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Eighteen Degree Water variability

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ABSTRACT

The Eighteen Degree Water of the western North Atlantic is formed by deep convection in winter. The circulation and changing properties of Eighteen Degree Water are studied using hydrographic data from a long time series at the *Panulirus* station (32°10′N, 64°30′W) and from the Gulf Stream '60 experiment. Due to its relative vertical homogeneity, which persists year-round, the Eighteen Degree Water can be identified by its low potential vorticity $(f/\rho)(\partial\rho/\partial z)$. The Eighteen Degree Water is formed in an east-west band of varying characteristics offshore of the Gulf Stream. The Eighteen Degree Water formed at the eastern end of the subtropical gyre recirculates westward past the *Panulirus* station. Renewal of Eighteen Degree Water occurred regularly from 1954 to 1971, ceased from 1972 to 1975, and began again after 1975. The properties (18°C, 36.5‰) of Eighteen Degree Water seen at the *Panulirus* station were nearly uniform from 1954 to 1964. There was a shift in properties in 1964 and by 1972 the Eighteen Degree Water properties were 17.1°C, 36.4‰. The new Eighteen Degree Water formed after 1975 had nearly the same characteristics as that of 1954.

The density, potential temperature, salinity and the temperature-salinity relation of the entire upper water column at the *Panulirus* station changed at the same time as the Eighteen Degree Water properties. The upper water column was denser and colder from 1964 to 1975 than from 1954 to 1964 and after 1975.

1. Introduction

In the open North Atlantic, two water masses are formed by deep convection in winter. One is the Eighteen Degree Water of the western North Atlantic (Worthington, 1959) and the other is the Subpolar Mode Water of the central and eastern North Atlantic (McCartney and Talley, 1982). Both are characterized by their year-round vertical homogeneity, due to their convective origin. The Eighteen Degree Water is formed southeast of the Gulf Stream and is found in a thick wedge centered at about 300 m in the subtropical gyre in the western North Atlantic. Its thickness (about 200 m) is due to its convective origin and is the basis for our method of identification. Worthington (1959) defines the Eighteen Degree Water as $\theta = 17.9°C \pm 0.3°C$, $S = 36.50‰ \pm 0.10‰$, and $\sigma_t \sim 26.4$ mg cm^{-3}.

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The purpose of this study is to identify the formation regions and circulation of Eighteen Degree Water in the northern Sargasso Sea and to look at the changing characteristics of the Eighteen Degree Water as seen at hydrostation *Panulirus*, which is situated in the westward return flow of the subtropical gyre. The seemingly stable characteristics of the Eighteen Degree Water over the history of hydrographic measurements in the western North Atlantic point to a relatively stable circulation and forcing, as discussed by Warren (1972). Schroeder *et al.* (1959) have also commented on the remarkable stability of the Eighteen Degree Water characteristics from 1873 to 1958, based on historical data and the first few years of the *Panulirus* data. Their definition of Eighteen Degree Water is broad enough to include the systematic variations in Eighteen Degree Water described in the present paper and by Pocklington (1972), Fieux and Stommel (1975) and Jenkins (1982).

Changes in the Eighteen Degree Water characteristics are part of the ocean climate changes in the North Atlantic. The sea-surface temperature of the entire northern North Atlantic, also an indicator of climatic change, varies over long periods, as demonstrated by Bjerknes (1964) and Colebrook and Taylor (1979). Bjerknes showed that a twenty-year cooling period in the early 1900's, followed by a warming period into the 1930's, was tied directly to changes in the winds. Colebrook and Taylor (1979) continued Bjerknes' discussion to show that there was general sea-surface cooling in the North Atlantic from 1948 to 1974.

Fieux and Stommel (1975) demonstrated that there was surface warming in a strip of the Sargasso Sea (20-40N and 50-60W) from 1910-1920 to 1950-1960, corroborating Bjerknes' results. They also demonstrated a cooling trend after 1960, as in Colebrook and Taylor. From sea-surface data in the Eighteen Degree Water formation latitudes, Fieux and Stommel (1975) concluded that the "Eighteen Degree Water" had large excursions in temperature, from a low of about 17.0°C in the early 1900's to a high of 18.3°C in the 1950's.

Conditions in the upper 1400 m at the *Panulirus* station from 1957 to 1969 were discussed by Pocklington (1972). Beneath the surface layer, he found a consistent decrease in temperature, increase in salinity, and increase in density during the period 1957 to 1967. The surface layer (from 1957 to 1960) behaved in direct contrast, with the implication being that local processes in the neighborhood of the *Panulirus* station were not responsible for the changes below the surface layer.

In the following sections, we discuss first our method for identifying the Eighteen Degree Water, second the characteristics of the Eighteen Degree Water and upper 600 m at the *Panulirus* station from 1954 to 1978 and finally the horizontal distribution and properties of Eighteen Degree Water in April, 1960. We then comment on the similarity between newly formed Eighteen Degree Water and that seen at the *Panulirus* station.

2. Method

Convectively formed water masses such as the Eighteen Degree Water are, by nature, pycnostads. A pycnostad, by definition (Seitz, 1967), has a weak vertical density gradient. When capped by a seasonal pycnocline at the surface, a pycnostad is recognized by a minimum in the vertical density gradient ($\partial\rho/\partial z$). When a pycnostad is advected away from its formation region by the general circulation, it tends to preserve its potential vorticity rather than its vertical density gradient, according to quasigeostrophic theory. Thus, the basic tool we use in identifying and assessing the strength of pycnostads is the potential vorticity, which, for negligible relative vorticity, is (f/ρ) $(\partial\rho/\partial z)$ where f is the Coriolis parameter. The potential vorticity, like the vertical density gradient, has a minimum in the vertical at a pycnostad. (As a pycnostad changes latitude, its vertical density gradient should change in order to preserve the potential vorticity. In the present case, the difference between trends in potential vorticity and vertical density gradient at the Eighteen Degree Water core are quite slight since the latitude band of interest is limited.)

The potential vorticity minimum is an excellent tracer for the Eighteen Degree Water which really has no other reliable tracer if standard hydrographic measurements are used. (An associated oxygen maximum is weak because the water mass is close to the surface.) Elsewhere in this volume (Jenkins, 1982), tritium-^{3}He measurements are successfully used to identify the Eighteen Degree Water. Such measurements made in 1974-75 and 1977-78 clearly showed a change in the Eighteen Degree Water renewal rate, consistent with the information gathered here based on the *Panulirus* hydrographic data.

Hydrographic station data were interpolated to standard potential density (σ_θ) levels separated by potential density increments of .02 mg cm^{-3}. The local density difference across each interval was then recalculated by referencing the interpolated temperature and salinity to the midpoint between the adjacent density surfaces. The differences of density and depth between adjacent levels were used to compute an approximate density gradient ($\Delta\rho/\Delta z$) for the layer. The potential vorticity (f/ρ) $(\Delta\rho/\Delta z)$ was then computed in cm^{-1} sec^{-1}. A potential vorticity value of 25×10^{-14} cm^{-1} sec^{-1} corresponds to a thickness of approximately 60 m while a value of 100×10^{-14} cm^{-1} sec^{-1} is about 15 m.

