

## **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 poten-

tial density, and high levels of oxygen (near saturation). Worthington (1959) summarized the inflection point properties in pre-1959 Sargasso Sea data as temperature  $17.9^{\circ} \pm 0.3^{\circ}\text{C}$  and salinity  $36.50\text{‰} \pm 0.10\text{‰}$ . 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  $17^{\circ}$ - $18^{\circ}$ - $19^{\circ}\text{C}$  isotherms are larger than those above and below, as are the spacings of the  $26.4$ - $26.5$ - $26.6 \text{ mg/cm}^3$  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

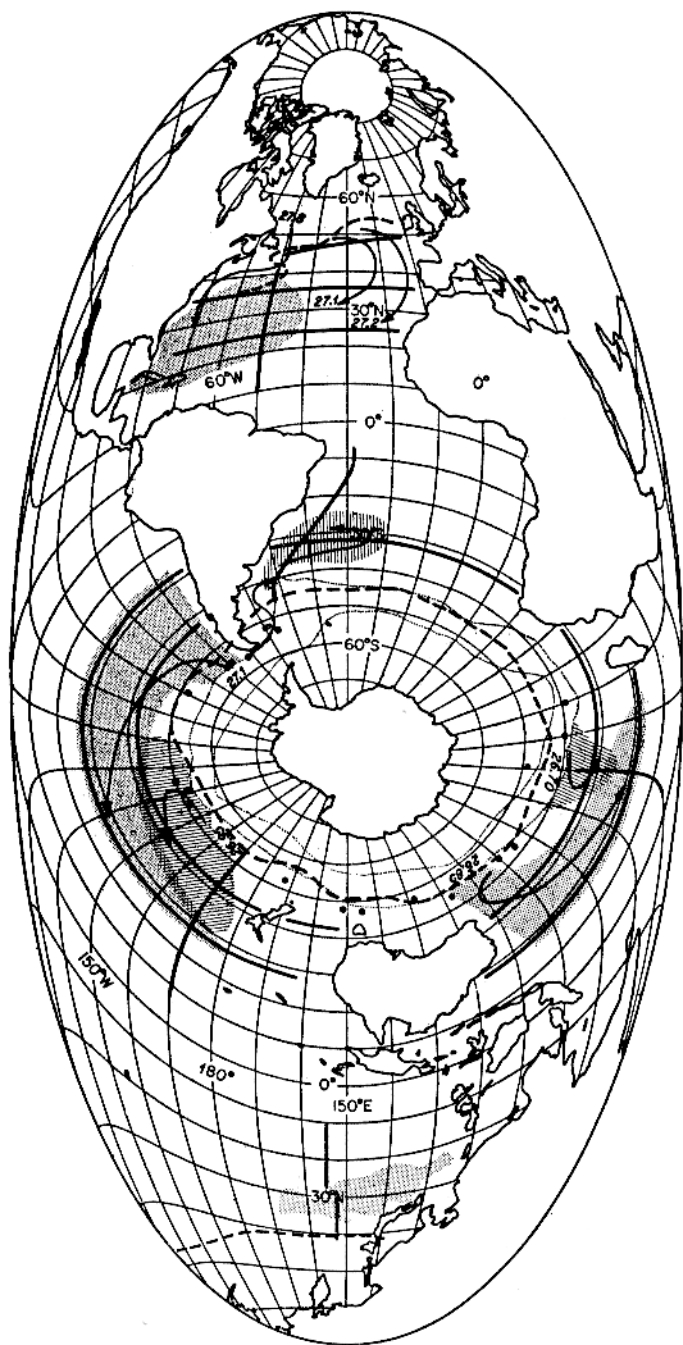


Figure 1. Global chart: an equal-area projection (transversed Mollweide). Locations of sections utilized in the figures of this paper are indicated by solid curves. The zero windstress curl curve in each ocean is indicated by a heavy dashed contour based on Taylor (1978; as reproduced by Baker, 1982) 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  $17^{\circ}\text{C}$ , thus including the Eighteen Degree

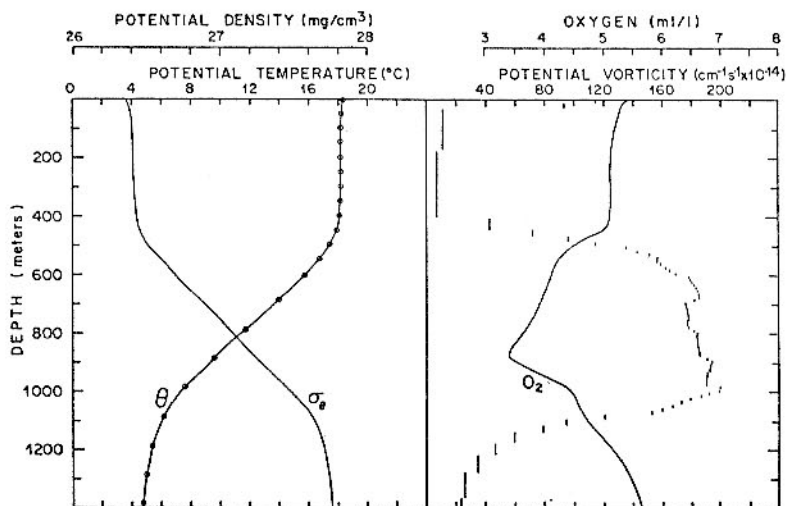
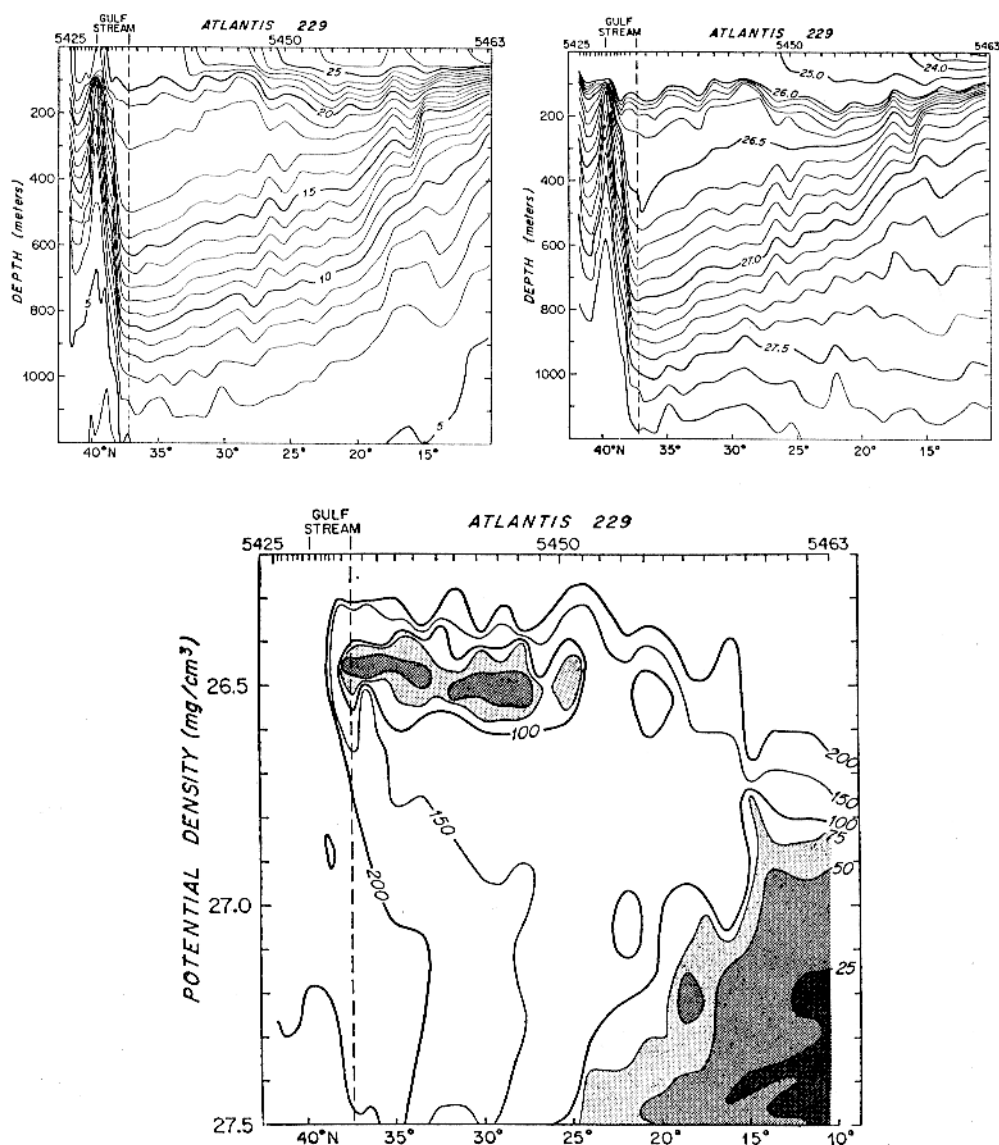


