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The subtropical recirculation of Mode Waters

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ABSTRACT

A "Mode Water" is a particular type of water mass characterized by its vertical homogeneity. There are two general varieties in the world ocean: Subtropical Mode Waters and Subpolar Mode Waters. The vertical homogeneity of a Mode Water is acquired by the process of deep vertical convection in winter. The low vertical density gradient imparted to the water column by convection persists laterally as the general circulation carries the Mode Water away from the formation zone. This lateral persistence is a consequence of the principle of conservation of potential vorticity. In this paper examples of Mode Waters from throughout the world ocean are illustrated using an approximation to the potential vorticity: the product of the Coriolis parameter and the hydrostatic stability. Relative vorticity is neglected. The Mode Waters are detectable to quite low latitudes within the subtropical gyres of the world ocean as pycnostads—layers of low vertical density gradient and therefore low potential vorticity. This subtropical influence occurs in two fashions: direct, via the interior anticyclonic recirculation of the subtropical gyres; and indirect, via equatorward flowing western boundary currents.

The "thick" nature of Mode Waters is reflected in their large volume contribution to the Central Waters of the subtropical gyres of the world ocean. While the image of advection along isopycnals from the convective source regions is particularly vivid using potential vorticity, it is noted that mixing does take place. Following likely advection paths, potential vorticity increases, potential temperature and salinity change, oxygen decreases and there is some evidence that potential density increases. The last observation may indicate a nonisopycnal character for the mixing processes.

1. Introduction

There is a particular type of water mass in the world ocean that has come to be called "Mode Water." The dominant property that characterizes a given variety of Mode Water is its homogeneity. The local Mode Water core at a station is defined by the existence of minima in vertical gradients. Commonly used properties are temperature and potential density anomaly, for which one speaks of thermostads and pycnostads for the layer of minimum gradient. In a regional volumetric census, this homogeneity leads to relatively large volumes in the temperature and salinity classes associated with the Mode Water compared to neighboring classes, i.e. there exists a bivariate "mode." The homogeneity of a Mode Water is acquired through

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the process of winter vertical convection. This convection takes place in only a subregion of the total region within which the Mode Water is found. Thus a Mode Water is not simply a locally formed water mass: lateral advection carries the Mode Water away from its formation region.

In the present paper the archetypal Mode Water—Worthington's (1959) Eighteen Degree Water—is discussed from a new perspective. Its traditional signatures and characteristics are first reviewed, and then its formation and circulation are illustrated using a nontraditional indicator, potential vorticity. This property is particularly useful as a Mode Water tracer for two reasons: first, because the potential vorticity is a conservative property, so that away from source and strong mixing regions, potential vorticity will tend to remain constant following a particle trajectory along an isopycnal; and second, because the potential vorticity is proportional to the water column hydrostatic stability. By definition a Mode Water is characterized by a minimum in vertical density gradient, i.e. minimum hydrostatic stability. A Mode Water layer is therefore a layer of low potential vorticity. Lowest values of potential vorticity are found in winter at the area of vertical convection for the Mode Water. The conservative nature of potential vorticity leads to tongues of low potential vorticity following an advective path away from the convective source region.

Following the analysis of the Eighteen Degree Water of the North Atlantic, further examples of Mode Waters are given from each of the other oceans of the world. All share the characteristics of low potential vorticity and of formation by winter convection in a small subregion of the region where the low potential vorticity layer is found. On the other hand, there is considerable variety in the geometry of the Mode Water distributions. Figure 1 shows a global chart with the locations of sections and regions discussed in this paper. The Subtropical Mode Waters are northwest intensified in the North Atlantic and North Pacific Ocean. The Subantarctic Mode Water influences large regions of all three southern hemisphere oceans. Lastly, a Subpolar Mode in the northern North Atlantic shows influence throughout the subtropical North Atlantic. These distributions will be illustrated in this paper.

2. Mode Water principles

a. Traditional Mode Water indicators. The basic characteristics of a Mode Water are best defined by illustration. A Mode Water stands out because of its relative vertical homogeneity in properties. An example of this homogeneity in temperature, oxygen and potential density is shown in Figure 2 for a station in the Sargasso Sea containing Worthington's Eighteen Degree Water. This is an early springtime station taken in the formation region shortly after a winter convection event (Leetmaa, 1977; Worthington, 1977). The Eighteen Degree Water core is near 300 m and is characterized by inflections in the vertical distributions of temperature and potential density, and high levels of oxygen (near saturation). Worthington (1959) summarized the inflection point properties in pre-1959 Sargasso Sea data as temperature 17.9° ± 0.3°C and salinity 36.50‰ ± 0.10‰. More recently, Talley and Raymer (1982) have noted that there were significant trends in the Eighteen Degree Water core properties between the late 1950's and 1976, but that in 1977, the properties (remarkably!) returned to those of the 1950's.

A common oceanographic data presentation is a vertical section, with depth as the ordinate and latitude, longitude or distance as the abscissa. The homogeneity of a Mode Water shows up in these presentations by the increased vertical spacing of isopleths. Examples of temperature and potential density sections containing Eighteen Degree Water are shown in Figures 3a and 3b. The spacings of the 17°-18°-19°C isotherms are larger than those above and below, as are the spacings of the 26.4-26.5-26.6 mg/cm^3 isopycnals.

The above illustrations utilize the traditional indicators of Eighteen Degree Water. These tend to be qualitative. Inflections or excess thicknesses draw attention to the Mode, and such features span some depth range or distance range—for example, the wedge of excess thickness in Figure 3a seems detectable to about 20N. One can be more quantitative than this by using various vertical derivatives of property, and thereby determine in more systematic fashion how strong a given inflection is, or how "excess" the thickness is. The particular indicator used in the present study is the potential vorticity.

b. Potential vorticity as a Mode Water tracer. The principle of potential vorticity conservation plays a central role in the general field of geophysical fluid dynamics (Pedlosky, 1979). For the particular case of the mesoscale and large-scale circulations of the ocean, the dynamical nature of potential vorticity conservation is appearing increasingly often as the cornerstone of theories of the ocean circulation. An example of this growing literature is Rhines and Young (1982), who discuss a mechanism of potential vorticity homogenization within the main pycnocline. Another type of usage of the principle of potential vorticity bridges the gap between theoretical modeling of the ocean and the interpretation of real ocean data. A recent example of this usage is Luyten and Stommel (1982) who apply the principle to the 50W section given in Figure 3. The principle is applied in integral form to a series of four layers bounded by isopycnals. In such integral formulation the potential vorticity in each layer takes the simple form $[f + (V_x - U_y)]/H$, where f is the Coriolis parameter, $(V_x - U_y)$ is the relative vorticity, and H the layer thickness. U and V are the velocity components assumed independent of depth within each layer. If sources and internal mixing are negligible, then the potential vorticity of a column of fluid in this layer will be conserved following its advection path along the layer.