Potential vorticity and density values can be affected by depth, salinity and temperature errors. The salinity errors were less than .01‰ after 1960 (before this they were on the order of .02‰). Temperature errors were on the order of ± .02°C (Wright, personal communication). The resulting error in density at the potential vorticity minimum is as large as ± .01 mg cm^{-3} (± .02 mg cm^3 before 1960). The largest errors in potential vorticity at the potential vorticity minimum are about 25% (50%), assuming maximum temperature and salinity errors between adjacent bottles.

The *Panulirus* station has been occupied since 1954 with hydrographic stations made generally every two weeks. Monthly averaged data were examined by the following techniques. First, the Eighteen Degree Water was identified and its potential temperature, salinity, potential density, and potential vorticity were plotted as a function of time. Second, a graph of potential vorticity as a function of density and time showed a low potential vorticity band, the Eighteen Degree Water. Finally, plots of potential density vs. depth as a function of time and potential temperature as a function of potential density and time showed variation in both density and the θ-S relation of the mixed layers and of the entire upper water column. Ocean-atmosphere heat fluxes, computed by Bunker's (1976) method, were available through 1972.

In addition, the synoptic Gulf Stream '60 survey of April, 1960, was used to chart the properties of Eighteen Degree Water in the northern Sargasso Sea. The property distributions were related to the general circulation and the Eighteen Degree Water seen at the *Panulirus* station.

3. Eighteen Degree Water variability

The *Panulirus* hydrostation is located at 32°10′N, 64°30′W, in the deep ocean close to Bermuda (Fig. 1). The *Panulirus* station is south of the Eighteen Degree Water formation region. The latter is an east-west band near the Gulf Stream as can be seen from Fieux and Stommel's (1975) late winter sea-surface temperatures and from discussion of the Gulf Stream '60 results in this paper. According to Worthington's (1976) model of the subtropical gyre, the *Panulirus* station is in the westward return flow. This model is corroborated by mean flow data at 55W (Schmitz, 1980) where the flow is westward and strong at 36N and westward and weak at 32N. Thus, the Eighteen Degree Water at the *Panulirus* station is downstream in a mean sense from its source close to the Gulf Stream.

The Eighteen Degree Water core was first identified by its vertical potential vorticity minimum. The properties (potential vorticity, potential density, potential temperature and salinity) of the Eighteen Degree Water core, averaged over one month, are shown in Figure 2. Some of the potential vorticity minima, particularly in late winter, were probably locally produced, lighter pycnostads rather than Eighteen Degree Water. This occasional, simultaneous occurrence of both Eighteen Degree Water and local surface pycnostads resulted in double potential vorticity minima. The denser pycnostad was usually chosen as the Eighteen Degree Water. Bearing this in mind, the potential vorticity of the Eighteen Degree Water shown in Figure 2 was relatively uniform from 1954 through 1971. The potential vorticity increased in 1971 and remained high until 1977, reflecting a thinning of the Eighteen Degree Water core.

Both potential density and temperature of the Eighteen Degree Water core

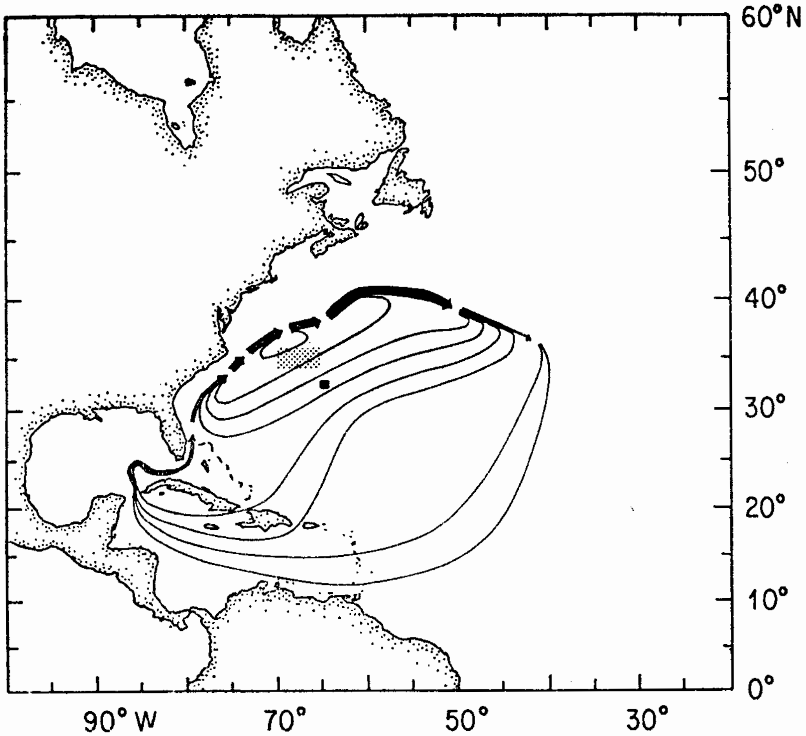

Figure 1. Circulation of the warm water (> 17°C) of the North Atlantic from Worthington, 1976 (Fig. 41). The subset of Marsden Square 115 used in the heat flux calculation is indicated by the shaded area. The black square indicates the position of the *Panulirus* Station (32°10'N, 64°30'W).

remained relatively constant until 1964. From 1964 to 1971 the Eighteen Degree Water became denser, with increasing salinity and decreasing temperature. This cold dense core lingered until 1975, becoming much thinner after 1971. After 1975 a thick Eighteen Degree Water core reappeared at much lighter densities. By 1977 it had the characteristics of the Eighteen Degree Water of the 1950s.