Figure 2. Hydrographic station 19 from a spring cruise of the *Researcher*, taken on April 8, 1977, at 34N, 68W, about 400 km south of the Gulf Stream. The low vertical stability of the density field gives a potential vorticity minimum at the potential density increment between  $\sigma_\theta = 26.41$  and  $26.43 \text{ mg/cm}^3$ . This minimum defines the core of the Eighteen Degree Water at the station:  $\theta = 18.17^\circ\text{C}$ ;  $S = 36.512\text{‰}$ ;  $\sigma_\theta = 26.42 \text{ mg/cm}^3$ ;  $\text{O}_2 = 5.12 \text{ ml/l}$ ; potential vorticity  $= 7.0 \times 10^{-14} \text{ cm}^2\text{s}^{-1}$ . The  $\theta$ ,  $\sigma_\theta$  and  $\text{O}_2$  curves have been interpolated from discrete samples at the depths indicated by dots on the  $\theta$  curve. The potential vorticity is calculated for potential density layers of thickness  $\Delta\sigma_\theta = .02 \text{ mg/cm}^3$ .

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  $27.2 \text{ mg/cm}^3$  labeled arrows) and indirectly as a deep western boundary current ( $\sigma_\theta = 27.8 \text{ mg/cm}^3$  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  $\sigma_\theta \geq 27.1 \text{ mg/cm}^3$  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 ( $39^{\circ}37'N$ ) and 5439 ( $37^{\circ}16'N$ ). The vertical dashed line marks the southern edge of the Gulf Stream: station 5479, the dynamic height maximum. (a) Potential temperature ( $\theta$  in  $^{\circ}C$ , depth as ordinate): Eighteen Degree Water marked by larger isotherm spacing centered at  $\theta = 18^{\circ}C$ . (b) Potential density ( $\sigma_{\theta}$  in  $mg/cm^3$ , depth as ordinate): Eighteen Degree Water marked by larger isopycnal spacing centered at  $\sigma_{\theta} = 26.5$   $mg/cm^3$ . (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  $\sigma_{\theta} = 26.5$   $mg/cm^3$  represents the Eighteen Degree Water. The calculation of  $E$  has been made using potential density increments of .02  $mg/cm^3$ .

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  $\sigma_\theta$  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  $\sigma_\theta$ . The calculation of  $E$  is, therefore, done for a set of standard  $\sigma_\theta$  surfaces separated by  $.02 \text{ mg/cm}^3$  in  $\sigma_\theta$ , 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  $26.43 \text{ mg/cm}^3$  has the lowest potential vorticity, less than  $10 \times 10^{-14} \text{ cm}^{-1} \text{ sec}^{-1}$ , 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  $\sigma_\theta = 26.5 \text{ mg/cm}^3$  in Figure 3b. An illustration of a section of potential vorticity is shown in Figure 3c. The shading near  $\sigma_\theta = 26.5 \text{ mg/cm}^3$  emphasizes the low potential vorticity of the Eighteen Degree Water.<sup>2</sup>

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  $\sigma_\theta = 27.45 \text{ mg/cm}^3$ , 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—anti-cyclogenesis—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  $\sigma_\theta < 26.4 \text{ mg/cm}^3$  to  $\sigma_\theta \approx 26.6 \text{ mg/cm}^3$ . 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  $\sigma_\theta \approx 26.45 \text{ mg/cm}^3$  that characterized the core between 1954 and 1964, to near  $\sigma_\theta \approx 26.55 \text{ mg/cm}^3$ , 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  $\sigma_\theta$  near  $26.3 \text{ mg/cm}^3$  and high potential vorticity, to a relatively dense variety, with  $\sigma_\theta$  near  $26.45 \text{ mg/cm}^3$  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 ( $\theta \leq 4^\circ\text{C}$ ) 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.<sup>3</sup> 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 ( $> 17^\circ\text{C}$ ) 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 non-synoptic 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  $\sigma_\theta = 26.5 \text{ mg/cm}^3$  surface, calculating potential vorticity from the spacing of the  $\sigma_\theta = 26.4$  and  $26.6 \text{ mg/cm}^3$  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:  $\sigma_\theta = 26.3\text{--}26.5 \text{ mg/cm}^3$  and for  $\sigma_\theta = 26.5\text{--}27.0 \text{ mg/cm}^3$ .

