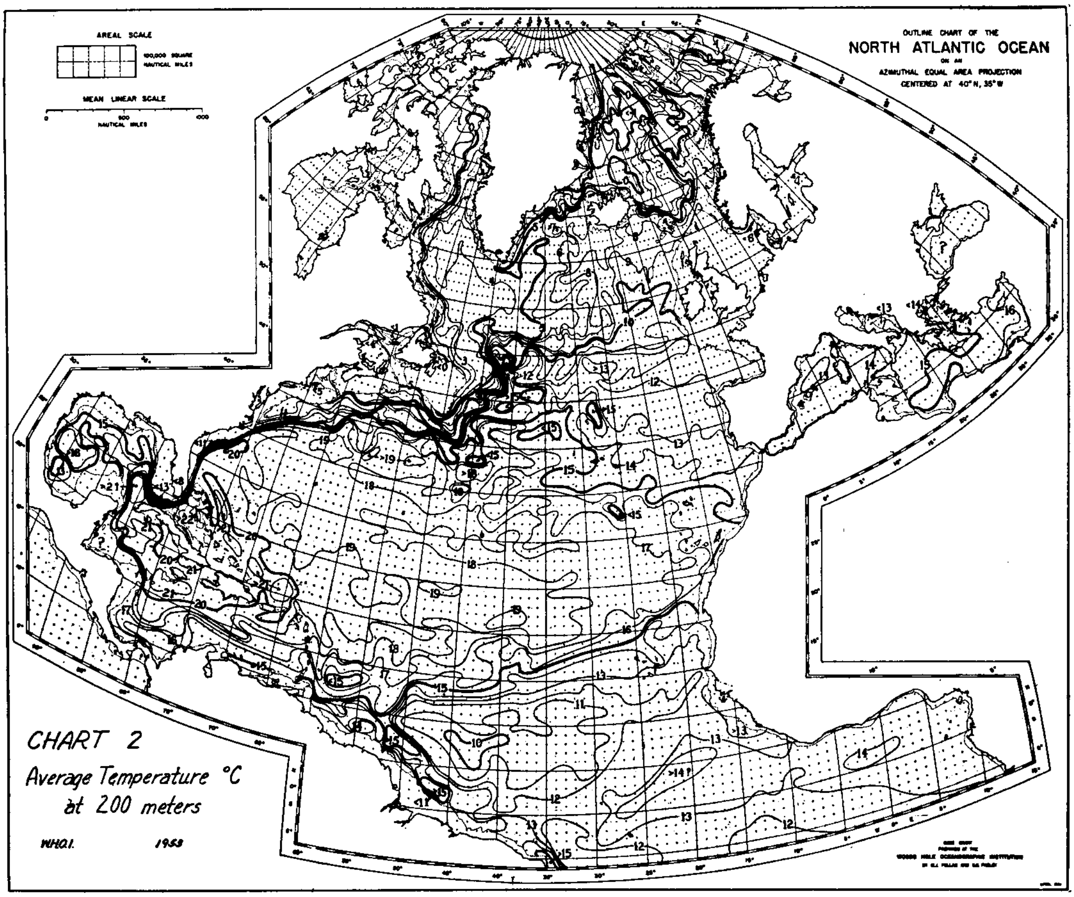

Chart 2. Average Temperature.

at the southern tip of Greenland northward along the east coast of Greenland to the Polar Sea.

The most pronounced gradient on both temperature charts is the one associated with the Gulf Stream. Between the Florida Straits and the 65th meridian the temperature contrast on the new chart is 2 to 3 degrees centigrade less than on the older chart. In the region between Cape Hatteras and the Grand Banks the zone of maximum temperature, south of the gradient, is displaced further to the south. Both of these changes can be explained in the following manner. If the current is continually shifting its geographical position and we assume the cross-current gradient to be constant then, up to a certain point, an increase in the number of observations averaged in the area will tend to spread out the gradient, decrease the total range of temperature across the gradient, and displace the maximum value to the right, facing downstream. If, as shown in Figure 1, the solid line represents the normal

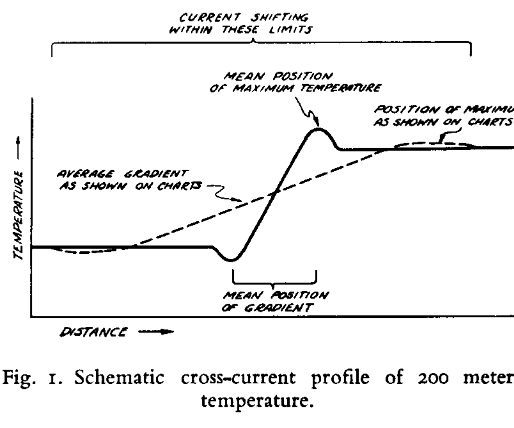

Fig. 1. Schematic cross-current profile of 200 meter temperature.