The pronounced potential vorticity minimum marking the Eighteen Degree Water is seen in Figure 3, which shows the potential vorticity as a function of density from 1954 to 1978. The density range shown includes all of the Eighteen Degree Water and extends up to near the surface, particularly in the winters of the 1960s. The depth of the greatest density used was between 500 and 600 m. There was a strong annual signal in the potential vorticity in the lighter layers, particularly in years when the local winter mixed layer was dense enough to be included in this figure. (The annual cycle of Eighteen Degree Water characteristics was much less pronounced.) A typical annual cycle at the *Panulirus* station began in March or April with a thick mixed layer at the surface. In the ensuing months, the water

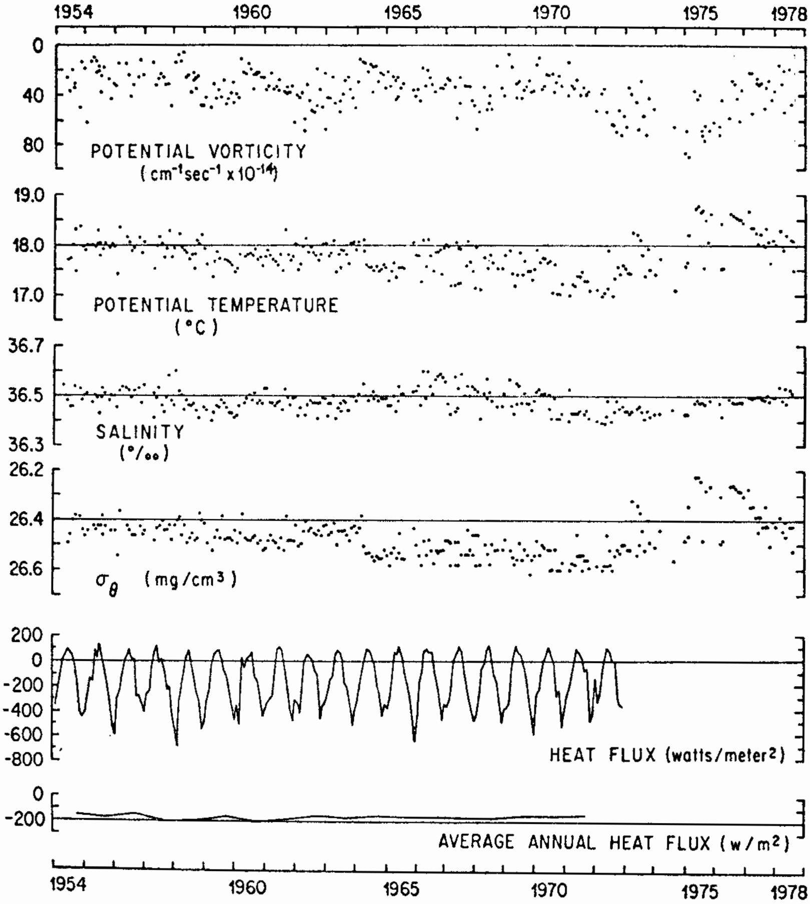

Figure 2. (a) Potential vorticity, (b) potential temperature, (c) salinity and (d) potential density of the Eighteen Degree Water core at the *Panulirus* station, plotted against time. Monthly and yearly averaged heat fluxes from a subset of Marsden Square 115 are plotted through 1972. The core is defined as the vertical potential vorticity minimum. From 1954 to 1958, the Eighteen Degree Water had potential temperature, salinity and density near 18°C, 36.5‰ and 26.4 mg cm^{-3}. The potential density increased slightly by 1964 and then increased more systematically to 26.6 mg cm^{-3} until 1972. Potential temperature remained nearly uniform through 1958 and then decreased to 17.9°C in 1964 to 17.1°C in 1972. Salinity increased from 36.5‰ in 1954-1958 to almost 36.6‰ in the 1960s to a low of 36.4‰ in 1972. The new Eighteen Degree Water of 1977-1978 had the characteristics of that in the 1950s: 18.1°C, 36.5‰ and 26.4 mg cm^{-3}.

of lowest potential vorticity became denser and colder, reaching its greatest density between September and December. This densest pycnostad was generally similar in properties and continuous with the densest pycnostad of previous and following years and was identified as the "true" Eighteen Degree Water when looking at the long term changes of the water mass. The late winter mixed layer at the *Panulirus*

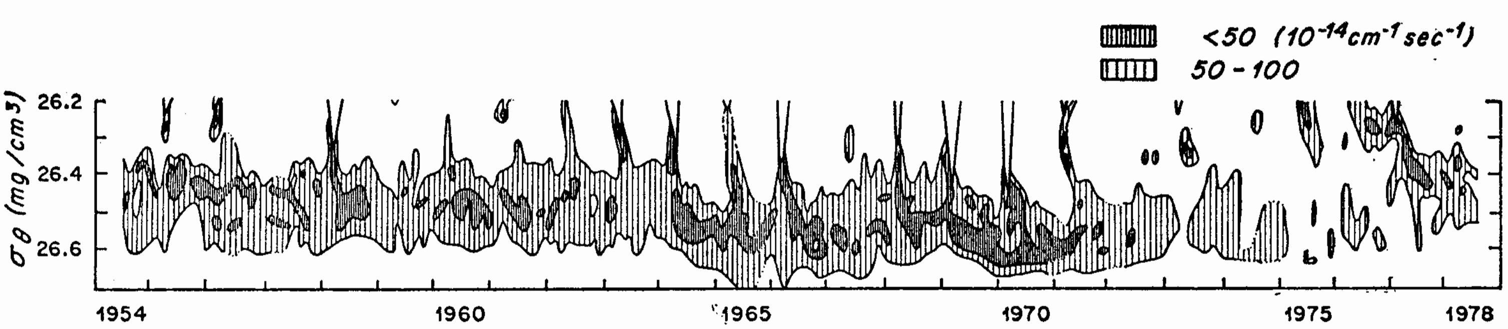

Figure 3. Potential vorticity (f/ρ) $(\partial\rho/\partial z)$ as a function of potential density (σ_θ) for 1954-1978, based on monthly averages of hydrographic data at the *Panulirus* station. Contours of 50 and 100 × 10^{-14} cm^{-1} sec^{-1} are shown. When the potential vorticity is low, there is a thick layer of water at that density. The minimum in potential vorticity is the Eighteen Degree Water. Heavy lines at lighter densities indicate the sea surface. Interpolated contours are dashed.

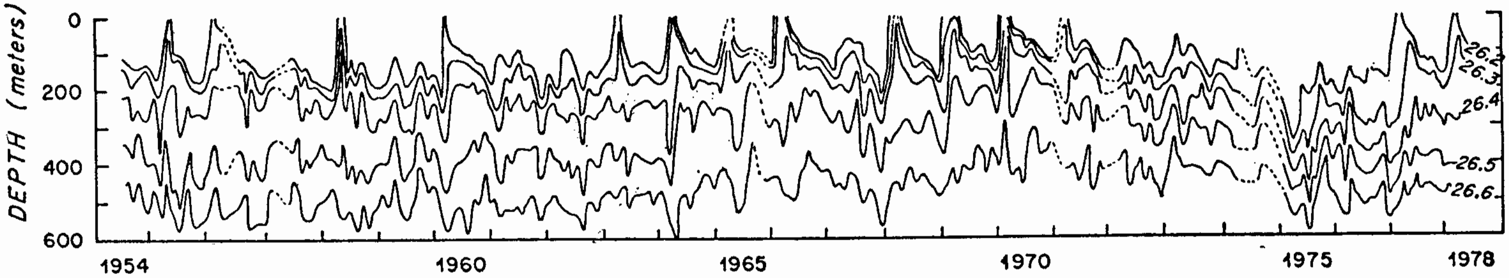

Figure 4. σ_θ vs. depth at the *Panulirus* station from 1954 to 1978. Monthly averages of hydrographic data were used and only densities from 26.2 to 26.6 mg cm^{-3} are shown.

station was always lighter and at a higher temperature than the underlying Eighteen Degree Water, which was identified as the nearly continuous, low potential vorticity axis at densities of 26.4 to 26.6 mg cm^{-3}.