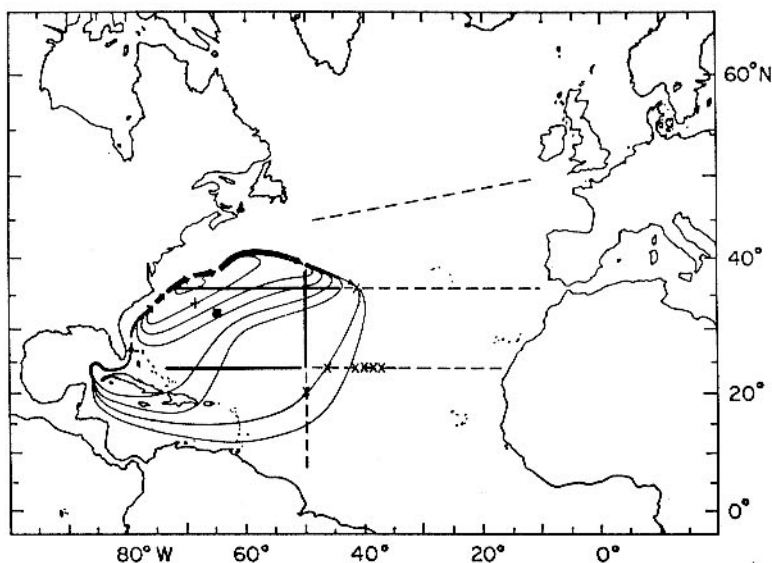


Figure 4. Warm water ( $> 17^{\circ}\text{C}$ ) circulation diagram of Worthington (1976, Fig. 42). Locations of sections used in Figures 3, 5, 13 and 14 are shown, and also the locations of the station used in Figure 2 (plus sign) and of the *Panulirus* station (square symbol) discussed in section 3a. The solid segments of section lines indicate the location of a strong continuous potential vorticity minimum layer near  $\sigma_{\theta} = 26.5 \text{ mg/cm}^3$ , and therefore the main recirculation of Eighteen Degree Water. In this layer the potential vorticity falls below  $75 \times 10^{-14} \text{ cm}^{-1} \text{ sec}^{-1}$ . The X's denote single station or observation of weaker ( $< 100 \times 10^{-14} \text{ cm}^{-1} \text{ sec}^{-1}$ ) 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  $\sigma_{\theta}$ ) probably penetrated to the core of low potential vorticity near  $\sigma_{\theta} = 26.5 \text{ mg/cm}^3$ . 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  $50 \times 10^{-14} \text{ cm}^{-1} \text{ sec}^{-1}$ , 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  $\sigma_{\theta} = 26.5 \text{ mg/cm}^3$  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

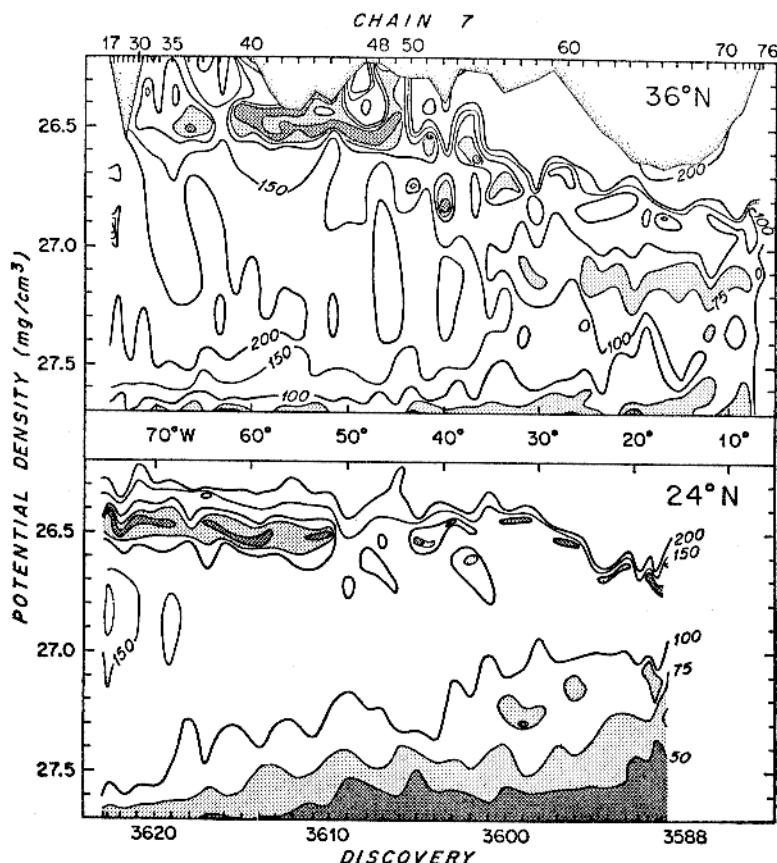


Figure 5. North Atlantic potential vorticity [ $fE$  in  $10^{-14} \text{cm}^{-3} \text{sec}^{-1}$ ] sections with potential density as section ordinate. The  $36^\circ\text{N}$  section is from *Chain* cruise 7, stations 17-76, occupied between April 19 and May 12, 1959 (between stations 17 and 30, every other station has been skipped). The  $24^\circ\text{N}$  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  $50 \times 10^{-14} \text{cm}^{-3} \text{sec}^{-1}$ . At  $36^\circ\text{N}$ , the Gulf Stream crosses the section between stations 25 and 34, flowing northeastward. A branch of the Gulf Stream returns southward across the  $36^\circ\text{N}$  section between stations 48 and 50. The northward flow of the Florida Current lies west of the Bahamas and is not included in the  $24^\circ\text{N}$  section. The calculation of  $E$  has been made using potential density increments of  $.02 \text{ mg/cm}^3$ .

boundary current is the Florida Current passing through the Florida Strait, near  $79^\circ\text{W}$ . The  $24^\circ\text{N}$  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  $16.5^{\circ}\text{C}$ ,  $34.75\%$ . While this is the dominant mode, he found significant thickening of isotherm spacing for the rather broad temperature range of  $16^{\circ}$  to  $19^{\circ}\text{C}$ . 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  $240 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$  thermosteric anomaly surface ( $\sigma_t = 25.60 \text{ mg/cm}^3$ ). 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  $155^{\circ}\text{W}$  is shown in Figure 6. Note that this section is a composite of 1981 data north of  $28^{\circ}\text{N}$  and 1973 south of  $28^{\circ}\text{N}$ . 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,  $\Delta\sigma_{\theta} = .1 \text{ mg/cm}^3$  has been used, reflecting this larger pycnocline gradient and the resulting reduction in density resolution by discrete observations. The Mode Water layer is near  $\sigma_{\theta} = 25.6 \text{ mg/cm}^3$ , and extends southward from the middle of the Kuroshio to  $24^{\circ}\text{N}$  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  $17^{\circ}\text{N}$  would appear to mark the southern edge of the subtropical gyre, as the similar rise at  $15^{\circ}\text{N}$  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  $20^{\circ}\text{N}$ .

#### 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

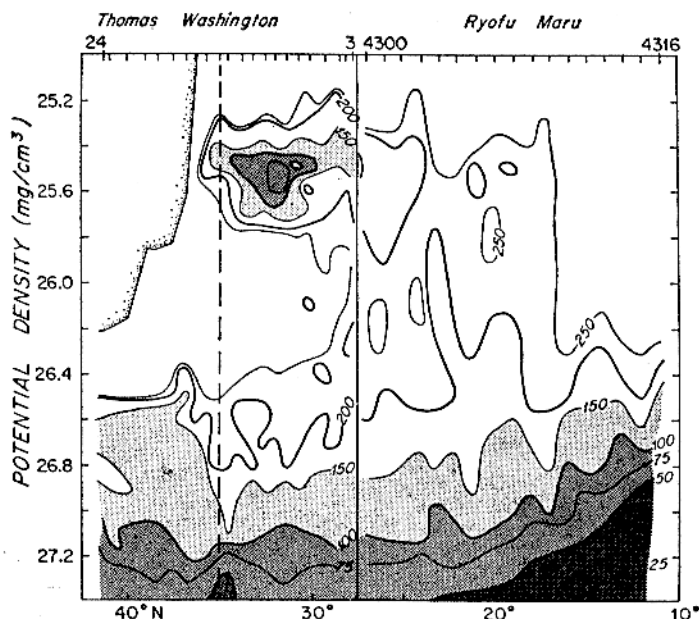


Figure 6. North Pacific potential vorticity [ $\text{JE}$  in  $10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ ] sections with potential density as section ordinate. The section is a composite from two cruises, vertical solid line denoting the break. Southern end: *Hakuho Maru*, stations 4300-4316, occupied 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,  $50 \times 10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ . 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,  $\Delta\sigma_\theta = 0.1 \text{ mg/cm}^3$  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  $5^{\circ}$  latitude north of the Subantarctic Front, so on Figure 1 the Subantarctic Zone should be visualized as a band of about  $5^{\circ}$  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