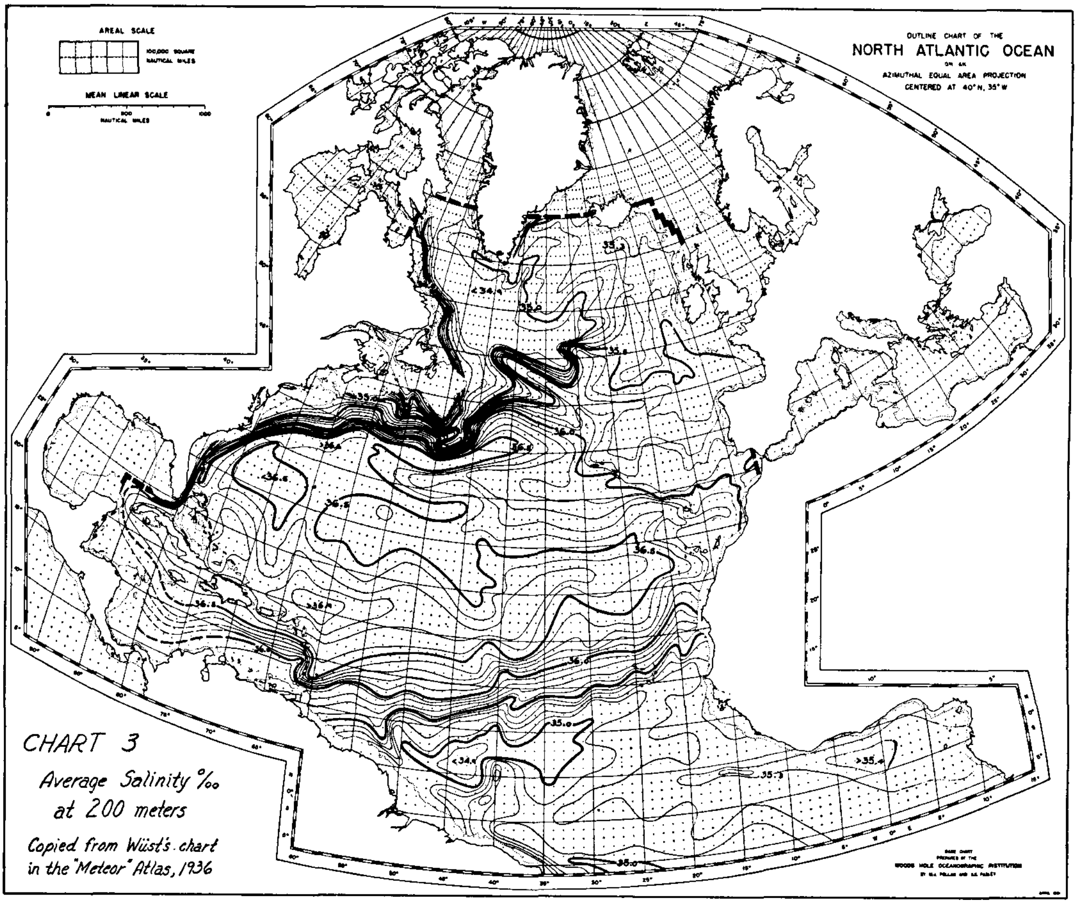

Chart. 3. Average Salinity (after Wüst).

temperature gradient across the current and the current shifts between the limits shown, then the average chart will show the more gradual gradient and the less pronounced maximum and minimum values as represented by the dashed line.

In the area to the south of Nova Scotia and Newfoundland there is what might be termed an intermediate development of the average in the Gulf Stream zone. The single gradient that appears on the German Chart is now broken down into at least two separate gradients. Although this separation of the isotherms appears to support the theory of multiple currents in the area (FUGLISTER, 1951) it is possible that increasing numbers of observations may again blend the picture and eventually show a single, gradual gradient across the zone. Much of the complicated pattern of isotherms on the new chart, in the Gulf Stream area in particular, but also to some extent in the equatorial regions, may be interpreted as showing the non-continuity or multiple current characteristics of the major ocean currents. This characteristic is not suggested by the German Chart, except perhaps in the area to the east of the Grand Banks, and it may not be indicated again when an average chart based on many more thousands of observations is produced.

The most confused area on the new charts is in the portion of the Gulf Stream System to the east of the Grand Banks. Disregarding the complex details for a moment, it is obvious that the many new observations in this area show that the warm water (> 10° C) flows closer to Flemish Cap and further to the north and west than is indicated on the Meteor