In the present study, this tendency toward conservation of potential vorticity will be utilized. In a given ocean, there is a small range of potential density for which

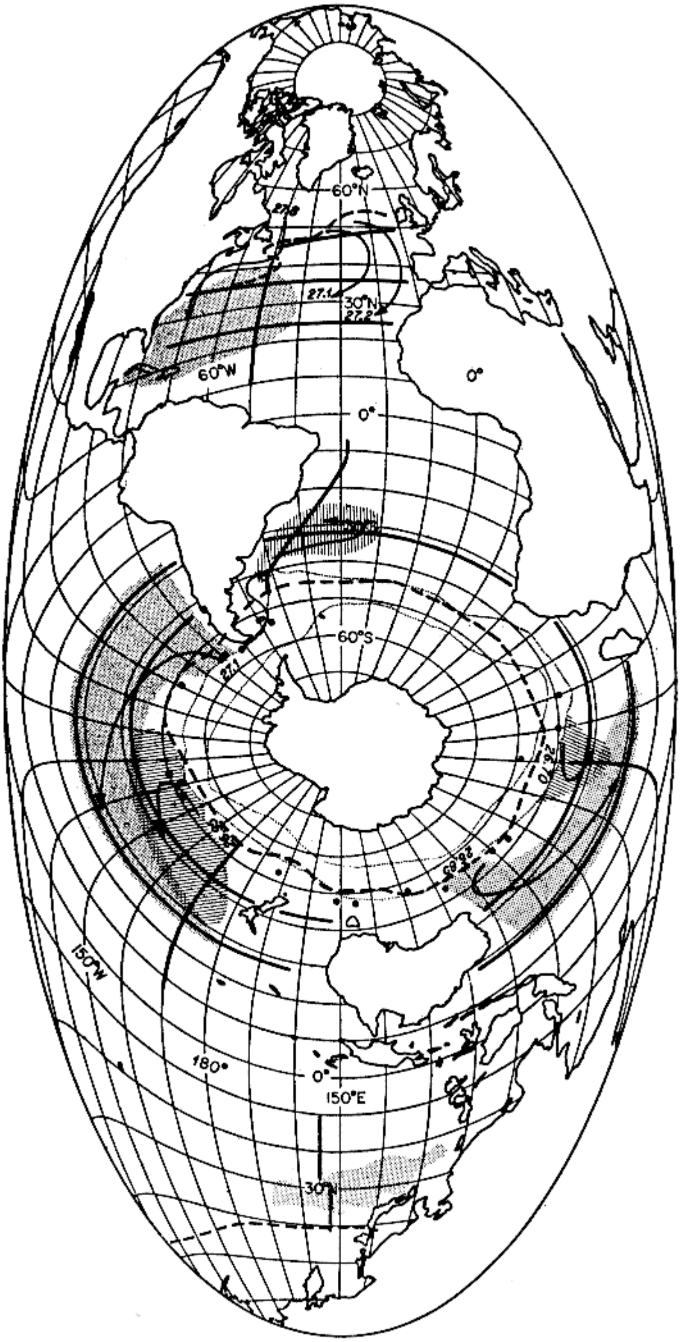


Figure 1. Global chart: an equal-area projection (transversed Molleweide). Locations of sections utilized in the figures of this paper are indicated by solid curves. The zero windstress curl curve in each ocean is indicated by a heavy dashed contour based on Taylor (1978; as reproduced by Baker, 1982) in the southern hemisphere, Leetmaa and Bunker (1978) in the North Atlantic, and Hantel (1972) for the North Pacific.

North Atlantic. The shaded region is Worthington's (1976, Fig. 42) interpretation of the boundary of the circulation of water warmer than 17°C, thus including the Eighteen Degree

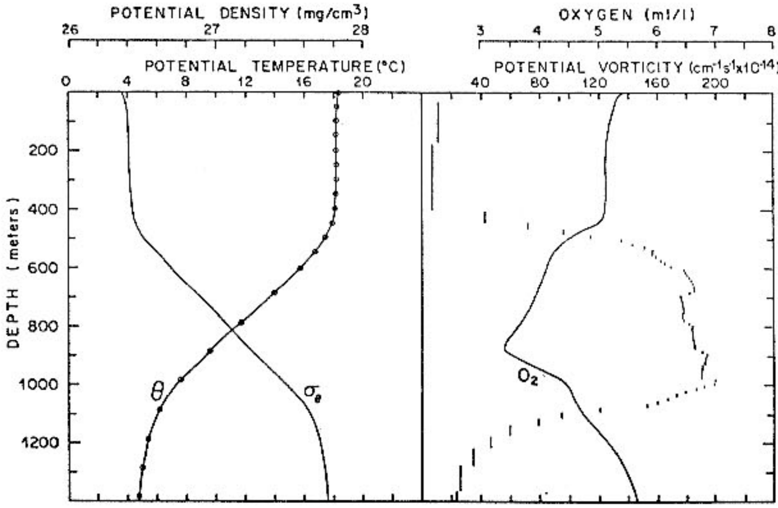


Figure 2. Hydrographic station 19 from a spring cruise of the *Researcher*, taken on April 8, 1977, at 34N, 68W, about 400 km south of the Gulf Stream. The low vertical stability of the density field gives a potential vorticity minimum at the potential density increment between $\sigma_\Theta = 26.41$ and 26.43 mg/cm³. This minimum defines the core of the Eighteen Degree Water at the station: $\Theta = 18.17$°C; $S = 36.512‰$; $\sigma_\Theta = 26.42$ mg/cm³; $O_2 = 5.12$ ml/1; potential vorticity $= 7.0 \times 10^{-14}\text{cm}^{-1}\text{sec}^{-1}$. The Θ, σ_Θ and O_2 curves have been interpolated from discrete samples at the depths indicated by dots on the Θ curve. The potential vorticity is calculated for potential density layers of thickness $\Delta\sigma_\Theta = .02$ mg/cm³.

Water (section 3a). The solid arrows represent deduced advection paths for low latitude influence of higher latitude convective sources of low potential vorticity: the North Atlantic Subpolar Mode Water (section 4b). This influence occurs directly as anticyclonic recirculation ($\sigma_\Theta = 27.1$ and 27.2 mg/cm³ labeled arrows) and indirectly as a deep western boundary current ($\sigma_\Theta = 27.8$ mg/cm³ labeled arrows).

North Pacific. The shaded region is Tsuchiya's (1982) rendition of Masuzawa's (1969, 1972) interpretation of the area of circulation of the North Pacific variety of Subtropical Mode Water (section 3b).

Southern Hemisphere. In the southern hemisphere, the dotted lines indicate the boundary of the Antarctic Circumpolar Current, as delineated by the band of high dynamic height gradient in the 0/1000 db chart of Gordon *et al.* (1978). North of this band, a selection of station locations of winter deep convection is indicated by dots (McCartney, 1977; and appendix to present paper). Areas of shading and areas of slashing are the geographic regions of low potential vorticity at, respectively, the heavier and lighter types of local Subantarctic Mode Water, with boundaries defined only by the indicated sections. Arrows represent deduced advection paths for the low latitude influence of high latitude convective sources of low potential vorticity: the Subantarctic Mode Water (section 4a). This influence is predominantly direct as anticyclonic recirculation. An indirect influence occurs in the western South Atlantic, where pycnostads with $\sigma_\Theta \gtrsim 27.1$ mg/cm³ outcropping in the Drake Passage are advected northward as a western boundary current and enter the South Atlantic subtropical gyre near 40S, 55W.