The annual cycle can be interpreted as follows: (1) a deep mixed layer is formed in the late winter at the *Panulirus* station; (2) the pycnostad thus formed advects out of the region and is replaced by progressively denser, colder pycnostads; (3) the densest pycnostads arrive between September and December. Such a cycle occurred in 1958, 1964, and 1966, for example. An alternative to (3) is that the densest pycnostad (the Eighteen Degree Water) advects through the region throughout the year but the lighter pycnostads advect through and are gone by September (such as in 1965 and 1969). The interval between the time that Eighteen Degree Water is formed elsewhere in the gyre and the time that it arrives at the *Panulirus* station is ambiguous because we cannot tell in what year the Eighteen Degree Water seen at the *Panulirus* station was formed. The clearest annual cycle was in 1977, after a prolonged period when no substantial amount of Eighteen Degree Water appeared at the *Panulirus* station. If the Eighteen Degree Water is identified as the thick layer of dense water which appeared after the late winter events of 1976-1977, then its density was about 26.42 mg cm^{-3} and it was first seen at the *Panulirus* station in September, 1977, or about six months after formation (Leetmaa, 1977).

The persistent band of low potential vorticity water at densities between 26.4 and 26.6 mg cm^{-3} is thus identified as the Eighteen Degree Water. This band of water always lies between the local mixed layer or seasonal thermocline and the main thermocline at the *Panulirus* station. The water of lowest vorticity, usually less than 50×10^{-14} cm^{-1} sec^{-1}, is the Eighteen Degree Water core. The core increased in density from 26.4 mg cm^{-3} in 1954 to 26.6 mg cm^{-3} in 1971. From 1972 to 1976 the persistent band of low potential vorticity broke up. There was Eighteen Degree Water at the *Panulirus* station in these years, but it was very weak, with potential vorticity in excess of 50×10^{-14} cm^{-1} sec^{-1}. After 1976, a thick Eighteen Degree Water core again appeared, but at the 1954 density of 26.4 mg cm^{-3}.

As pointed out by Pocklington (1972), density and the temperature-salinity relation in the entire upper 600 m also changed over the same periods as the Eighteen Degree Water. (Of course, the Eighteen Degree Water is about 200 m thick and occupies a large portion of the upper water column.) A density vs. time section at the *Panulirus* station is shown in Figure 4. Densities of 26.2 to 26.6 mg cm^{-3} are plotted. All of the water in the upper 600 m was denser from 1964 to 1972 than it was from 1954 to 1964. Wintertime mixed layers were therefore also denser during that period. The upper 600 m was more stratified from 1972 to 1975 than it was previously because the upper 200 m was lighter. By 1978 the upper 600 m looked as it did from 1954 to 1964.

Because of the upper water density increases in the 1960s, the densest wintertime mixed layers at the *Panulirus* stations in the 1960s were as dense as "classical" Eighteen Degree Water. However, the Eighteen Degree Water of the 1960s was denser than the "classical" Eighteen Degree Water. At no time in the full record did it appear that the underlying Eighteen Degree Water was directly renewed at the *Panulirus* station. The increased stratification of the upper water from 1972 to 1975 paralleled the observed lack of Eighteen Degree Water renewal from 1972 to 1975. Presumably this implies that the increased stratification observed at the *Panulirus* station was typical of the Eighteen Degree Water formation region also.

Plots of both yearly-averaged potential temperature at various densities (Fig. 5) and temperature-salinity relations for four periods in the record (Fig. 6) show that the temperature-salinity relation changed over the years. It is clear from Figure 5 that the temperature at a given density was not at all constant. The temperature at all densities was higher from 1964 to 1971 by about .2 to .3°C than it was from 1954 to 1963. Thus during the late 1960s, at a time of Eighteen Degree Water renewal, there was an increase in temperature on isopycnals and hence an increase in salinity. The latter is consistent with the Jenkins' (1982) data and model. He argued that when the Eighteen Degree Water production is vigorous, the increased latent heat flux increases the salinity on isopycnals. Even though the temperature increased on isopycnals, we observe that the temperature of the entire water column decreased along with the density increase illustrated by Figure 4, both of which are consistent with increased heat flux.

Four long periods between 1954 and 1978 were evident in all variables (Fig. 6). (1) There was "classical" Eighteen Degree Water from 1954 to 1964, basically fitting Worthington's (1959) description with slight variations. (2) The Eighteen Degree Water became progressively denser and colder from 1964 to 1972, its temperature and density reaching 17.1°C and 26.6 mg cm^{-3} by 1972. Annual cycles at densities of 26.2 to 26.6 mg cm^{-3} were most pronounced in these years at the *Panulirus* station. (3) There was no strong Eighteen Degree Water from 1972 to 1975. We conclude that Eighteen Degree Water formation ceased during these years, as the only Eighteen Degree Water observed appeared to be remnants of the Eighteen Degree Water of 1971. (4) In 1975 or 1976, Eighteen Degree Water formation resumed at a rather high temperature and low density (Leetmaa, 1977; Worthington, 1977). By 1978, the Eighteen Degree Water had nearly the same characteristics as from 1954 to 1964.

4. Heat flux

Changes in Eighteen Degree Water production and characteristics may be caused by changes in the ocean-atmosphere heat flux. The importance of negative heat flux in sustaining the Eighteen Degree Water has been discussed by Worthington

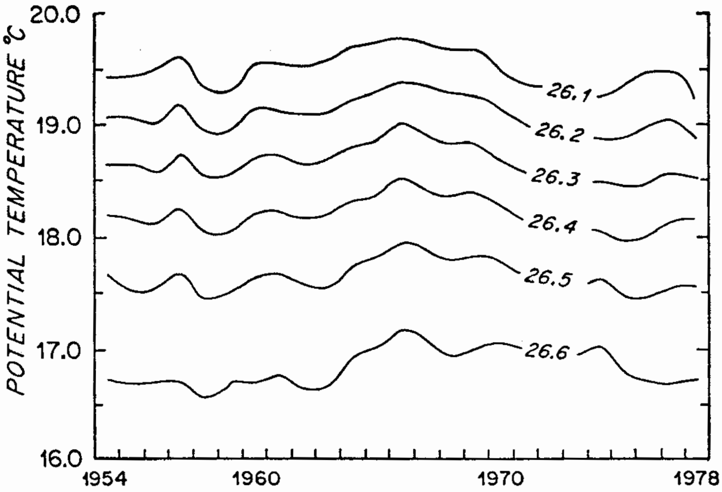

Figure 5. Potential temperature on the isopycnals 26.1 to 26.6 mg cm^{-3} from 1954 to 1978 at the *Panulirus* station.