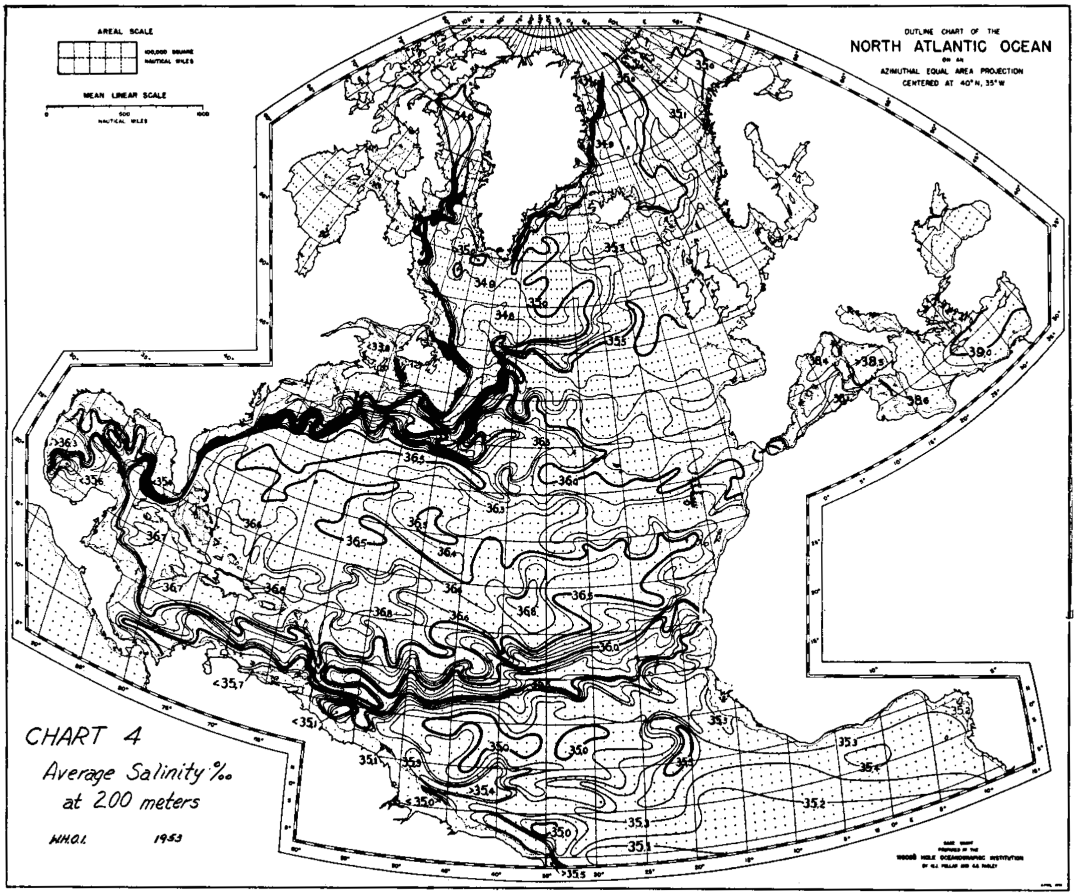

Chart 4. Average Salinity.

Chart. The pronounced gradient, indicating a northwesterly current, which turns abruptly towards the east near 50° north latitude is one of the most interesting features shown on either chart. One may be tempted to say that it is the bottom topography in this area that is the controlling factor but then it would be necessary to explain how bottom contours at depths of 4,000 meters could affect the course of a current which, according to its density structure, does not extend deeper than 1,500 meters.

To return to the details shown on the new chart in the region to the east of the Grand Banks we see that there are several isolated areas of maximum and minimum temperatures. If this were a truly average picture of the temperature conditions in the area we would interpret these areas as the locations of permanent eddies in the system. A more logical explanation is that this is a region of shifting currents and countercurrents and the distribution of observations is such that the resulting picture is a combination of average and instantaneous values. As we approach the Grand Banks from this area the number of observations increases and the isotherms smooth out.

East of the 30th meridian neither chart defines the area of the Gulf Stream System. The new chart shows a pronounced gradient in the eastern Norwegian Sea but there is no recognizable connection between it and the gradients in the area east of the Grand Banks. If the cross-current gradients decrease in magnitude and the currents shift over wide areas in the northeastern Atlantic then we can expect to find a widespread gradient on the average.

However, as will be shown later, no gradient of as much as 2° C. in a one degree field has ever been observed in the area southeast of the Faeroe-Shetland Channel where the northern branch of the Gulf Stream System presumably flows toward the Norwegian Sea. More will be said on this subject in connection with the discussion of the temperature range and temperature anomaly charts.

In the Norwegian Sea there is a scarcity of data north of the latitude of Jan Mayen (66° N) but in the southern portion, especially in the east, there is an excellent distribution of observations. The most interesting feature is the indicated current area extending northward along the Greenwich Meridian. The Norwegian Current is generally depicted as flowing along the coast of Norway and it is surprising that the chief concentration of gradients lies so far to the west. The pronounced gradient area along the southern boundary of the Norwegian Sea is evidently associated with the ridge that separates the Norwegian Basin from the main body of the North Atlantic. These gradients define a frontal zone and must be associated with relatively permanent currents, but because of the salinity gradients near the Greenland end of the ridge and the generally shoal depths several interpretations of current direction are possible.