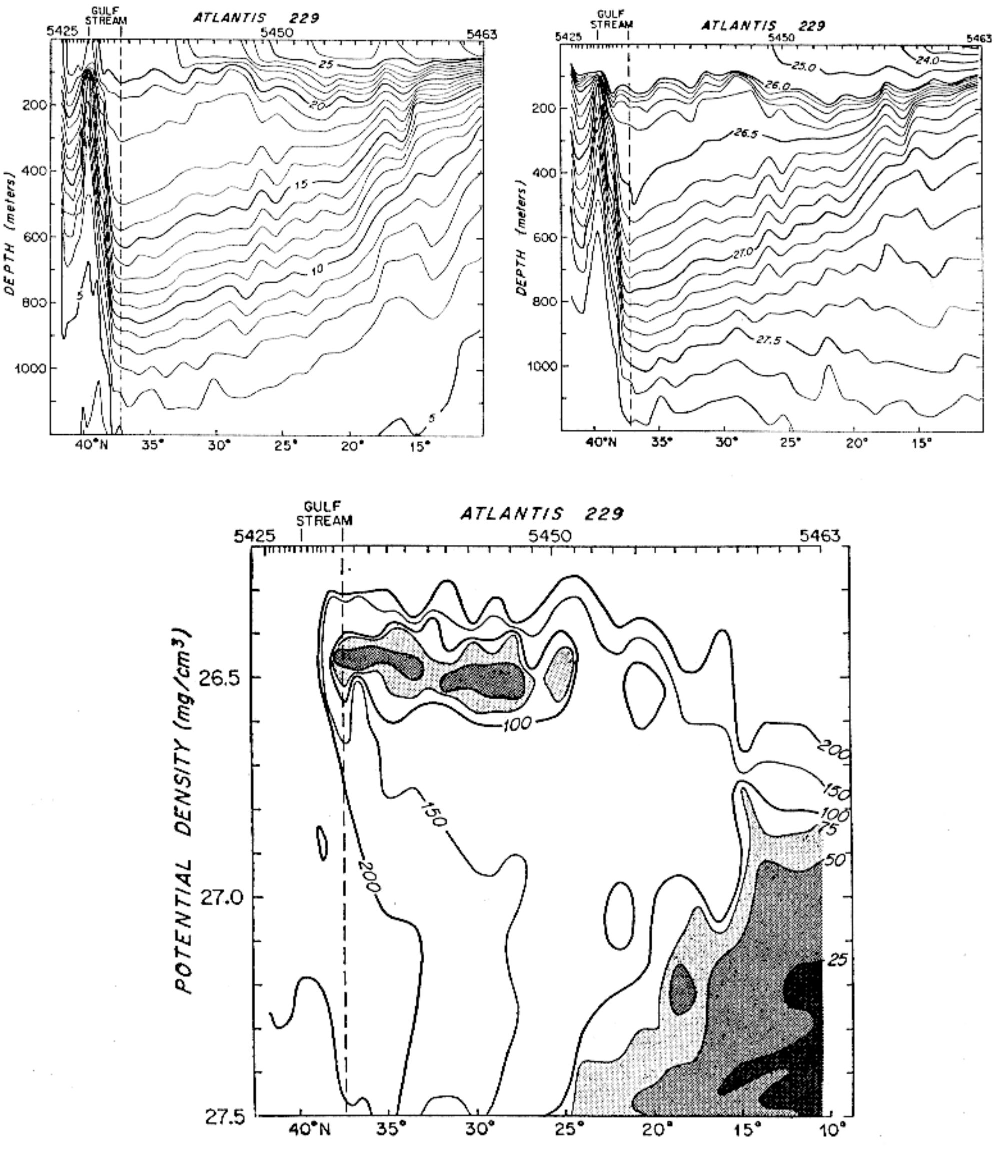


Figure 3. Property sections for a section along 50W made by *Atlantis* in 1956, between November 13 (north) and November 30 (south). Color sections of temperature and salinity are included in Fuglister (1960), section location is included on Figures 1 and 4. The eastward flow of the Gulf Stream lies between stations 5432 (39°37′N) and 5439 (37°16′N). The vertical dashed line marks the southern edge of the Gulf Stream: station 5479, the dynamic height maximum. (a) Potential temperature (Θ in °C, depth as ordinate): Eighteen Degree Water marked by larger isotherm spacing centered at $\Theta = 18$°C. (b) Potential density (σ_Θ in mg/cm³, depth as ordinate): Eighteen Degree Water marked by larger isopycnal spacing centered at $\sigma_\Theta = 26.5$ mg/cm³. (c) Potential vorticity, approximated by fE (fE in 10^{-14}cm^{-1}-sec^{-1}, potential density as ordinate. Shading has been chosen to emphasize the low potential vorticity water masses: single, double and triple intensity denoting, respectively, less than 75, 50 and 25 $\times$ 10^{-14}cm^{-1}sec^{-1}. The potential vorticity minimum layer centered near $\sigma_\Theta = 26.5$ mg/cm³ represents the Eighteen Degree Water. The calculation of E has been made using potential density increments of .02 mg/cm³.

deep convection occurs somewhere within that ocean. Small differences in potential density can correspond to quite different geographic regions for deep convection. It is important to retain relatively fine resolution in σ_Θ in order to be able to recognize these different source regions. The connection between deep convection and source regions for potential vorticity will be discussed below. The expression for potential vorticity in a continuously variable density distribution is $[f + (u_x - v_y)]E$ where f is again the Coriolis parameter, $(u_x - v_y)$ is the relative vorticity at x, y, z and E is the hydrostatic stability (Hesselberg and Sverdrup, 1914). E is proportional to the adiabatically adjusted vertical density gradient at the point x, y, z, and can be written in various forms using the equation of state of sea water and the formula for adiabatic temperature gradient (Fofonoff, 1962) or less explicitly, but equivalently, in terms of potential density anomaly.

A familiar usage of E is in the evaluation of the basic T, S, z data for a station, and E is then based on the potential density difference between successive samples, with the potential density referenced to the mean pressure of a pair of samples. If one uses standard level interpolated data, one then visualizes the stability as a function of depth. In the present study, the main emphasis will be on potential vorticity as a function of potential density σ_Θ. The calculation of E is, therefore, done for a set of standard σ_Θ surfaces separated by .02 mg/cm³ in σ_Θ, rather than for fixed depth intervals.

An illustration of the relationship between the traditional Mode Water indicators—the property-depth curve inflections—and the potential vorticity is included in Figure 2. The layer between 26.41 and 26.43 mg/cm³ has the lowest potential vorticity, less than $10 \times 10^{-14}\mathrm{cm}^{-1}\mathrm{sec}^{-1}$, and thus constitutes the Eighteen Degree Water core. The higher potential vorticity values below this core lie in the main pycnocline, while the higher values above this core are in the weak spring seasonal pycnocline.

The Eighteen Degree Water core is associated with a very narrow range of potential density as was first noted by Worthington (1959). This association is suggestive of a strong isopycnal advection signature: the Eighteen Degree Water wedge seems centered at $\sigma_\Theta = 26.5$ mg/cm³ in Figure 3b. An illustration of a section of potential vorticity is shown in Figure 3c. The shading near $\sigma_\Theta = 26.5$ mg/cm³ emphasizes the low potential vorticity of the Eighteen Degree Water.[2]

An example of the dynamic nature of potential vorticity can be seen in the neighborhood of the Gulf Stream in Figure 3. Worthington has commented (1976, pp. 92-94, and Table 3 on p. 40) that a significant fraction of the Gulf Stream transport

2. There is an additional region of low potential vorticity in the tropical zone in Figure 3c. This water first appeared in the volumetric studies of Cochrane (1958), Pollak (1958), and Montgomery (1958) as a volumetric mode centered near $\sigma_\Theta = 27.45$ mg/cm³, common to all the world oceans. This "tropical type of water" (Montgomery, 1958) appears in this paper in Figures 3c, 5, 6, 7, 9 and 10 as a low potential vorticity layer under-cutting the subtropical main pycnocline. The processes maintaining this layer could be related to the circulation "shadow zones" described by Luyten, Pedlosky and Stommel (1982).

is Eighteen Degree Water. In Figure 3c, the potential vorticity minimum layer of the Eighteen Degree Water can be seen in the southern half of the Stream, but with its potential vorticity apparently elevated over that characterizing the region south of the Stream. The explanation for this is given by Stommel (1965, pp. 108-114): it is the total potential vorticity that should be conserved following the flow in the absence of mixing. The potential vorticity calculations herein neglect the relative vorticity as negligible in magnitude in most of the ocean, and as uncalculable anyway. Stommel illustrated how this approximation breaks down in the Gulf Stream, showing that as the relative vorticity magnitude increases the Eighteen Degree Water thickness decreases in compensation to conserve the total potential vorticity. This thickness decrease can be seen in Figures 3a and 3b. In Figure 3c it is manifested by fE increasing northward across the Stream in response to the neglected term $(v_x - u_y)\,E$ becoming non-negligible, with $[f + (v_x - u_y)]\,E$ presumably staying more nearly constant.