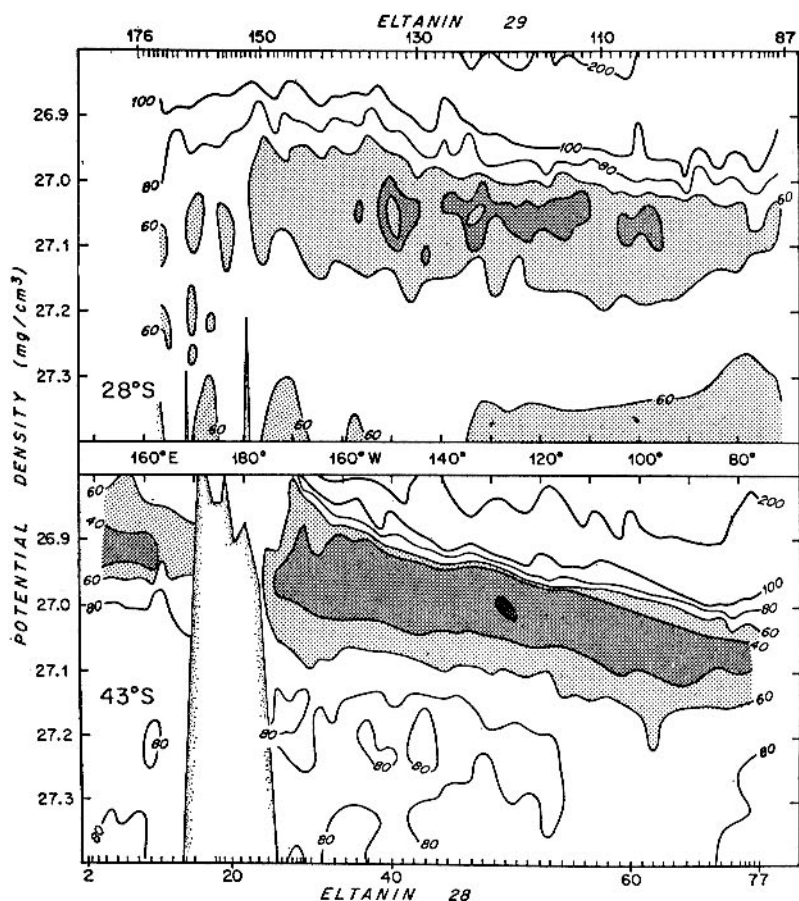


is a manifestation of the principle of conservation of potential vorticity: in a geographically compact region, a strong mixing process: deep vertical convection in winter, acts as a source of low potential vorticity (low hydrostatic stability) for a given density surface. This low potential vorticity is carried away from the source region by lateral (isopycnal) advection.

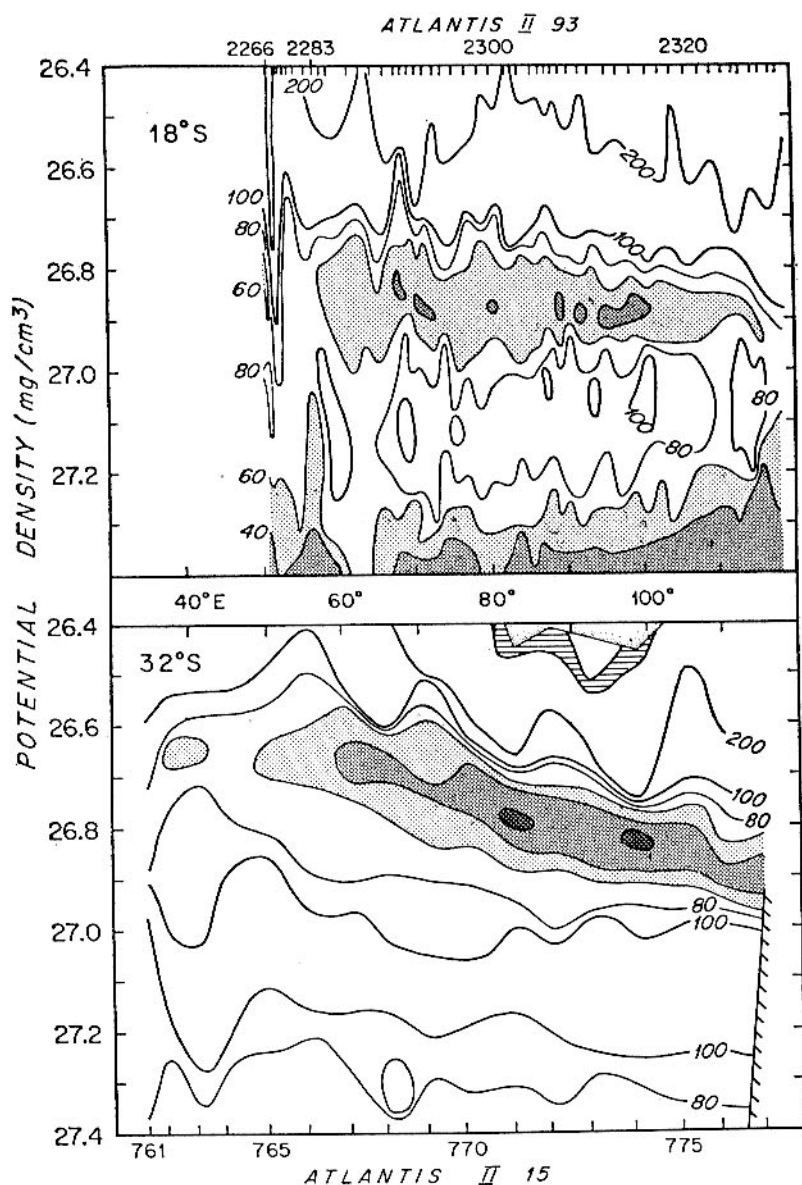
Winter data is sparse in the Subantarctic Zone. A few stations were published earlier (McCartney, 1977) and some more recent ones are included in an appendix to the present paper (the locations of all these stations are included in the chart in Figure 1). In Figure 8 the  $\sigma_\theta$  and longitude 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<sup>3</sup> 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<sup>3</sup> 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<sup>3</sup> 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<sup>3</sup>, Figures



**Figure 7.** Zonal potential vorticity [ $fE$  in  $10^{-14} \text{cm}^{-1} \text{sec}^{-1}$ ] 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  $20 \times 10^{-14} \text{cm}^{-1} \text{sec}^{-1}$ . The calculation of  $E$  has been made using potential density increments of  $.02 \text{ mg/cm}^3$ . (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  $170^\circ\text{E}$  and  $175^\circ\text{W}$ . 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. Wyrki (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.