In the north equatorial regions the principal differences between the new and the old charts appear in the area near the West Indies and off the coast of South America. The maxima and minima in these areas can be explained in the same way as were those phenomena in the area east of the Grand Banks, that is, the new chart represents a combination of average and synoptic data. As in the Gulf Stream the gradient across the north equatorial current has decreased slightly, the zones of 20° water to the north of the current have disappeared and the area of $< 10°$ water to the south has become smaller.

The Equatorial Countercurrent is only vaguely suggested by the 200 meter temperature distribution except in the western area, around 8° N, 50° W, where a pronounced gradient appears on the new chart. There is no evidence of the existence of the Antilles Current on either the new or the old chart.

In the Mediterranean Sea there are no pronounced gradients of temperature at 200 meters. The positions of the few isotherms on the new chart are somewhat doubtful but it is evident that conditions are relatively uniform with a slight increase in temperature toward the east and south across this sea.

To conclude this discussion of the 200 meter average temperatures, it is evident that a new chart, based on ten times as many observations as were used in the Meteor Atlas, does not alter the general picture as shown by that atlas. Except for a few significant detailed changes the new chart only confirms the average conditions as depicted by Wüst and Defant. The implication that the 200 meter temperature chart may serve as a useful tool in the study of the major ocean currents appears to be sound and, as we have seen, it does raise some interesting and provocative questions.

Range of Observed Temperatures

Chart number 6 shows the range of observed temperatures at a depth of 200 meters in the North Atlantic. These ranges are the maximum minus the minimum observed temperature within each one degree field regardless of the date of the observation. The total range was calculated in order to show where, in the North Atlantic, pronounced horizontal gradients of the temperature at 200 meters have been observed. The assumption is made here that, except for slight seasonal changes, the temperature at 200 meters does not gradually change with time and any marked differences in observed temperatures in a unit field indicate that a pronounced horizontal gradient has existed in the area. Since no averaging process is involved in the production of this chart it should prove useful as a supplement to the average temperature chart in studying the major ocean current of the North Atlantic.

In general the maximum range of temperature occurs in those regions where the average temperature chart shows the maximum horizontal gradients. The highest values occur in the area shown in black off the northeast coast of North America where ranges of from 10° to as high as 16° have been observed. Over most of the ocean the range is less than 2°. Calculations of the seasonal varia-

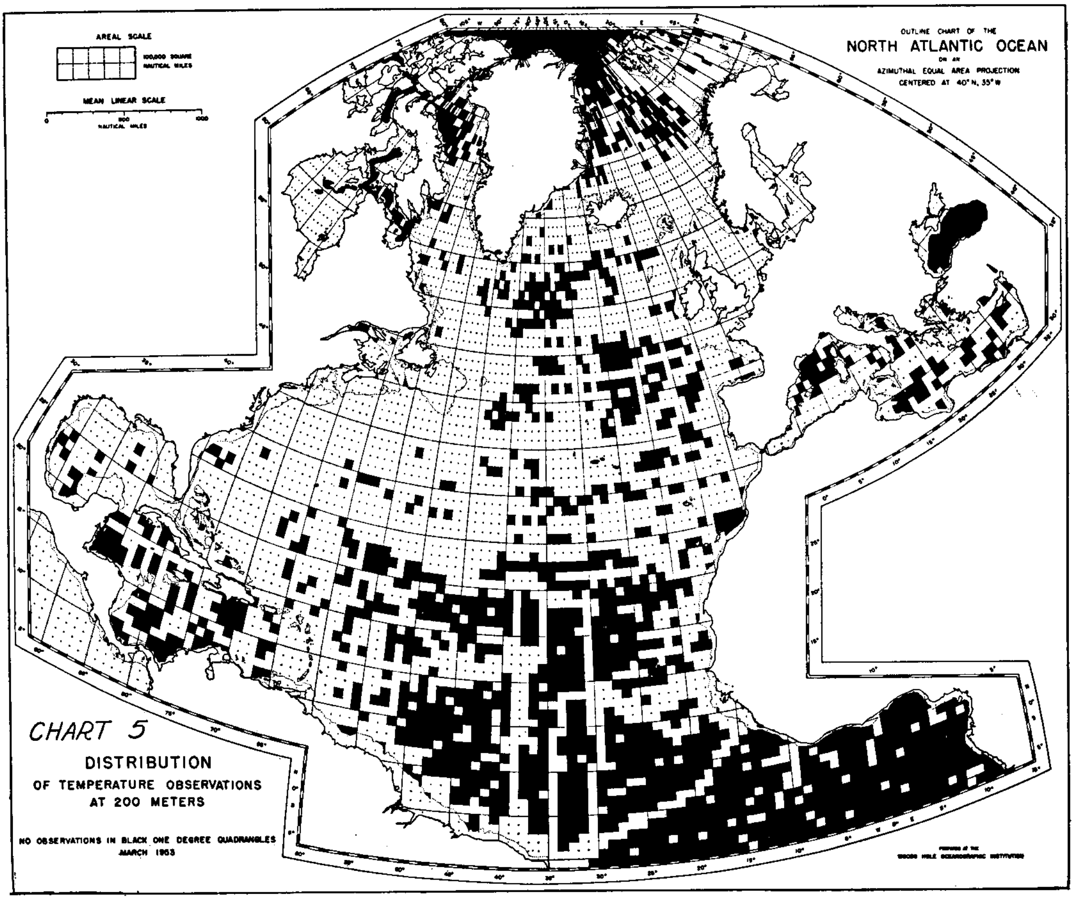

Chart 5. Distribution of Temperature Observations.

tions in the 200 meter temperature, in a few areas where observations are available for all months of the year, indicate that this variation is between 1° and 1.6°. We may assume then that changes in temperature, that we associate with currents, occur in all the areas where the range is greater than 2°. These areas are shaded or black on chart number 6.