(1972). However, Jenkins (1982) found that the relation between changing heat flux and the Eighteen Degree Water properties was rather tenuous. Jenkins found that there was a barely significant correlation, with a two- to three-year lag, between the heat flux and the isopycnal salinity, which he took to measure the strength of Eighteen Degree Water renewal. Although he attributed the weakness of the correlation to the selection of too large an area for the heat flux calculation, we found that the correlation was also weak if a smaller area encompassing the Eighteen Degree Water formation region was used for the heat flux calculation.

We recomputed the heat flux in a small subset of the region used by Jenkins, who used Marsden Square 115 (30-40N, 60-70W). This was done to see if the heat flux in a smaller region at the center of the subtropical gyre, just to the southwest of the Gulf Stream and encompassing the Eighteen Degree Water formation area, would correlate better with changes in the Eighteen Degree Water. The small region (34-36N, 65-70W) that we used is shown in Figure 1. The monthly- and annually-averaged heat flux for this region is plotted in Figure 2. The trends in heat flux differ little from the trends in total heat flux in either Marsden Square 114 or 115. We found (as did Jenkins) little direct relation between heat flux and either the Eighteen Degree Water's potential temperature or potential density. In fact, the heat flux was nearly out of phase with the Eighteen Degree Water properties. We expected a large negative heat flux to be associated with lower temperatures, higher density and greater renewal. However, when the (negative) heat flux weakened in the 1960s, the potential temperature decreased, the potential density increased, and the potential vorticity remained nearly constant. There may have been some correlation between properties and heat flux in the

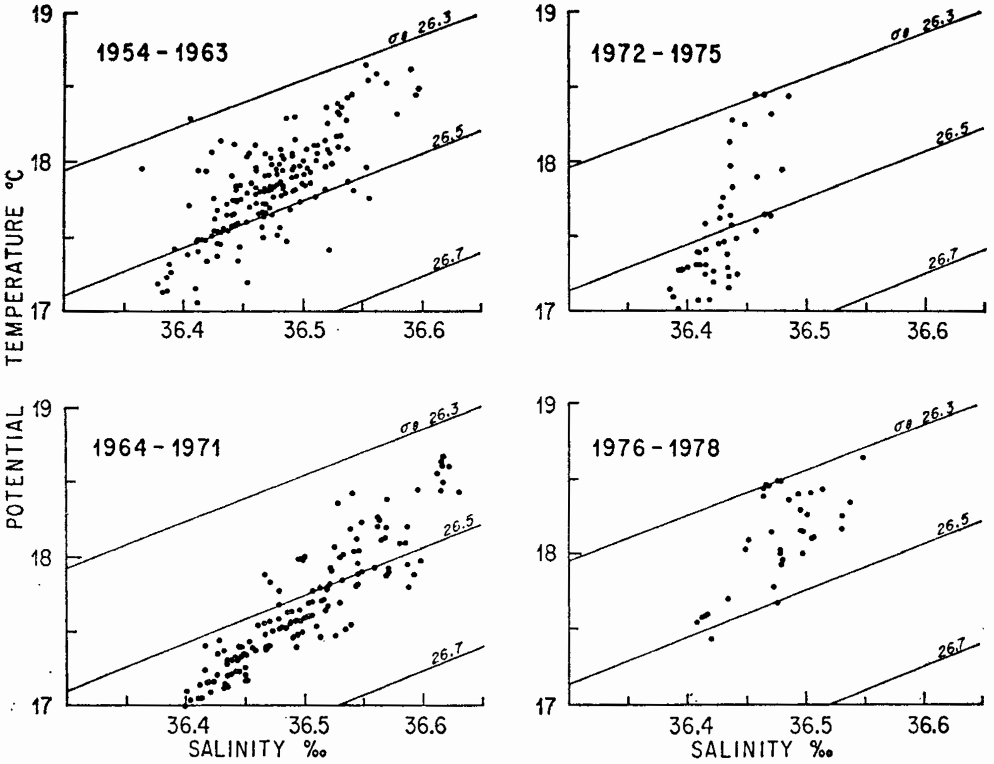

Figure 6. θ-S of the potential vorticity minimum with σ_θ contours plotted. The data is divided into four time frames: (a) 1954-1963; (b) 1964-1971; (c) 1972-1975; (d) 1976-1978.

lack of renewal of Eighteen Degree Water from 1972 and 1975 and the weakened heat flux in the several years preceding 1972. (Heat flux data after 1972 were not available.)

The lack of direct correspondence between heat flux and Eighteen Degree Water properties leads us to infer that either there is some long-period storage process which defers the effects of severe winters for several years (Jenkins' conclusion), or that some factor other than changing heat flux was important. One possibility is that changes in the heat flux and water characteristics far from the northern Sargasso Sea affect the production of Eighteen Degree Water by changing the Sargasso Sea surface water and Gulf Stream water, the sources of Eighteen Degree Water. Another possibility was suggested by Bjerknes (1964), who showed that strong Westerlies and Trades were correlated with decreasing Sargasso Sea surface temperatures and increasing Slope Water surface temperatures. Bjerknes (1964) reasoned that intensification of the Westerlies, and hence the Gulf Stream, may enhance lateral exchanges across the Gulf Stream, thus warming the Slope Water and cooling the Sargasso Sea water.

5. Eighteen Degree Water in April, 1960

We are fortunate to have one very comprehensive study of the northern Sargasso Sea in the Gulf Stream '60 data set (Fuglister, 1963). The distribution and properties of Eighteen Degree Water in this 2-3 week snapshot can be mapped and the information combined with the *Panulirus* record to suggest circulation patterns, estimates of advection times, and a hypothesis about Eighteen Degree Water formation.

The Eighteen Degree Water distribution in Gulf Stream '60 was rather complex. At many stations there were two or even three identifiable potential vorticity minima. Because the expedition occurred as much as a month after the severest part of winter, the seasonal thermocline had begun to build over a large region. Figure 7 shows the temperature, density and potential vorticity of the densest Eighteen Degree Water found at each station. Only on the extreme east and west of the map was Eighteen Degree Water found at the surface. It was approximately 200 to 300 m thick. These two regions are identified as Eighteen Degree Water formation areas in 1960 and are stippled in Figure 7. The Eighteen Degree Water in the westernmost region was warm, saline and light (18.0-18.2°C, 36.53-36.54‰, and 26.44-26.46 mg cm^{-3}). In the eastern region, the Eighteen Degree Water was colder, fresher and denser (17.4-17.6°C, 36.46-36.50‰, and 26.53-26.55 mg cm^{-3}). These two patches were separated by an area where the Eighteen Degree Water core was somewhat deeper and topped by warmer, more stratified layers. It is possible that the large meander of the Gulf Stream at 60W was important in separating the two formation regions.