In the remainder of this paper the quantity fE will be used exclusively, and it will be simply called the potential vorticity. There will be known current regimes like the Gulf Stream and Kuroshio where the relative vorticity is not negligible and where, therefore, fE is not a good approximation to the total potential vorticity. There may also be unknown current regimes where this is a problem, for example a region with a strong barotropic current that is "invisible" to density based current calculations, but has non-negligible horizontal shear.

3. Subtropical Mode Water

The first detailed study of a Subtropical Mode Water was conducted by Worthington (1959), and some of his major points about Eighteen Degree Water have been repeated in the previous section. He noted the existence in the North Pacific of a similar inflection of the temperature-depth profile at 16.5°C. Masuzawa (1969) later completed a thorough study of this North Pacific variety and coined the name Subtropical Mode Water. This terminology has been adopted as a convenient name for both the North Pacific and North Atlantic water masses.

Both varieties of Subtropical Mode Water exhibit western intensification. The winter formation regions for these Mode Waters lie offshore of intense western boundary currents—the Gulf Stream and Kuroshio. The strongest pycnostads lie immediately offshore of these currents, but the Mode Waters can be easily detected as a low potential vorticity stratum farther offshore than the region of winter outcropping extends. In both the North Atlantic and North Pacific Oceans the low potential vorticity layer is associated with the strong anticyclonic recirculation of the northwest intensified subtropical gyre.

a. North Atlantic Ocean. Eighteen Degree Water is by far the most thoroughly studied variety of Mode Water. Aspects of its distribution are discussed in several papers, with Worthington (1959, 1976) being the most complete. Schroeder *et al.* (1959) discussed the climatic *stability* of the Eighteen Degree Water properties, while Talley and Raymer (1982) and Jenkins (1982) use much longer data sets and finer vertical resolution to focus on the climatic *variability* of the water mass. Worthington (1959, 1972a) discussed the role of air-sea heat exchange in forming Eighteen Degree Water, but the field observation of actual convection proved difficult (McCartney *et al.*, 1978; Leetmaa, 1977). Warren (1972) discussed the theoretical framework behind the relative insensitivity of a Mode Water to the year-to-year climatic variations. A hypothesis of a dynamical coupling between the late winter convective formation and the intensity of the Gulf Stream gyre circulation—anticyclogenesis—was advanced by Worthington (1972b, 1976). It later gained some observational support (Worthington, 1977) and more recently has become a topic of theoretical modeling. Stommel and Veronis (1980) have treated the circulation response to rapid cooling as a geostrophic adjustment problem. Csanady (1982) has taken a somewhat different point of view and discussed a quantitative analogy between the Eighteen Degree Water system and the atmospheric Hadley cell.

There is one aspect of the Eighteen Degree Water phenomenon that should be emphasized for the present study. This concerns the temporal variability of the Eighteen Degree Water, and the difficulties it causes in producing charts of the water mass distribution. By extension these difficulties can be expected for other Mode Waters of the world.

The variability of Eighteen Degree Water has been discussed in considerable detail by Talley and Raymer (1982). They utilize the long time series (1954-1978) of hydrographic observations available near Bermuda—the *Panulirus* station—and present time series plots of the Eighteen Degree Water core potential vorticity, potential temperature, salinity and potential density. The *Panulirus* station is conveniently located in the western North Atlantic in the region of the westward flow of the gyre interior. The potential vorticity of the Eighteen Degree Water at *Panulirus* ranged from less than $10 \times 10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ to greater than $60 \times 10^{-14}\text{cm}^{-1}\text{sec}^{-1}$. This is very troublesome, because this *temporal* range at one location is similar in magnitude to the *spatial* range in synoptic sections like that of Figure 3. The potential density variability of the core is similarly troublesome. At *Panulirus*, Talley and Raymer show core values ranging from $\sigma_\theta < 26.4$ mg/cm^3 to $\sigma_\theta \cong 26.6$ mg/cm^3. This temporal range at one location is again similar to the spatial range along synoptic sections.

A last difficulty is that the temporal variability reported by Talley and Raymer has several different time scales. There are multiple year trends visible in their data, e.g. a gradual cooling of the core from 1954 to 1972. There are hints of annual cycles—a tendency for the recently convected water of a given winter to arrive by advection at *Panulirus* several months later. There appear to be episodic changes. At the end of winter 1964, the Eighteen Degree Water abruptly shifted in potential density from the level near $\sigma_\Theta \cong 26.45$ mg/cm³ that characterized the core between 1954 and 1964, to near $\sigma_\Theta \cong 26.55$ mg/cm³, typical of 1964 through 1971. A further example of an episodic change is given by Talley and Raymer using hydrographic sections along 55W. The first was taken in October 1976, the second in July 1977. Halfway through the nine-month period between the two occupations of the 55W section occurred the deep convection event reported by Leetmaa (1977) and Worthington (1977). Talley and Raymer find a complete alteration of the Eighteen Degree Water properties during this period, from a relatively light variety, with σ_Θ near 26.3 mg/cm³ and high potential vorticity, to a relatively dense variety, with σ_Θ near 26.45 mg/cm³ and much lower potential vorticity. Simultaneously, the associated temperature-salinity correlation reverted from anomalously fresh to normal (McCartney *et al.*, 1980).

The mix of episodic, seasonal and multi-year variability of the Eighteen Degree Water potential density and potential vorticity precludes the preparation of meaningful distribution charts from any nonsynoptic data set. An attempt was made by this author to produce a chart of the potential vorticity core of the Eighteen Degree Water using data from the IGY period—basically 1954 through 1961. This data was used successfully by Worthington and Wright (1970) for charting salinity on potential temperature surfaces for the deep water ($\Theta \leqslant 4°C$) of the North Atlantic Ocean. The attempt for Eighteen Degree Water was a failure, and is not shown here. While this time period contains no episodic changes, according to the time series analysis of Talley and Raymer (1982), it does have considerable month-to-month variability and a mild trend through its seven years. As a result, contours tend to close between section lines from different seasons and/or years. The non-synoptic field is fundamentally unmappable on the fine density scale used in the present study due to the time variability. Only by means of smoothing can reasonable maps of nonsynoptic data be produced.[3] Synoptic data are mappable, and Talley and Raymer (1982) have produced a chart of Eighteen Degree Water properties from an extensive data set collected in spring 1960 (Fuglister, 1963).

Individual synoptic sections can be contoured in reasonably smooth fashion. Figure 3 depicts an example of a meridional section crossing the warm water subtropical gyre. Figure 4 shows the location of this North Atlantic section, and several other sections and distributions used in this paper, and includes the warm water (> 17°C) circulation distribution from Worthington (1976, Fig. 41). The two zonal transects of the North Atlantic are shown as potential vorticity sections in Figure 5. The poleward section, 36N, crosses the northeast flowing Gulf Stream near 72W.

3. Note added in proof. Two papers have recently appeared that contain smoothed maps of nonsynoptic data. The smoothing is accomplished by using a large $\Delta\sigma_\Theta$ for the potential vorticity calculation. Sarmiento *et al.* (1982) map properties on the $\sigma_\Theta = 26.5$ mg/cm³ surface, calculating potential vorticity from the spacing of the $\sigma_\Theta = 26.4$ and 26.6 mg/cm³ surfaces. Their layer therefore encompasses 10 of the layers used in the present study. McDowell *et al.* (1982) similarly present maps for two related layers: $\sigma_\Theta = 26.3$-26.5 mg/cm³ and for $\sigma_\Theta = 26.5$-27.0 mg/cm³.