The most interesting feature on the range chart is the four prongs of $> 2°$ ranges extending eastward from the Grand Banks area and the fact that the northernmost prong does not extend to the Norwegian Sea. In the area southeast of the Faeroe-Shetland Channel (54° to 61° N. Lat., 9° to 20° W. Long.) there are 402 observations giving range values in 66 of the 77 one degree fields. The seven months from May through November are represented. If a major ocean current exists in this area it is indeed surprising that this number of observations could have been made without once showing a temperature gradient of more than 2° in a unit area.

Unlike the average temperature chart the range chart does indicate the existence of current in the Antilles region. Unfortunately there are too few observations in the eastern equatorial area, in the Caribbean and in the western Norwegian Sea to determine the ranges. It may be argued that the calculation of the total, or maximum, observed range in temperature is too crude a method of study. The range is calculated from only two observations in each unit field and these observations, the maximum and minimum observed temperatures, are the ones most likely to be in error. Of course, every effort has been made to

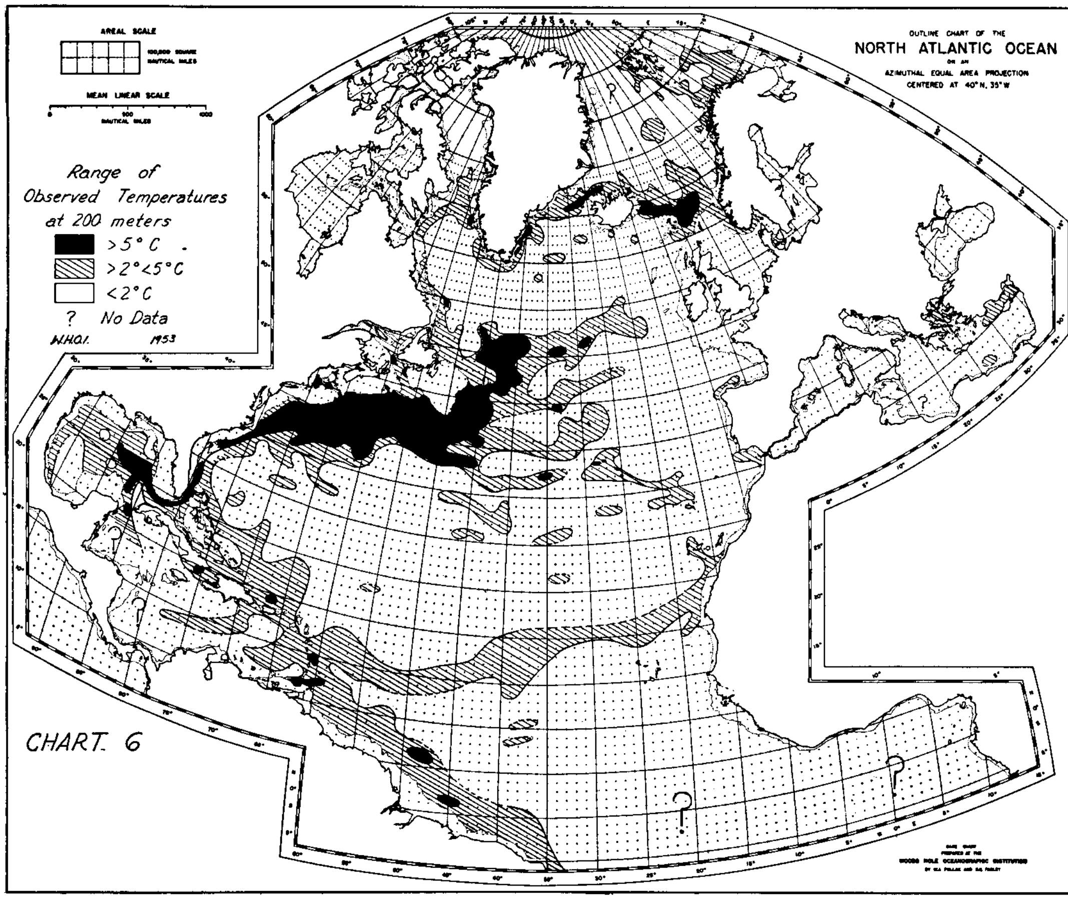

Chart 6. Range of Observed Temperatures.

remove from the files any data that could be shown to be in error but, in many cases, no such check was possible. The scarcity of observations in many areas is a more serious drawback than the inclusion of occasional errors. Nevertheless, the range chart produced here achieves a continuity that appears to be reasonable in the light of what is known about the North Atlantic circulation.