Anticyclonic flow within the Sargasso Sea is consistent with the property distributions, which can be grossly compared with simultaneous current observations (Fuglister, 1963). In Figure 7, a tongue of warmer Eighteen Degree Water extends to the northeast. The colder Eighteen Degree Water extends to the southwest. Surface buoys, GEK measurements and geostrophic velocity profiles between 60W and 66W (Fuglister, 1963) substantiate inferred clockwise flow of the warmer water to the northeast and the colder water to the southwest.

The Eighteen Degree Water properties seen in April, 1960, correspond with Eighteen Degree Water properties seen at the *Panulirus* station in the following months. The *Panulirus* hydrostation is in the westward return flow, according to Worthington's (1976) model, Schmitz's (1980) current meter records and the Gulf Stream '60 (Fuglister, 1963) current observations. In the *Panulirus* record from April, 1960, to January, 1961, the Eighteen Degree Water had the following properties (Fig. 3): (1) in April, 26.44 mg cm^{-3}, 17.9°C; (2) in May, 26.48 mg cm^{-3}, 17.6°C; (3) in October, 26.48 mg cm^{-3}, 17.7°C; (4) in January, 1961, 26.52 mg cm^{-3}, 17.6°C. In April, the water column was dominated by a light, warm mode (26.39 mg cm^{-3}, 18.5°C) which was probably formed locally and which was not identified as Eighteen Degree Water. The Eighteen Degree Water

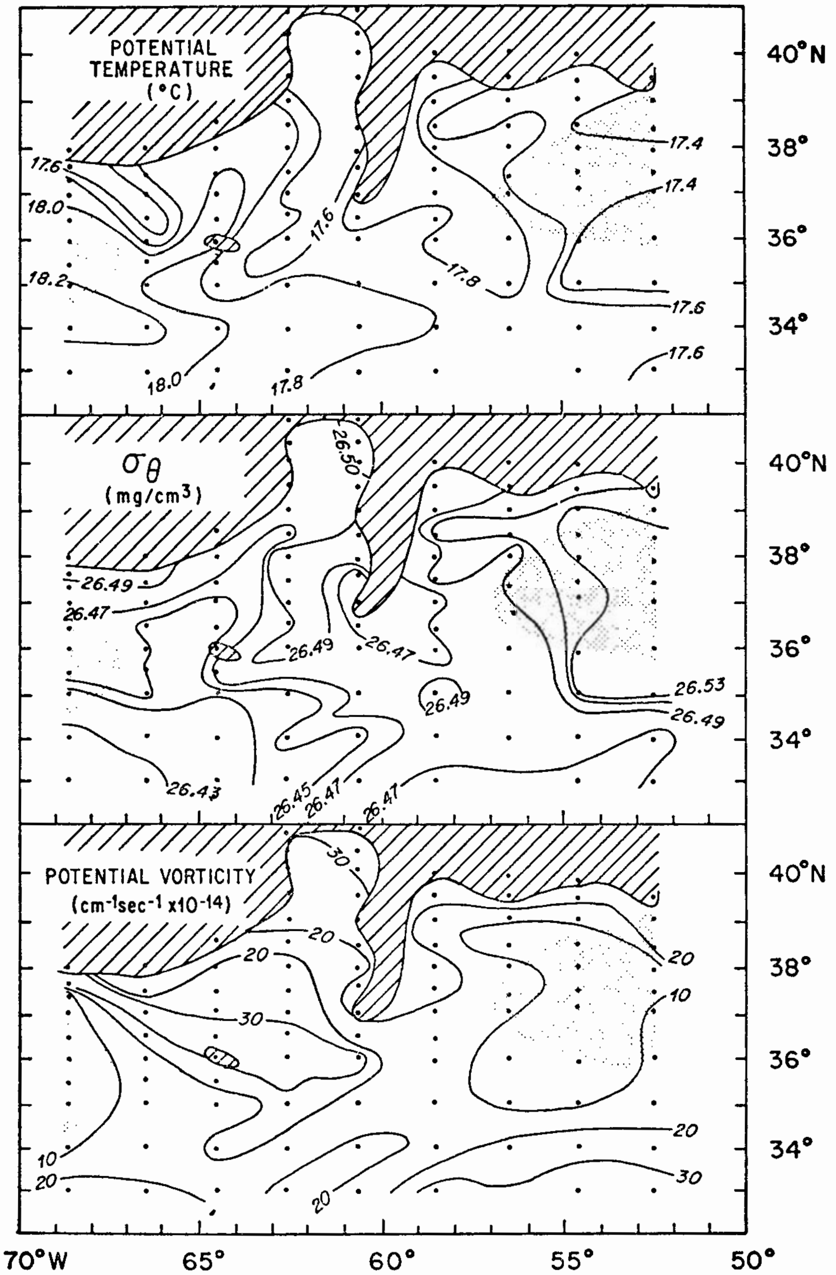

Figure 7. (a) Potential temperature, (b) σ_θ, and (c) potential vorticity of the densest Eighteen Degree Water, using Gulf Stream '60 data from April, 1960. The stippled regions indicate the outcropping of Eighteen Degree Water at the sea surface.

was weak and low in oxygen, appearing to be a remnant from the previous year. In the following months, the potential vorticity of the Eighteen Degree Water was lower, and its properties corresponded with the properties of the Eighteen Degree Water northeast (upstream) of the *Panulirus* station in April, 1960 (Fig. 7). These waters were advected southwest past the *Panulirus* station. The Eighteen Degree Water which arrived in January, 1961, was seen about 1000 km upstream in April, 1960, and thus traveled at a rate of about 4 km/day.

Eighteen Degree Water may be formed in a similar pattern most winters. The cycle which is proposed is the following. (1) At the start of the winter cooling cycle, there is a warm seasonal thermocline over the Sargasso Sea. Beneath the seasonal thermocline, there may be remnants of the deep mixed layers of the preceding winter, displaced from their formation areas by the anticyclonic circulation. These pycnostads, which include the previous winters' Eighteen Degree Water, have a wide range of temperature and salinity, depending on where they were formed. (2) As the cooling cycle begins, the seasonal thermocline is eroded, exposing the pycnostads beneath. In the northwest corner of the Sargasso Sea in winter, these pycnostads may come from the south and east and are warmer and lighter than the Eighteen Degree Water. Once they are exposed, the pycnostads are further cooled, deepened and freshened as they are advected eastward. At any given time in the winter, there is an east-west gradient in properties of the surface pycnostads because of the anticyclonic circulation. (3) The most severe winter events in late March produce the coldest and deepest mixed layers for each location. The deepest mixed layers in the Sargasso Sea occur just south of the Gulf Stream and are termed Eighteen Degree Water. The Eighteen Degree Water is warmer and saltier in the west and colder and fresher in the east. (4) The ensuing warming cycle covers the Eighteen Degree Water with a seasonal thermocline. The colder forms of Eighteen Degree Water, formed in the eastern Sargasso Sea, are recirculated to the southwest and are seen below the locally-influenced surface layer at the *Panulirus* station later in the year. An occasional short circuit might occur, such as appeared to happen in April, 1960, when a warmer, western form of Eighteen Degree Water was seen at the *Panulirus* station.