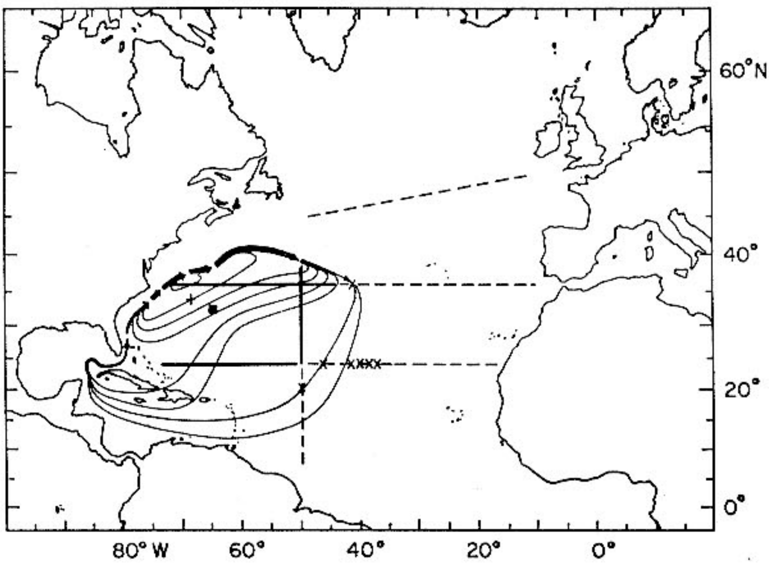


Figure 4. Warm water (> 17°C) circulation diagram of Worthington (1976, Fig. 42). Locations of sections used in Figures 3, 5, 13 and 14 are shown, and also the locations of the station used in Figure 2 (plus sign) and of the *Panulirus* station (square symbol) discussed in section 3a. The solid segments of section lines indicate the location of a strong continuous potential vorticity minimum layer near $\sigma_\Theta = 26.5$ mg/cm³, and therefore the main recirculation of Eighteen Degree Water. In this layer the potential vorticity falls below 75×10^{-14}-cm^{-1}sec^{-1}. The X's denote single station or observation of weaker ($< 100 \times 10^{-14}$cm^{-1}-sec^{-1}) potential vorticity minima at this same density level, but geographically isolated from the region of the strong continuous minimum layer.

Between 60 and 50W the sea-surface density reaches nearly the level of the Eighteen Degree Water. This part of the section was taken in late April 1959; a month or so earlier, convection (and the sea-surface σ_0) probably penetrated to the core of low potential vorticity near $\sigma_\Theta = 26.5$ mg/cm³. The Gulf Stream (or a branch of the Stream) passes back southward across 36N near 44W. West of 44W, the Eighteen Degree Water is a thick well-defined layer with potential vorticity less than 50×10^{-14}cm^{-1}sec^{-1}, while east of there it is not. Instead, potential vorticity minima are found at higher potential densities, with only two single station observations (42W and 37W) of minima at potential densities near the Eighteen Degree Water value. The denser minima are a North Atlantic variety of Subpolar Mode Water, discussed below in section 4b. At 24N, the equatorward section in Figure 5, a similar distribution is found. There is a well-defined potential vorticity minimum layer near $\sigma_\Theta = 26.5$ mg/cm³ west of 51W, while east of there only a few isolated observations of potential vorticity minima at the Eighteen Degree Water density are seen. There is no Gulf Stream in the open ocean at this latitude; instead, the western

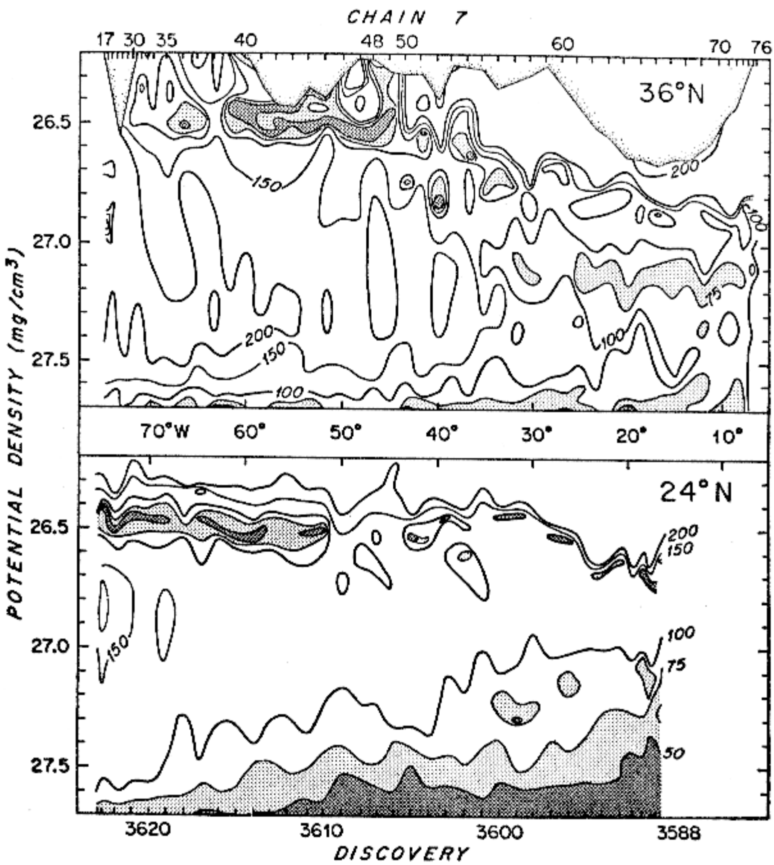


Figure 5. North Atlantic potential vorticity [fE in 10^{-14}cm^{-1}sec^{-1}] sections with potential density as section ordinate. The 36N section is from *Chain* cruise 7, stations 17-76, occupied between April 19 and May 12, 1959 (between stations 17 and 30, every other station has been skipped). The 24N section is from *Discovery II* IGY cruise 2, stations 3588-3624, occupied between October 6 and October 28, 1957. Fuglister (1960) lists these data, and includes color sections of temperature and salinity, with depth as the section ordinate. The section locations are included on Figures 1, 4 and 12. Shading has been chosen to emphasize the low potential vorticity water masses: single and double intensity denoting, respectively, less than 75 and 50 × 10^{-14}cm^{-1}sec^{-1}. At 36N, the Gulf Stream crosses the section between stations 25 and 34, flowing northeastward. A branch of the Gulf Stream returns southward across the 36N section between stations 48 and 50. The northward flow of the Florida Current lies west of the Bahamas and is not included in the 24N section. The calculation of E has been made using potential density increments of .02 mg/cm³.

boundary current is the Florida Current passing through the Florida Strait, near 79W. The 24N section ends east of the Bahamas.

The basic distribution of Eighteen Degree Water has a simple relationship to the warm water circulation. The water mass shows a continuous well-defined potential vorticity minimum in the western North Atlantic where there is an intense subtropical recirculation, and a convective source for low potential vorticity. In the eastern North Atlantic, there is no convective source for low potential vorticity at Eighteen Degree Water densities, and only isolated mesoscale cells of Eighteen Degree Water are found.

b. North Pacific Ocean. Following up on Worthington's (1959) comment on the existence of inflections in property-depth curves south of the Kuroshio Current, Masuzawa (1969, 1972) published two papers describing distributions of this subtropical Mode Water. Masuzawa produced a volumetric temperature-salinity census of the Subtropical gyre, and found a bivariate mode at 16.5°C, 34.75‰. While this is the dominant mode, he found significant thickening of isotherm spacing for the rather broad temperature range of 16° to 19°C. The region of this thickening has been indicated on Figure 1, after Tsuchiya's (1982) rendition of Masuzawa's charts. Tsuchiya (1982) has produced charts of properties of the $240 \times 10^{-8} m^3 kg^{-1}$ thermosteric anomaly surface ($\sigma_t = 25.60$ mg/cm^3). This surface lies in the middle of the North Pacific Subtropical Mode Water layer. The reader is referred to Tsuchiya's paper for a thorough discussion of the circulation near this density level.