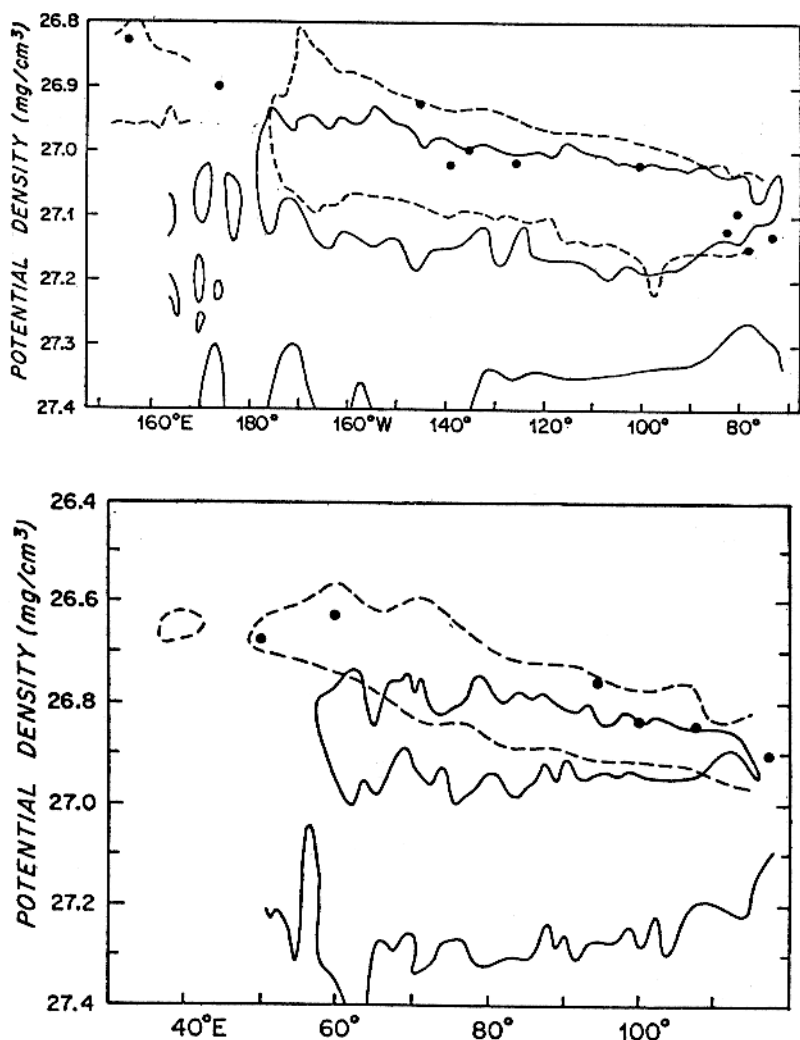


Figure 8. Composites of the  $60 \times 10^{-14} \text{cm}^{-1} \text{sec}^{-1}$  potential vorticity contours from the sections in Figure 7 with the formation zone potential density values tabulated in McCartney (1977) and the appendix to the present paper. Solid contours are the northern sections from 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  $\sigma_\theta = 26.70 \text{ mg/cm}^3$ , 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).

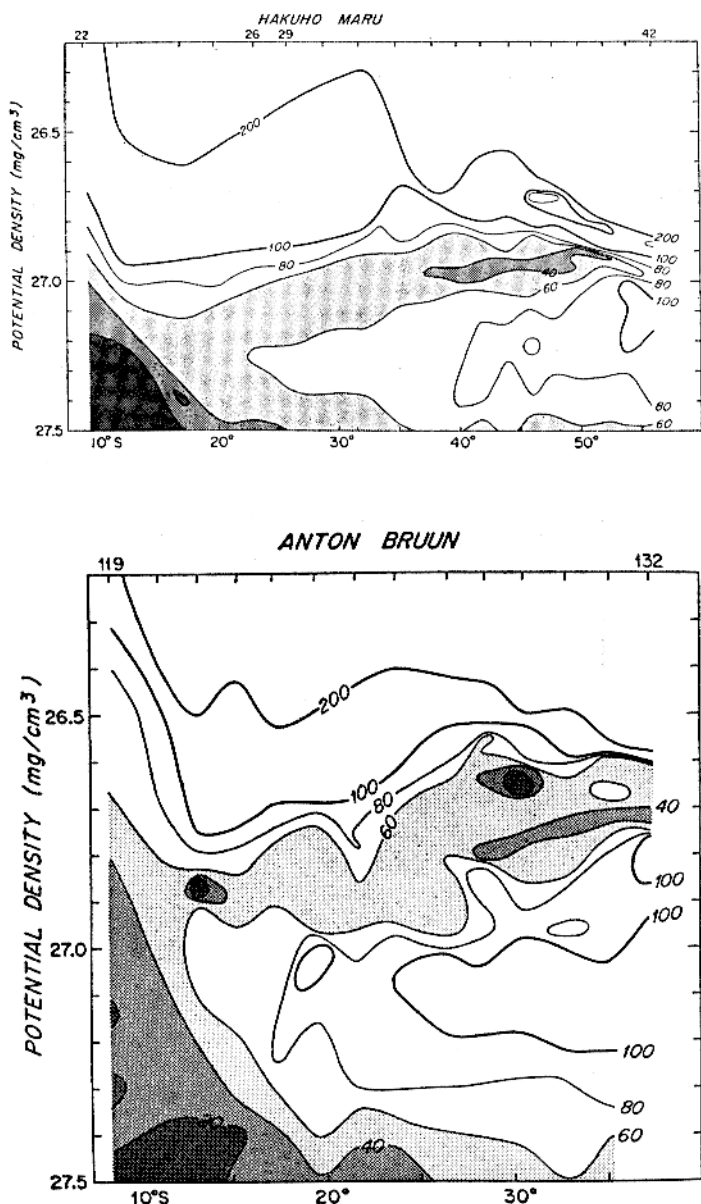


Figure 9. South Pacific and Indian: Meridional potential vorticity [ $fE$  in  $10^{-14} \text{ cm}^{-1} \text{ sec}^{-1}$ ] sections with potential density as section ordinate. Section locations on Figure 1. Shading as Figure 7. The calculation of  $E$  has been made using potential density increments of  $.02 \text{ mg}/\text{cm}^3$ . (a) Western South Pacific: *Hakuho Maru* station 22-26, 29-42, occupied between December 9, 1968 and January 14, 1969. (b) Southwestern Indian: *Anton Bruun*, IIOE cruise 2, stations 119-132, occupied between June 6 and July 2, 1963. Wyrki (1971) includes color sections of potential temperature, salinity, potential density and nutrients.