Standard Deviation from the Mean Temperature

The standard deviation from the mean temperature could be calculated for each unit area in order to show the probable variation (and to minimize the effect of errors in the extreme values). These calculations were not carried out for the North Atlantic chiefly because of the amount of labor involved but also because the number of observations over large areas did not warrant this approach. The standard deviation was calculated for two areas in the Gulf Stream region in order to compare the results with the average temperature and the range of temperature.

The first area contains the one degree fields that fall on a line between Bermuda and the continental shelf off Long Island. Figure 2 A shows the latitude and longitude of each degree field, the number of observations, the number of months, the average temperatures, the ranges and the standard deviation. The average temperature curve shows that the maximum gradient (the Gulf Stream) lies between the unit fields whose centers are at 37° 30′ and 38° 30′ north latitude; the standard deviation is highest in the unit field

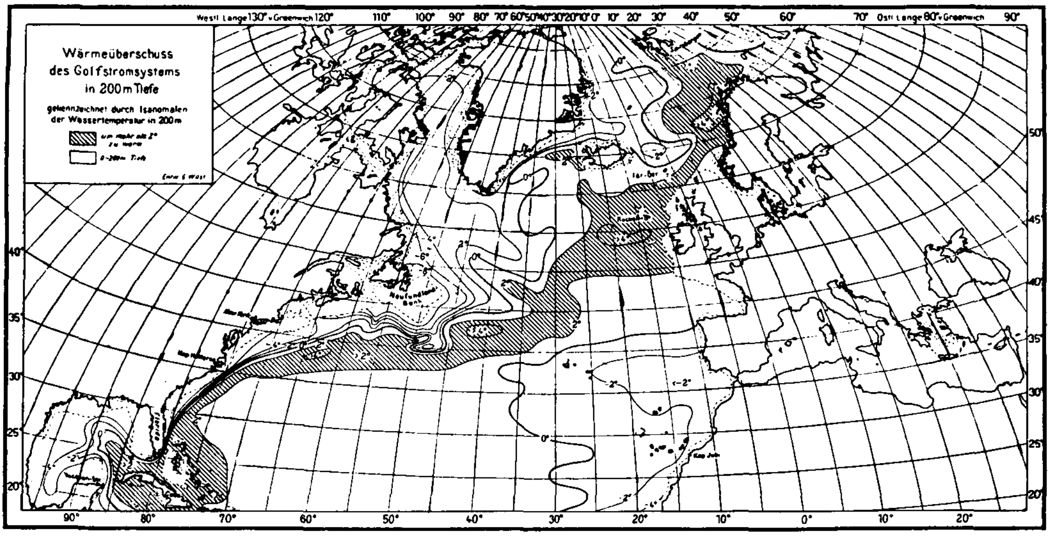

Chart 7. Temperature Anomalies (after Wüst)

centered at 37° 30′ N and the high ranges are spread over three unit fields from 36° to 39° north latitude. We can interpret the standard deviation curve as showing that there is one major current in the area and that its mean position is at about 37° 30′ N. The range curve can be interpreted as showing that the major current in this area varies in position between 36° and 39° north latitude.

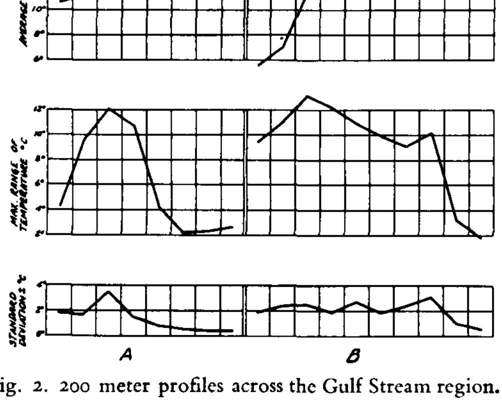

Fig. 2. 200 meter profiles across the Gulf Stream region.

In the second example shown in Figure 2 B the unit fields were enlarged to include five degrees of longitude. The area extends from the continental shelf south to 35° N crossing the Gulf Stream between 55° and 60° west longitude. The average temperature curve shows the maximum gradient between 40° and 44° N. The standard deviation is highest at 37° 30′ N with secondary maxima at 40° 30′ N and 42° 30′ N. The high ranges are spread over eight unit fields from 37° to 45° N. The average temperature curve indicates that the Gulf Stream has become wider in this zone, with perhaps two branches both north of 40° north latitude. The range and the standard deviation curves both show high values for all the area north of 37° north latitude. The standard deviation curve may be interpreted as showing three zones of maximum gradients.