For comparison to the North Atlantic Subtropical Mode Water in Figure 3c, a section of potential vorticity in the neighborhood of 155W is shown in Figure 6. Note that this section is a composite of 1981 data north of 28N and 1973 south of 28N. Vertical density gradients are rather larger throughout the main pycnocline in the North Pacific than the North Atlantic, and the Mode Water not as vertically homogeneous. A larger potential density increment, $\Delta\sigma_\Theta = .1$ mg/cm^3 has been used, reflecting this larger pycnocline gradient and the resulting reduction in density resolution by discrete observations. The Mode Water layer is near $\sigma_\Theta = 25.6$ mg/cm^3, and extends southward from the middle of the Kuroshio to 24N as a continuous feature. Within the southern half of the Kuroshio, the level of fE rises, presumably in proportion to the neglected relative vorticity as for the Gulf Stream. South of the continuous minimum layer there are two single station observations of potential vorticity minima at this density level. The rise of potential vorticity south of 17N would appear to mark the southern edge of the subtropical gyre, as the similar rise at 15N in the North Atlantic did (Fig. 3c). Another point of similarity is the pool of low potential vorticity at higher density levels that undercuts the subtropical gyre near 20N.

4. Subpolar Mode Water

Two varieties of Subpolar Mode Water have now been described in the literature, a circumpolar one in the southern hemisphere, and a North Atlantic variety. Subpolar Mode Waters have their winter formations at higher latitudes than the Subtropical

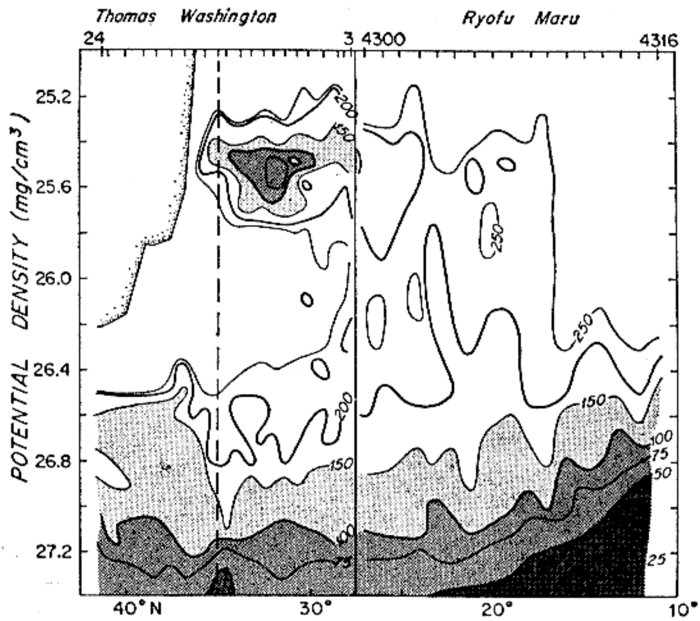


Figure 6. North Pacific potential vorticity [fE in 10^{-14}cm^{-1}sec^{-1}] sections with potential density as section ordinate. The section is a composite from two cruises, vertical solid line denoting the break. Southern end: *Hakuho Maru*, stations 4300-4316, occupied between June 9 and June 14, 1973, along 155E. Northern end: *Thomas Washington* cruise Rama 13 stations 3-24, occupied between May 13 and May 28, 1981, along 152E. Section location included on Figure 1. Shading has been chosen to emphasize the low potential vorticity water masses: single, double and triple intensity denoting, respectively, less than 150, 100, 50 × 10^{-14}cm^{-1}sec^{-1}. The eastward flow of the Kuroshio lies between stations 15 and 21. The vertical dashed line marks the southern edge of the Kuroshio: station 15, the dynamic height maximum. A larger potential density increment, $\Delta\sigma_\theta = 0.1$ mg/cm^3 has been used in the potential vorticity calculation for this section.

Mode Waters. The potential density range of the Subpolar Mode Waters generally corresponds to that of the middle or lower pycnocline of the subtropical gyre. This is in contrast with the Subtropical Mode Waters which are upper pycnocline water masses.

The first variety of Subpolar Mode Water is the Subantarctic Mode Water (McCartney, 1977; Piola and Georgi, 1982). This variety has its winter formation region in the circumpolar Subantarctic Zone, immediately north of the Antarctic Circumpolar Current (Fig. 1). This cyclonic current system links together the subpolar regions of all three southern hemisphere oceans. Within the subtropical gyres of the South Pacific and southern Indian Oceans the Subantarctic Mode Water exhibits a basin-wide influence at mid-pycnocline, an influence detectable to quite low latitudes. In the South Atlantic, the Subantarctic Mode Water is comparatively weak in strength, and its influence is laterally restricted to only the southwestern sector of the subtropical gyre.

The second variety of Subpolar Mode Water is formed in the central and eastern North Atlantic (McCartney and Talley, 1982). Its formation region is associated with the cyclonic circulation system of the subpolar North Atlantic. Within the subtropical gyre of the North Atlantic this variety exhibits a middle pycnocline influence in the east, and a lower pycnocline/upper deep water influence in the west (Talley and McCartney, 1982).

The varieties of Subpolar Mode Water exhibit diversity in the geometry of their distributions. The winter formation regions for these Mode Waters lie adjacent to the boundary currents separating the subtropical anticyclonic gyre recirculation from the subpolar cyclonic gyre recirculations. The influence on lower latitudes of deep convection in these subpolar regions occurs both directly and indirectly. The direct influence occurs as anticyclonic recirculation from the outcropping regions around the subtropical gyres. Two specific types of Subpolar Mode Water circulate indirectly to lower latitudes. The densest North Atlantic Subpolar Mode Water, the Labrador Sea Water, moves equatorward as part of the Deep Western Boundary Current of the North Atlantic Ocean. The densest Subantarctic Mode Water is formed in the southeastern Pacific and Drake Passage and enters the subtropical South Atlantic as the Falkland Current flowing toward the equator.

a. The Southern hemisphere. The winter deep convection region that is the source of Subantarctic Mode Water is the Subantarctic Zone. Equatorward across the Southern Ocean, isopycnals in the upper kilometer of the ocean descend in a sequence of fronts. In the Drake Passage, for example, high resolution hydrographic sections often show three fronts (Nowlin and Clifford, 1982): from south to north, the Continental Water Boundary, the Polar Front, and the Subantarctic Front. The dynamic height increases dramatically across these three fronts and this corresponds to the large transport of the Antarctic Circumpolar Current. On Figure 1, the circumpolar belt of high dynamic height gradient (Gordon *et al.*, 1978) is shown as an indicator of the main eastward flow of this Current. The northern edge of this belt is the Subantarctic Front, and the Subantarctic Zone is the region immediately north of this belt. Within this zone, the main pycnocline generally reaches its maximum depth along a given meridional section, and above this pycnocline the seasonal outcropping of deep mixed layers occurs in winter.