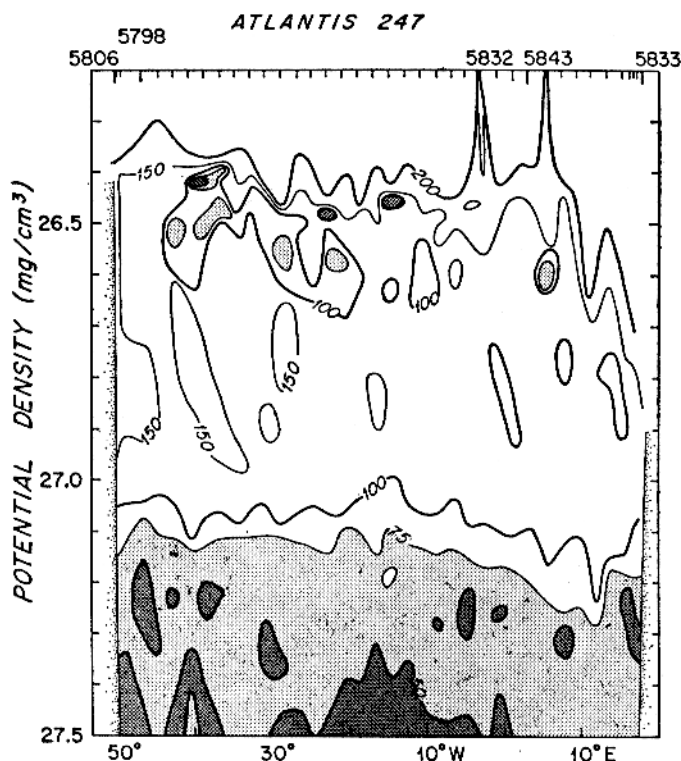
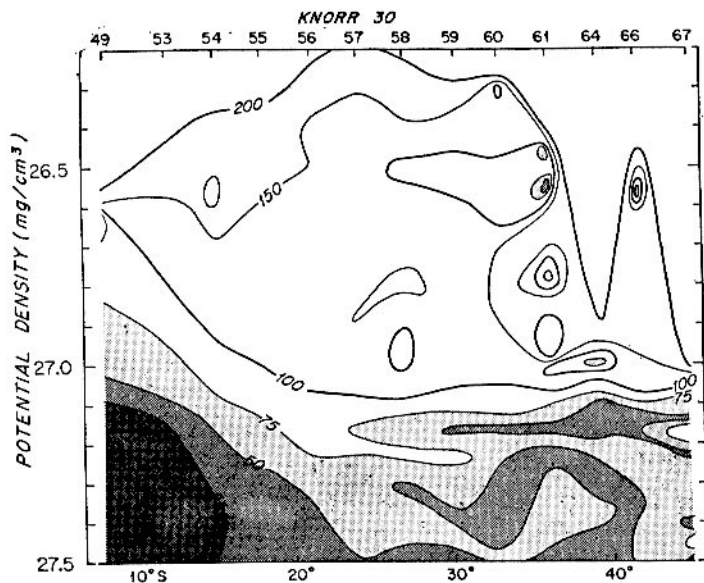


Figure 10. South Atlantic potential vorticity [ $fE$  in  $10^{-14}\text{cm}^{-2}\text{sec}^{-1}$ ] sections with potential density as section ordinate. Section locations are included in Figure 1. The calculation of  $E$  has been made using potential density increments of  $.02\text{ mg/cm}^3$ . Shading as in Figure 3c. (a) Zonal section along 32S: *Atlantis 247*, stations 5798 and 5806-5843, occupied on April 11 and between April 26 and June 3, 1959. Fuglister (1960) includes color section of temperature and salinity, with depth as section ordinate. (b) Quasi-meridional section, western basin: *Knorr 30*, GEOSECS Expedition stations 49, 53-61, 64, 66 and 67, occupied October 29 and December 9, 1972. Bainbridge (1980) includes color sections of potential temperature, salinity, potential density, oxygen, nutrients, and other quantities, with depth as section ordinate. A meander of the circumpolar currents intersects the section at station 64, a region studied in considerably more detail by Gordon (1981).

The Mode Water of the South Atlantic is weak and its distribution is of very limited lateral extent. In the South Atlantic the Subantarctic Zone lies near 40S (Fig. 1). Data coverage is sparse this far south in the Atlantic, but at 32S and farther north there is a fine set of zonal transects from the IGY (Fuglister, 1960). Figure 10a shows the potential vorticity section for 32S, while Figure 10b shows a meridional section from the GEOSECS Atlantic expedition. These two sections exhibit a weakly developed potential vorticity minimum layer at a density near  $\sigma_\theta = 26.5\text{ mg/cm}^3$ . The other IGY transects lie at 24, 16, and 8S, and none of these show



low potential vorticity influence in the density field of the main pycnocline. The distribution of Subantarctic Mode Water of the South Atlantic Ocean is thus much intensified poleward and westward compared to the Subantarctic Mode Water in the South Pacific and southern Indian Oceans (Fig. 1).

An additional irregular potential vorticity layer exists in the western South Atlantic near  $\sigma_\theta = 27.1\text{--}27.4$   $\text{mg}/\text{cm}^3$  (Fig. 10). The properties of this layer are traceable to the deep convection in the Subantarctic Zone of the southeastern Pacific and Drake Passage (Figs. 1, 8, and appendix). The Falkland Current carries this water northward along the Argentine continental shelf to about 35S, where it encounters the southward flowing Brazil Current. The Brazil Current overrides the heavier Falkland Current waters, the superimposed system then turns eastward within the Subantarctic Zone of the South Atlantic. Some further discussion of this confluence is contained in Gordon (1980). Figure 11 shows a GEOSECS station from the region where this overriding occurs. The low potential vorticity layer at 800 m represents the Drake Passage variety of Mode Water carried northward by the Falkland Current. The subtropical gyre recirculation then leads to a low potential vorticity layer at the base of the main pycnocline of the southwestern Atlantic. The layer is unfortunately at the edge of the resolution by discrete bottle sampling, and a complete description must await the analysis of data from well-calibrated continuous profiling instruments. The strength of influence of the Falkland Current is an important parameter in interpretations of the origin of the Antarctic Intermediate Water in the subtropical gyre of the South Atlantic (McCartney, 1977; Georgi, 1979; Molinelli, 1981; and Piola and Georgi, 1982).

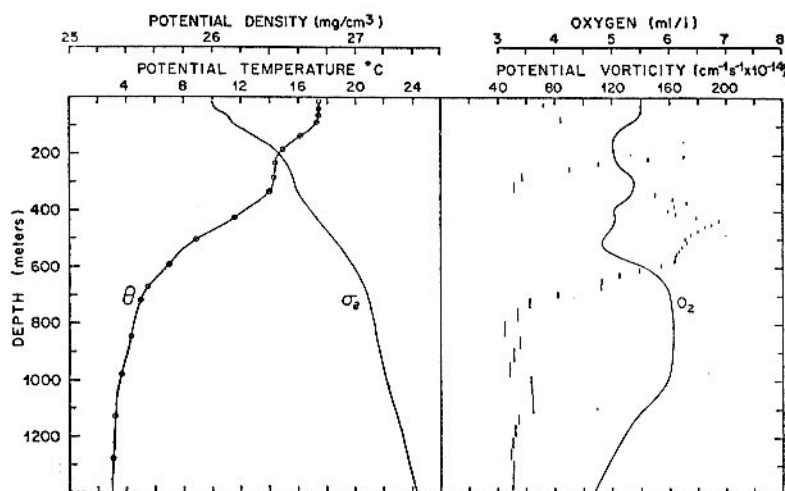


Figure 11. Hydrographic station 66 from the GEOSECS Expedition: *Knorr* cruise 30, station occupied December 8, 1972, at  $41^{\circ}32'S$ ,  $50^{\circ}57'W$ , in the region of confluence between the Brazil and Falkland Currents. Two low potential vorticity layers occur, at 300 m and near 800-1000. The shallower is the locally convected Subantarctic Mode Water of the South Atlantic, with  $\sigma_{\theta} \approx 26.58 \text{ mg/cm}^3$ ,  $\theta = 14.2^{\circ}\text{C}$ ,  $S = 35.53\text{‰}$ ,  $O_2 = 5.4 \text{ mg/l}$ , and potential vorticity of  $51.5 \times 10^{-19} \text{ cm}^{-1}\text{s}^{-1}$ . The deeper layer is less sharply characterized, but the lowest potential vorticity,  $44.4 \times 10^{-19} \text{ cm}^{-1}\text{s}^{-1}$ , occurs at  $\sigma_{\theta} = 27.14 \text{ mg/cm}^3$ ,  $\theta = 4.5^{\circ}\text{C}$ ,  $S = 34.23\text{‰}$ , and  $O_2 = 6.06 \text{ ml/l}$ . These denser modal properties are quite close to those of the deep convection in the Subantarctic Zone of the eastern South Pacific and Drake Passage (Fig. 8 and appendix). The  $\theta$ ,  $\sigma_{\theta}$ , and  $O_2$  curves have been interpolated from discrete samples at the depths indicated by dots on the  $\theta$  curve. The potential vorticity is calculated for potential density layers of thickness  $\Delta\sigma_{\theta} = .02 \text{ mg/cm}^3$ .