Temperature Anomalies

In order to show the continuity of the Gulf Stream and the Norwegian Current, Wüst (1937) calculated the zonal mean temperatures at a depth of 200 meters for each $2\frac{1}{2}$° of latitude from 20° to 75° north latitude in the North Atlantic. From these mean temperatures he calculated the anomalies. He considered that the areas showing a positive anomaly of greater than 2° defined the position of the Gulf Stream System. The chart that Wüst published is reproduced here as Chart 7.

On the bases of the 40,000 observations now available the zonal mean temperature for each one degree of latitude was calculated. These values are plotted in Figure 3, the values obtained by Wüst are shown on the diagram by × marks and it can be seen that there is a surprising agreement in the two sets of zonal averages.

The temperature anomalies as calculated from the zonal averages (for every 2° temperature difference) are shown on Chart 8. Here it is apparent that the new chart differs from Wüst's in several respects and this in spite of the fact that the zonal averages used were virtually the same. In the Gulf Stream area south of 40° north latitude the changes appearing on the new chart may be attributed to the effects of averaging. This was discussed on page 49 where it was pointed out that when averaging many observations in an area of a shifting current the zone of maximum temperature is displaced to the right — facing downstream — and the maximum temperature values are decreased. This may account for the break in the shaded zone (> 2° positive anomalies) off Florida and the very nearly broken segment south of the Grand Banks. To the east of the Grand Banks the shaded zone is much more extensive on the new chart. This is due to the fact that at the time when Wüst made his chart there were very few observations in the region between 35° and 45° west longitude and 40° and 50° north latitude and the new data show that warm currents exist in the northern portion of this area.

In connection with the discussion of the continuity of the Gulf Stream System in the northeastern Atlantic, the difference between the two anomaly charts in the area southeast of Iceland is of particular interest. Wüst's chart shows a pronounced flow of warm water into the Norwegian Sea, through the Faeroe-Shetland Channel, with only a suggestion of a branch of warm water pointed toward the west of Iceland. The new chart reverses this picture, most of the warm water is concentrated to the south and west of Iceland with only a suggestion of flow into the Norwegian Sea along the European continental shelf. This difference in the two

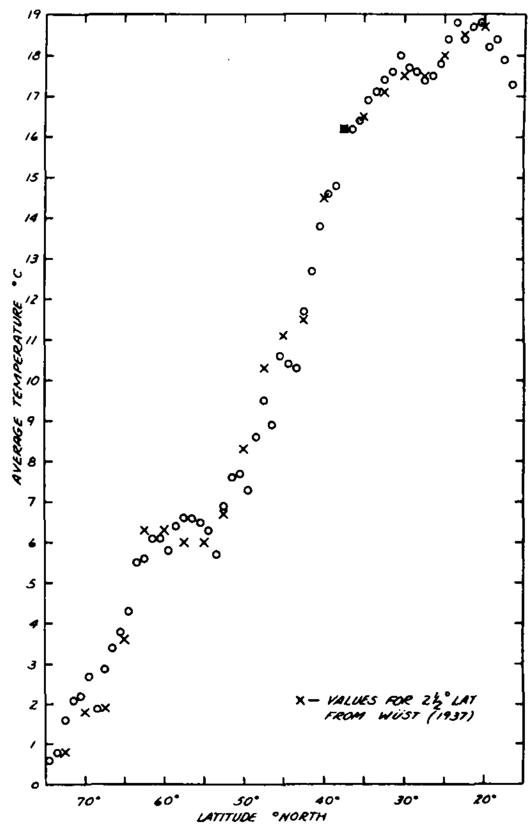

Fig. 3. Average temperatures at a depth of 200 meters for each degree of latitude for the North Atlantic Ocean.

charts may be interpreted in various ways, as in fact the entire subject of temperature anomalies may be, but taken together with the evidence of the average temperature chart and the range chart it does suggest that the high positive anomalies in the eastern Norwegian Sea are not entirely the result of a flow through the Faeroe-Shetland Channel. It is interesting to speculate on what these anomalies would be if the Norwegian Sea was entirely disconnected from the Atlantic.

The 200 Meter Salinity Charts

Although the new salinity chart (Chart 4) is based on far fewer observations than the new temperature chart the same trend of differences from the Meteor Atlas Chart (Chart 3) is evident. Virtually all the statements made concerning the new average temperature chart can be applied to the new salinity chart.