The northern boundary of the Subantarctic Zone is not sharply defined. Instead, there is a rather broad and shallow frontal feature traditionally called the Subtropical convergence. It is generally on the order of 5° latitude north of the Subantarctic Front, so on Figure 1 the Subantarctic Zone should be visualized as a band of about 5° width adjacent to the Circumpolar Current. It is evident that this Zone is a region where exchange occurs between the subtropical gyres and the Southern

Ocean. The most dramatic evidence of this is the Agulhas Current system, which flows southwest along the southeast coast of Africa, flows west into the South Atlantic, turns south and then east adjacent to the Circumpolar Current (Jacobs and Georgi, 1977). In this turning process the Agulhas Current overrides the northern sector of the Circumpolar Current. The Agulhas Current heat transport thereby acts as a major source of warm water for the entire Southern Ocean south of 40S (Georgi and Toole, 1982). The other western boundary currents of the southern hemisphere subtropical gyres also exhibit interactions with the Southern Ocean. The southward flowing Brazil Current encounters the northward flowing Falkland Current in the western South Atlantic (McCartney, 1977; Reid *et al.*, 1977; Gordon, 1981). Together they turn and join the eastward flow of the Circumpolar Current. In the South Pacific, New Zealand is the western boundary for most of the subtropical circulation south of 35S. East of New Zealand along the Chatham Rise the southward flowing East Cape Current is the western boundary current for this subtropical sector. It encounters the northward flowing Southland Current near 43S. Together they turn and flow eastward across the South Pacific (Heath, 1981). In the Tasman Sea west of New Zealand, the East Australian Current is the western boundary current, and it turns eastward and leaves the Australian coast near 35S (Hamon, 1965). Thompson and Edwards (1981) have recently discussed the formation of Subantarctic Mode Water south of the Tasman Sea and its impact on the Tasman Sea. For all these western boundary currents, the offshore turning of the currents and the overriding of the Subantarctic Zone effects a net exchange of water. The currents inject warm water into the Subantarctic Zone, where it is cooled, freshened and vertically homogenized by air-sea heat and freshwater exchange. The subtropical gyres receive in compensation the homogenized products of this convection.

Dramatic evidence for this exchange of subtropical and subantarctic waters can be seen in Figure 7, which shows potential vorticity sections for four zonal transects in the South Pacific and southern Indian Oceans. The section locations are shown in Figure 1: in each of the two oceans the poleward sections lie 5 or 10° north of the Subantarctic Front, and thus represent data from near the winter convection regions of the Subantarctic Zone. The equatorward sections lie about 20-25° north of the Subantarctic Front, and represent data from well within the subtropical gyres of those two oceans. All four sections show low potential vorticity at density levels corresponding to that of the deep convection farther south in the winter outcropping regime of the Subantarctic Zone. It is possible that the low potential vorticity layer on the poleward sections may at some longitudes represent a local persistence from the winter deep mixed layer. The winter data discussed below makes this seem unlikely, but it cannot be ruled out at every longitude. It seems more likely that the low potential vorticity layer represents advection from the deep mixed layers by the anticyclonic recirculation of the subtropical gyre. This "lateral persistence" then is a manifestation of the principle of conservation of potential vorticity: in a geographically compact region, a strong mixing process: deep vertical convection in winter, acts as a source of low potential vorticity (low hydrostatic stability) for a given density surface. This low potential vorticity is carried away from the source region by lateral (isopycnal) advection.

Winter data is sparse in the Subantarctic Zone. A few stations were published earlier (McCartney, 1977) and some more recent ones are included in an appendix to the present paper (the locations of all these stations are included in the chart in Figure 1). In Figure 8 the σ_Θ and longitude of these deep convection observations have been composited with the contours of low potential vorticity from the preceding Figure. The low potential vorticity layers on the poleward sections can be seen to have a density range similar to that of the winter deep convection within the Subantarctic Zone farther south. The low potential vorticity layers on the equatorward sections have less density range, and seem to be dominated by the region of denser convection in the southeastern part of each ocean's Subantarctic Zone. Longitude shifts consistent with anticyclonic circulation can be seen in Figure 8. The way to see this is as follows. Pick a particular value for the potential density of a winter deep convection, say 26.85 mg/cm^3 in Figure 8b. This outcrops near 110E, by coarse interpolation between the sparse winter observations, and near 40-45S (Fig. 1). Along the poleward section (32S), low potential vorticity at $\sigma_\Theta = 26.85$ mg/cm^3 is found between 110E and 80E. Along the equatorward section low potential vorticity at this potential density is found even farther west, between 110E and 55E. This distribution is thus indicative of a general north and west advection away from the convective source of low potential vorticity, and following the expected anticyclonic recirculation of the subtropical gyre (Fig. 1).

For the South Pacific, Figure 8a, $\sigma_\Theta = 27.10$ mg/cm^3 exhibits winter deep convection near 85W. Along the poleward section, low potential vorticity at this potential density is found between 75W and 130W, while along the equatorward section, the low potential vorticity extends all the way west to the International Date Line. Again, the distribution is suggestive of north and west advection from the convective source of low potential vorticity at this density (Fig. 1).

In each of these two oceans, the lighter varieties of Subantarctic Mode Water show geographically more isolated distribution than the heavier varieties. This can be seen in Figures 7 and 8, and is further illustrated in Figure 9, which shows potential vorticity sections for two meridional transects in the western part of these oceans. In each ocean the low potential vorticity layer is indicated by the same shading scheme as Figure 7. The layer thus delineated has a pronounced trend of increasing potential density from south to north. Thus the lighter varieties of Mode Water that outcrop in the southwest part of each Subantarctic Zone lead to a low potential vorticity influence only in the southwestern part of each subtropical gyre. For example, in the South Pacific Ocean at densities above $\sigma_\Theta = 26.95$ mg/cm^3, Figures

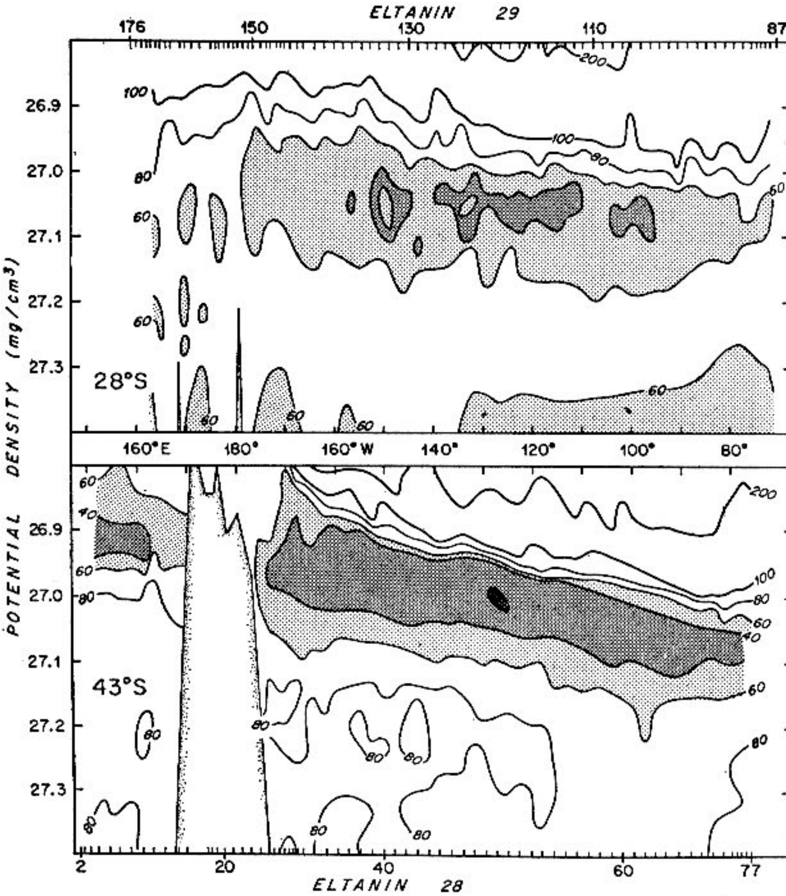
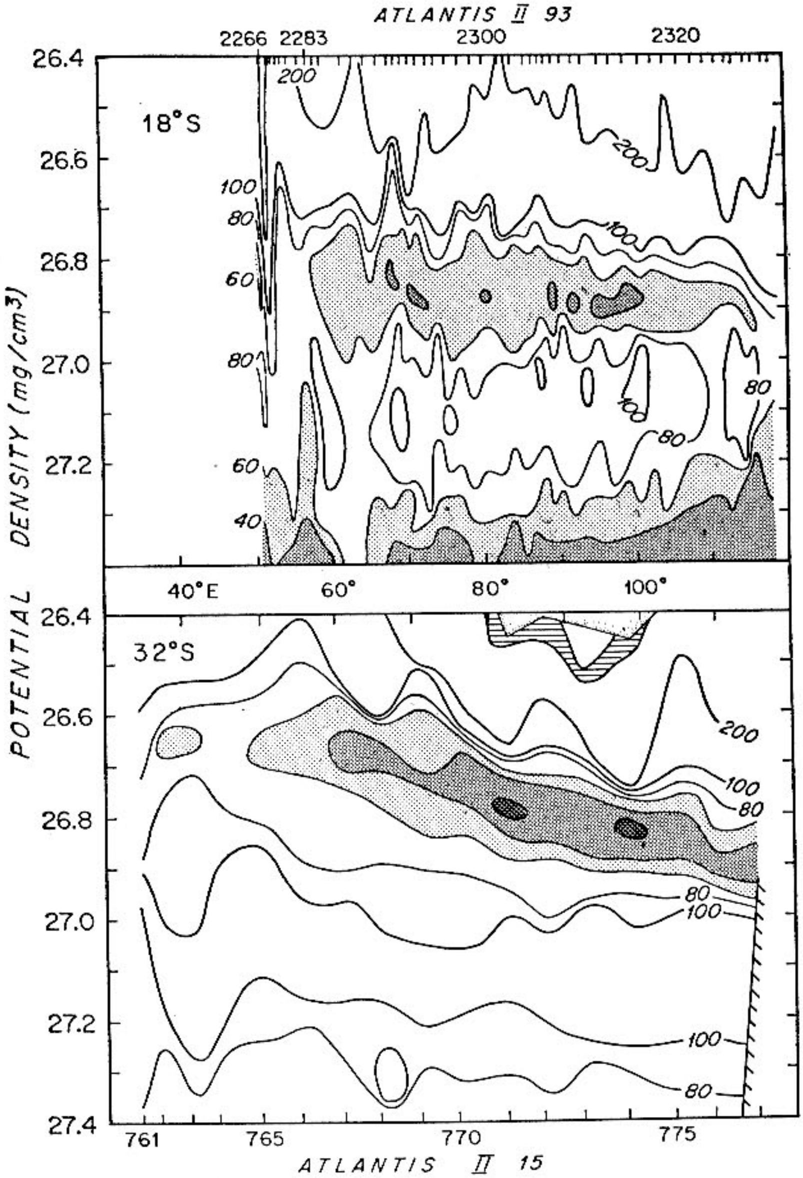