Observations of Eighteen Degree Water at 55W in 1976 and 1977 (McCartney *et al.*, 1980; Schmitz and McCartney, 1982) support the hypothesis of east-west gradients in the properties of newly-formed Eighteen Degree Water. The Eighteen Degree Water formed in 1976-77 was uncontaminated by older Eighteen Degree Water since little had been formed from 1972 to 1975. The winter of 1975-76 produced a light ($\sigma_\theta = 26.3$ mg cm^{-3}) form of Eighteen Degree Water (Fig. 3). The winter of 1976-1977 was particularly cold, and convection produced new, denser Eighteen Degree Water (Leetmaa, 1977; Worthington, 1977).

The two hydrographic sections, whose potential vorticity distributions are shown in Figure 8, were made in October, 1976 and July, 1977. In 1976 (*Knorr* 60)

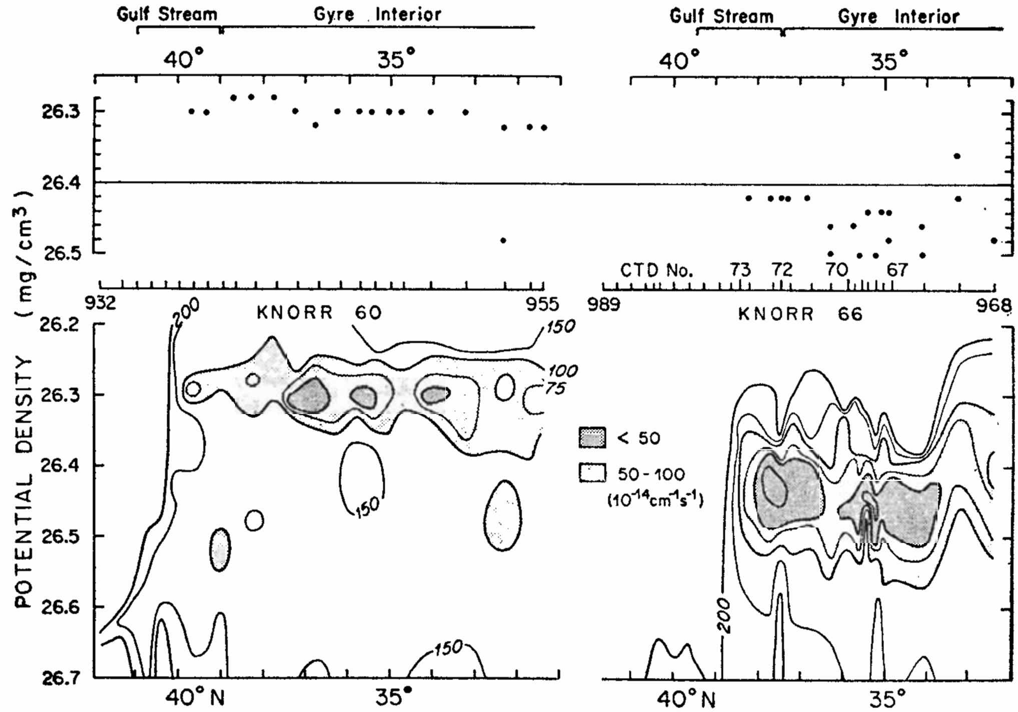

Figure 8. Potential vorticity vs. σ_θ at 55W. The density of the Eighteen Degree Water core is plotted above the sections if the potential vorticity value was less than 100×10^{-14} cm^{-1} sec^{-1}. The sections (*Knorr* 60 and *Knorr* 66) were made in October, 1976 and July, 1977, respectively.

the light ($\sigma_\theta = 26.3$ mg cm^{-3}) Eighteen Degree Water was flowing westward in the gyre interior with potential vorticity values around 50×10^{-14} cm^{-1} sec^{-1}. This weak, light Eighteen Degree Water matched the Eighteen Degree Water seen at the *Panulirus* station in 1976. In July, 1977 (*Knorr* 66), after a good winter for Eighteen Degree Water production, two types of Eighteen Degree Water were seen at 55W. On the northern end of the section there was Eighteen Degree Water at $\sigma_\theta = 26.42$ mg cm^{-3} associated with the eastward flow of the Gulf Stream. Further south, well within the westward return flow of the subtropical gyre, Eighteen Degree Water was found at densities of $\sigma_\theta = 26.44$-26.48 mg cm^{-3}. These two types were separated by 100 km near 36N, where there was much higher potential vorticity. The implication is that the northern Eighteen Degree Water was formed to the west of the section in late winter and was advected eastward to 55W in the ensuing three months. The southern Eighteen Degree Water was formed somewhere east of the northern type and was advected to its position at 55W by the anticyclonic flow. Thus the density of newly-formed Eighteen Degree Water increased from west to east in the late winter of 1977 just as in April, 1960.

6. Comparison of newly formed Eighteen Degree Water and Eighteen Degree Water found at Panulirus

To attach any large-scale significance to upper water and Eighteen Degree Water changes at the *Panulirus* station, we must know how representative changes at the *Panulirus* station are for Eighteen Degree Water in the subtropical gyre. According to Worthington's (1959) charts of the Eighteen Degree Water distribution, Eighteen Degree Water is found throughout the western North Atlantic, that is, the entire subtropical gyre. The *Panulirus* station is in the center of the region of Eighteen Degree Water influence. In addition, Bjerknes' (1964) charts of sea-surface temperature anomalies of the North Atlantic link the entire region southeast of the Gulf Stream together. Thus, we would expect the Eighteen Degree Water at the *Panulirus* station to eventually mirror long-term changes in the Eighteen Degree Water.

However, the *Panulirus* station is also at the southern edge of the vigorous recirculation area for the Gulf Stream (Worthington, 1976). If the recirculation were time dependent, horizontal gradients in properties (temperature, salinity and density) of newly-formed Eighteen Degree Water could complicate interpretation of the *Panulirus* results. We have implicitly assumed that the new Eighteen Degree Water from the eastern formation region is seen at the *Panulirus* station within a period of about one year. However, the temporal range in potential temperature of Eighteen Degree Water at the *Panulirus* station is the same as the total lateral range in April, 1960. Thus, we could explain the time changes in Eighteen Degree Water at the *Panulirus* station by recirculation changes if water from the western formation area in 1954, shifting to the eastern formation area by 1970, had been brought to the *Panulirus* station.

We can see roughly whether long-term circulation changes are really a problem. In the previous section, we discussed the relation between the Eighteen Degree Water distribution in April, 1960, and the Eighteen Degree Water seen in subsequent months at the *Panulirus* station. The source of Eighteen Degree Water throughout 1960 at the *Panulirus* station was clearly the eastern part of the gyre, thus substantiating the hypothesis of mean westward flow past the *Panulirus* station in 1960. A similar interpretation was applied to the 1976 and 1977 observations at 55W.