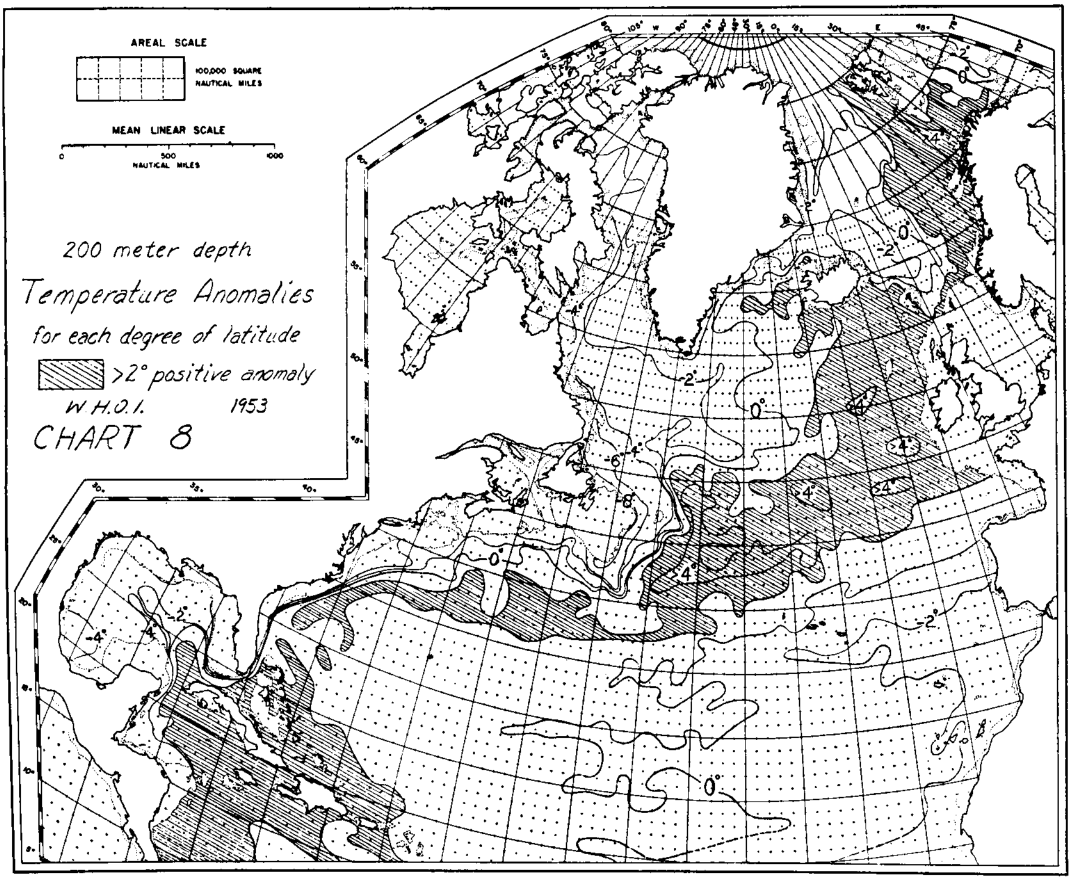

Chart 8. Temperature Anomalies.

However, no attempt has been made here to correlate the new temperature and salinity charts; each chart was drawn independently even though there were many areas where no salinity data were available and the placement of the isotherms. may have been used to determine the position of the isohalines.

Conclusions

It is quite apparent from the foregoing that, far from being obsolete, the charts in the Meteor Atlas that deal with conditions at a depth of 200 meters in the North Atlantic are still to be considered as accurate representations of the mean state. This atlas shows, as we might expect, a certain continuity of conditions with increasing depth and, therefore, we may assume that all the charts in this atlas are equally reliable. The major drawback of the Meteor Atlas is that it does not cover the Norwegian Sea, the Gulf of Mexico, the Mediterranean Sea and Baffin Bay.

The new set of charts presented with this paper show that, although much can be learned from studying the average conditions as depicted in the Meteor Atlas, if we wish to study the major ocean current systems the average picture is somewhat misleading. The value of charts showing the mean state can be greatly increased if they are supplemented by charts showing the range of conditions and the standard deviations from the mean. However, it is obvious that it will be many years before enough observations are obtained to do this for any depths greater than 200 meters. Even at this depth the distribution of observations over the North Atlantic is too uneven to make such charts completely reliable.

It may seem a paradox but the chief value of the new 200 meter average temperature chart, aside from the fact that it covers a more extensive area in the North Atlantic than the Meteor Atlas, is the fact that it does not represent a true average picture. Because of the uneven distribution of data and the non-averaging system of drawing the isotherms this chart focuses the attention on many details that would not exist on a chart more truly representative of the average. This is especially evident in the major ocean current areas.

Several interesting questions are posed if the new 200 meter temperature chart, supplemented by the range chart, is used as a current chart. Why does the Gulf Stream break down into more than one current long before it reaches the longitude of the Grand Banks and why does the system break down so much more rapidly into at least four currents after it has passed this longitude? Why is there no pronounced current extending from this system in mid-Atlantic to the Norwegian Sea and is the circulation in that sea largely self-contained? Why is the Antilles Current only vaguely suggested on the range chart and not at all on the average temperature chart? How far does the current that passes through the Yucatan Channel penetrate into the Gulf of Mexico before turning about to flow out through the Straits of Florida? Why is there so little evidence of an anticyclonic current system over the main body of the North Atlantic?

No attempt is made here to answer these questions. It has been assumed that a cross-current temperature gradient at a depth of 200 meters exists wherever there is a major ocean current. If this assumption is wrong then the above questions are meaningless. But if it is a justified assumption then these questions are valid and should be of considerable interest.

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