*b. North Atlantic Ocean.* The impact of deep convection in winter on the subpolar North Atlantic is extensive. On the chart in Figure 12, a region where convection extends deeper than 200 m is shown, based on the study by McCartney and Talley (1982). The northward flow of the North Atlantic Current is the source of warm water (Worthington's "upper thermocline" and "middle thermocline" waters) for this region. This Current turns offshore near  $50^{\circ}\text{N}$ . The region of deep convection is arrayed around this eastward-flowing warm water source. The potential density of these outcropping mixed layers is included on the chart: ranging from less than  $26.9 \text{ mg/cm}^3$  to greater than  $27.7 \text{ mg/cm}^3$ . The densest variety, outcropping in the Labrador Sea, represents the convective source of Labrador Sea Water, a water mass that exerts a strong influence on the characteristics of the subtropical North Atlantic water column near the base of the main pycnocline (Talley and McCartney, 1982). This particular dense variety communicates with the subtropical North Atlantic via the Deep Western Boundary Current. Figure 13 shows three potential



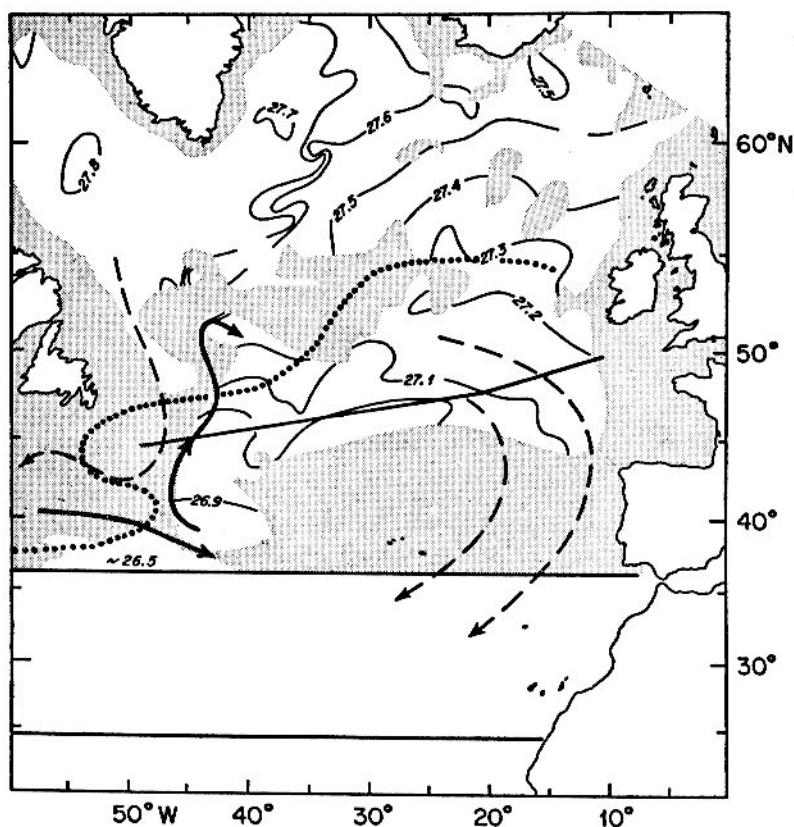


Figure 12. Potential density [ $\sigma_\theta$  in  $\text{mg}/\text{cm}^3$ ] of deep convective outcropping in late winter north of  $36^\circ\text{N}$  in the central and eastern North Atlantic: mixed layer depth greater than 200 m, based on charts from McCartney and Talley (1982). Norwegian and Greenland Seas are excluded. The shaded area indicates mixed layer depth less than 200 m for the region north of  $36^\circ\text{N}$ . Potential temperatures range from warmer than  $14^\circ\text{C}$  (near  $38^\circ\text{N}$ ,  $45^\circ\text{W}$ ) to colder than  $3.5^\circ\text{C}$  (near  $60^\circ\text{N}$ ,  $53^\circ\text{W}$ ). A small region of the Eighteen Degree Water ( $\sigma_\theta \approx 26.5 \text{ mg}/\text{cm}^3$ ) appears in the southwestern corner of the chart, bounded to the northeast by the Gulf Stream (arrow). Worthington's interpretation of the axis of the North Atlantic Current for the temperature range  $7^\circ\text{--}12^\circ\text{C}$  is shown east of Newfoundland and Labrador (Worthington, 1976; Fig. 26). Two advection paths are schematically indicated by dashed lines: a direct anticyclonic recirculation from the winter outcropping between  $\sigma_\theta \approx 27.0 \text{ mg}/\text{cm}^3$  and  $\sigma_\theta \approx 27.2 \text{ mg}/\text{cm}^3$ , and advection as part of the Deep Western Boundary Current from the Labrador Sea southward inshore of the North Atlantic Current. The solid lines show the locations of sections used in Figures 3, 5, 13 and 14. The dotted line is the axis of zero wind stress curl from Leetmaa and Bunker (1978).

vorticity sections crossing this Current. The Labrador Sea Water appears as a low potential vorticity layer near  $\sigma_\theta = 27.8 \text{ mg}/\text{cm}^3$ . On each section, the lowest potential vorticity is found on the inshore edge of this density surface, and these lowest