For information about other years, we refer to Fieux and Stommel's (1975) description of the new Eighteen Degree Water at the sea surface, which can be compared with the changes in the Eighteen Degree Water core at the *Panulirus* station. Fieux and Stommel showed average sea-surface temperatures between 50 and 60W, on the eastern side of the Sargasso Sea. In the Gulf Stream '60 data, this was the eastern zone of Eighteen Degree Water formation, with lower temperature and higher density than in the Eighteen Degree Water formation area to the west. In mean circulation schemes, such as in Worthington (1976), the *Panulirus* station is downstream of this eastern Eighteen Degree Water formation area. If the mean recirculation really does not change greatly from year to year, then changes in the new Eighteen Degree Water seen by Fieux and Stommel would be the changes observed downstream at the *Panulirus* station some time later.

Fieux and Stommel's (1975) Figure 3 indicates that the Eighteen Degree Water formation region is between 35 and 38N. Their Figure 6 shows an average decrease in sea-surface temperature in this latitude band from 1954 to 1970. This cooling corresponds well with the cooling of the *Panulirus* Eighteen Degree Water from 1954 to 1971. In addition, an abrupt decrease in sea-surface temperature in 1964 correlates well with an abrupt change in the Eighteen Degree Water and upper water column properties (Figs. 4 and 5). Fieux and Stommel's (1975) record extends only to 1972, so the warming indicated after 1970 is of interest only because it matches the general warming trend at the *Panulirus* station from 1971 to 1975. Thus, it is reasonable to conclude that the cooling of Eighteen Degree Water at the *Panulirus* station was due to actual cooling of new Eighteen Degree Water, rather than to a shift in the recirculation.

7. Summary

There are changes in the Eighteen Degree Water over time scales of five to ten years. The Eighteen Degree Water seen at the *Panulirus* station conformed to Worthington's (1959) definition from 1954 to 1958, although its density was already beginning to increase. From the beginning of the record (1954) until 1972, its density increased by about 0.2 mg cm^{-3}. From 1964 to 1972, its potential temperature decreased from about 18.0°C to 17.1°. The salinity showed systematic fluctuations but remained within Worthington's definition of $36.5 \pm .1‰$. No intense renewal occurred from 1972 to 1975. The new Eighteen Degree Water in 1977-78 had nearly the same properties as the Eighteen Degree Water in the 1950s.

The entire upper water column at the *Panulirus* station also showed changes over the same periods as the Eighteen Degree Water. It was denser and colder from 1964 to 1975 than from 1954 to 1964 and after 1975. Confusingly, the θ-S relation changed so that all water was warmer and saltier for a given σ_θ, from 1964 to 1975. The upper water was therefore not as cold as it would have been if the θ-S relation had not also changed. (This was also true of the Eighteen Degree Water: if its density had increased to 26.6 mg cm^{-3} with no change in the 1954 θ-S relation, its temperature would have been about 16.7°C, instead of the observed 17.1°C in 1971.)

In contrast with the situation in the Labrador Sea, (Talley and McCartney, 1982) there was little direct correspondence between the events at the hydrostation and the ocean-atmosphere heat flux in the formation area.

In April, 1960, there were two regions where Eighteen Degree Water of different characteristics had formed. The property distributions suggested that Eighteen Degree Water was formed along the southern side of the Gulf Stream, being colder and fresher to the east. The warm water sources for the Eighteen Degree Water are the warmer wintertime mixed layers of the southwestern Sargasso Sea and the Gulf Stream (Worthington, 1972). The type of Eighteen Degree Water usually seen at the *Panulirus* station is formed in the eastern part of the subtropical gyre and is thus a colder variety of Eighteen Degree Water than is seen in the northwestern part of the gyre.

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REFERENCES

Bjerknes, J. 1964. Atlantic air-sea interaction. Adv. in Geophys., *10*, 1–82.

Bunker, A. F. 1976. Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. Mon. Wea. Rev., *104*, 1122–1140.

Colebrook, J. M. and A. H. Taylor. 1979. Year-to-year changes in sea-surface temperatures, North Atlantic and North Sea, 1948 to 1974. Deep-Sea Res., *26A*, 825–850.

Fieux, M. and H. Stommel. 1975. Preliminary look at feasibility of using marine reports of sea surface temperature for documenting climatic change in the western North Atlantic. J. Mar. Res., *33*, 83–95.

Fuglister, F. C. 1963. Gulf Stream '60. Prog. Oceanogr., *1*, 265–383.

Jenkins, W. J. 1982. On the climate of a subtropical gyre: decade timescale variations in water mass renewal in the Sargasso Sea. J. Mar. Res., *40*,

Leetmaa, A. 1977. Effects of the winter of 1976-1977 on the northwestern Sargasso Sea. Science, *198*, 188–189.

McCartney, M. S. and L. D. Talley. 1982. The Subpolar Mode Water of the North Atlantic Ocean. J. Phys. Oceanogr., (submitted).

McCartney, M. S., L. V. Worthington and M. E. Raymer. 1980. Anomalous water masses distribution at 55W in the North Atlantic in 1977. J. Mar. Res., *38*, 147–172.

Pocklington, R. 1972. Secular changes in the ocean off Bermuda. J. Geophys. Res., *77*, 6604–6607.

—— 1978. Climatic trends in the North Atlantic. Nature, *273*, 407.

Schmitz, W. J. 1980. Weakly depth dependent segments of the North Atlantic circulation. J. Mar. Res., *38*, 111–133.

Schmitz, W. J. and M. S. McCartney, 1982. An example of long-term variability for subsurface current and hydrographic patterns in the western North Atlantic. J. Mar. Res., *40* (Supp.), 707–726.

Schroeder, E., H. Stommel, D. Menzel and W. Sutcliffe, Jr. 1959. Climatic stability of Eighteen Degree Water at Bermuda. J. Geophys. Res., *64*, 363–366.

Seitz, R. C. 1967. Thermostad, the antonym of thermocline. J. Mar. Res., *25*, 203.

Talley, L. D. and M. S. McCartney. 1982. Distribution and circulation of Labrador Sea Water. J. Phys. Oceanogr., (submitted).

Warren, B. A. 1972. Insensitivity of subtropical mode water characteristics to meteorological fluctuations. Deep-Sea Res., *19*, 1–19.

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

—— 1972. Negative oceanic heat flux as a cause of water-mass formation. J. Phys. Oceanogr., *2*, 205–211.

—— 1976. On the North Atlantic Circulation. Johns Hopkins Oceanographic Studies, Vol. VI. The Johns Hopkins University Press, Baltimore and London, 110 pp.

—— 1977. The intensification of the Gulf Stream after the winter of 1976-1977. Nature, *270*, 415–417.

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