Figure 7. Zonal potential vorticity [fE in $10^{-14}cm^{-1}sec^{-1}$] sections with potential density as section ordinate. Section locations are included on Figure 1. Shading has been chosen to emphasize the low potential vorticity water masses: single, double and triple intensity denoting, respectively, less than 60, 40 and 20 $\times$ $10^{-14}cm^{-1}sec^{-1}$. The calculation of E has been made using potential density increments of .02 mg/cm³. (a) South Pacific: The 43S section is from *Eltanin* cruise 28, Scorpio Expedition stations 2-77, occupied between March 12 and May 7, 1967. The 28S section is from *Eltanin* cruise 29, Scorpio Expedition stations 87-176, occupied between June 4 and July 28, 1967. Stommel *et al.* (1973) include color sections of temperature, salinity, oxygen and nutrients, with depth as the section ordinate. At 43S, New Zealand and the shallow Chatham Rise to its east interrupts the section between 170E and 175W. There the extra contour denotes the bottom potential density. (b) Southern Indian: The 32S section is from *Atlantis II* cruise 15, stations 761-777, occupied between June 28 and July 15, 1965. Wyrtki (1971) includes color sections of potential temperature, salinity, potential density, oxygen and nutrients, with depth as the section ordinate. The 18S section is from *Atlantis II* cruise 93, stations 2266-2329, occupied between July 7



and August 18, 1976. Warren (1981) includes color sections of temperature, salinity, potential density, oxygen and nutrients, with depths as the section ordinate. The western end of the 18S section is east of Madagascar; no data between Madagascar and Africa are included. The horizontal hatched region denotes a layer of low potential vorticity just below the sea surface on the eastern part of the 32S section.

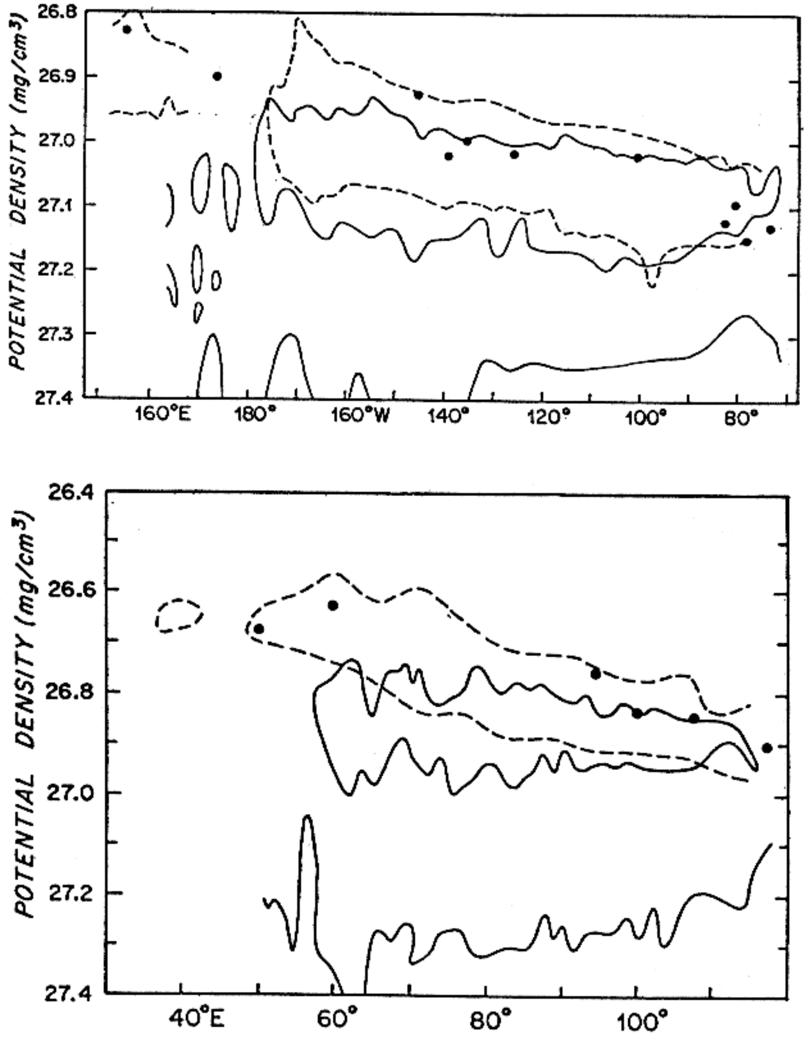


Figure 8. Composites of the $60 \times 10^{-14}\mathrm{cm}^{-1}\mathrm{sec}^{-1}$ potential vorticity contours from the sections in Figure 7 with the formation zone potential density values tabulated in McCartney (1977) and the appendix to the present paper. Solid contours are the northern sections from Figure 7, dashed contours are the southern sections. Data dots show the longitudinal variation of the potential density of winter deep convection in the Subantarctic Zone south of the southern sections. (a) South Pacific (from Fig. 7a). (b) Southern Indian (from Fig. 7b).

7a and 9a show low potential vorticity influence only west of 120W along 43S, south of 30S along 170W, and nowhere along 28S (Fig. 1). Similarly, in the southern Indian Ocean at densities above $\sigma_\theta = 26.70$ mg/cm³, Figures 7b and 9b show low potential vorticity influence only west of 80E along 32S, south of 24S along 70E, and nowhere along 18S (Fig. 1).