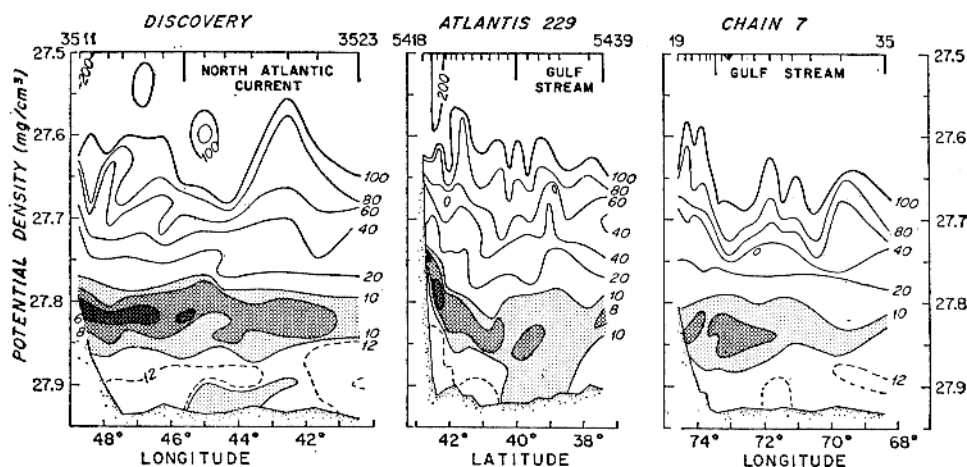


Figure 13. North Atlantic potential vorticity [ $fE$  in  $10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ ] at abyssal densities for sections crossing the Deep Western Boundary Current. Section locations on Figures 1, 4 and 12. Section ordinate is potential density. Shading has been chosen to emphasize the low potential vorticity layer of the Labrador Sea Water: single, double and triple intensity denoting, respectively, less than 10, 8 and  $6 \times 10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ . Boundaries of the North Atlantic Current and Gulf Stream based on shallow water indicators are given. Note that  $\sigma_\theta = 27.5 \text{ mg/cm}^3$  falls near the bottom of the subtropical main pycnocline of the North Atlantic (Fig. 3b). The calculation of  $E$  has been made using potential density increments of  $.02 \text{ mg/cm}^3$ . (a) East of Grand Banks of Newfoundland. Data from *Discovery II*, IGY cruise 1, stations 3511-3523, occupied between April 16 and April 19, 1957 (western end of same section used in Fig. 14). (b) South of Grand Banks of Newfoundland. Data from *Atlantis* cruise 229, stations 5418-5439, occupied between November 12 and November 17, 1956 (northern end of 50W section used in Figure 3). Station 5437 has bad salts in part of the deep cast, and has been omitted. (c) East of Cape Hatteras. Data from *Chain* cruise 7, stations 19-35, occupied between April 19 and April 22, 1959 (western end of 36N section used in Fig. 5).

values are higher on the southern section than on the northern section. At 48N and 50W the lowest values are inshore of the stations defining the inshore edge of the North Atlantic Current and the Gulf Stream. Farther south, the Gulf Stream is adjacent to the western boundary, and the Deep Western Boundary Current must pass under the Stream to continue its southward flow along the continental slope. This occurs off Cape Hatteras, and has been described by Richardson (1977). The 36N section in Figure 13 passes through this region, and the lowest values of potential vorticity of the Labrador Sea Water intrude under the inshore half of the Gulf Stream. In Talley and McCartney (1982), a more complete study is made of the geographical distribution and time variability of this low potential vorticity layer.

Influence of some of the lighter varieties of the Subpolar Mode Water of the North Atlantic can be seen in the two zonal sections in Figure 5. At 36N there is a low potential vorticity layer east of 35W at a potential density near  $\sigma_\theta = 27.15$

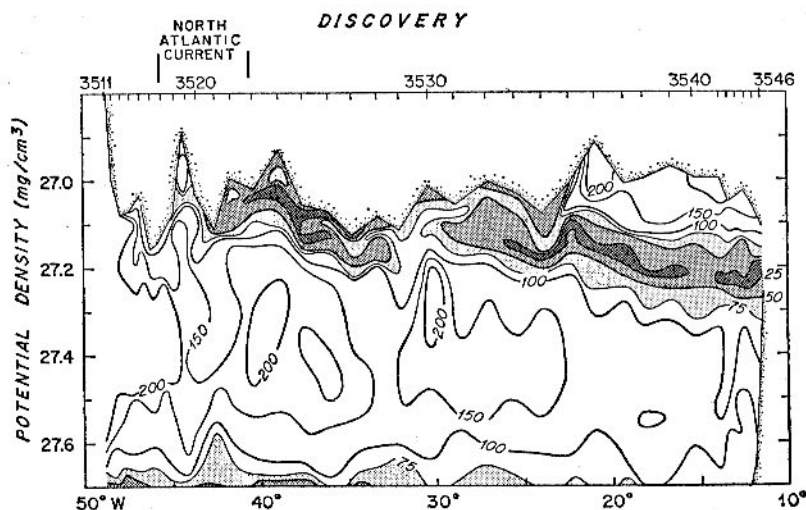


Figure 14. North Atlantic potential vorticity [ $fE$  in  $10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ ] at nominally  $48^\circ\text{N}$ , with potential density as the section ordinate. Section location on Figures 1, 4 and 12. Section from *Discovery II*, IGY cruise 1, stations 3511-3546, occupied between April 16 and April 22, 1957. Fuglister (1960) includes sections of temperature and salinity along this line, with depths as the section ordinate. The North Atlantic Current crosses the section between stations 3517 and 3523, with northward flow. Shading has been chosen to match that of Figure 5: single, double and triple intensity denoting, respectively, less than 75, 50, and  $25 \times 10^{-14}\text{cm}^{-1}\text{sec}^{-1}$ . The low potential vorticity layer near  $\sigma_\theta = 27.0 - 27.2 \text{ mg/cm}^3$  is just below the sea surface in this early spring data. The calculation of  $E$  has been made using potential density increments of  $.02 \text{ mg/cm}^3$ .

$\text{mg/cm}^3$ , and the 24N section shows a weaker, more intermittent low potential vorticity influence at the same density. This density level outcrops near  $50^\circ\text{N}$  in the eastern North Atlantic (Fig. 12); the low potential vorticity layer at  $36^\circ\text{N}$  is therefore about 800 miles south of its convective source region. This direct evidence of southward advection in the upper water column does not appear to have been previously noted. While the pycnostad character of this Mode Water is obvious from vertical profiles of density at a station, the thermostad and halostad character is masked in temperature and salinity profiles by the presence of the Mediterranean water at short distances beneath the potential vorticity minimum that defines the pycnostad. At  $36^\circ\text{N}$  this Mediterranean water is marked by the salinity inverting below  $\sigma_\theta \approx 27.2\text{-}27.4 \text{ mg/cm}^3$ , reaching a maximum at  $\sigma_\theta \approx 27.5\text{-}27.7 \text{ mg/cm}^3$ . The Mode Water pycnostad lies above the salinity minimum, and is separated from the salinity maximum by a layer of higher potential vorticity. At the level of the Mediterranean water, the large lateral salinity gradients make it appropriate to use a density parameter referenced to an intermediate pressure. In Talley and McCartney (1982)  $\sigma$  referenced to 1500 db is used to study the temporal and spatial

variability of the potential vorticity and other properties of the Labrador Sea Water.

The characteristics of winter deep convection at the sea surface in the subpolar North Atlantic are discussed more completely in McCartney and Talley (1982). Convection depths can be large. At  $\sigma_\theta = 27.1$  and  $27.2 \text{ mg/cm}^3$ , the convection depth can be over 500 m, which leads to very low potential vorticity values at these densities. Figure 14 shows a potential vorticity section for a transect from the Grand Banks of Newfoundland to Ireland in early spring 1957. The transect passes through the convection region for the lighter varieties of Subpolar Mode Water. There is a seasonal pycnocline starting to develop, and the low potential vorticity layer is capped by it and isolated from the sea surface, particularly in the eastern end of the section (later in time). The potential vorticity minimum layer is very strong, and indicates the local persistence of low potential vorticity acquired by local vertical convection, perhaps occurring less than a month preceding the section. This core ranges in potential density from around  $\sigma_\theta = 27.04 \text{ mg/cm}^3$ , immediately offshore of the North Atlantic Current, to  $\sigma_\theta = 27.22 \text{ mg/cm}^3$  offshore of Ireland. This range of densities of the Subpolar Mode Water matches quite well with that characterizing the potential vorticity minimum layer at 36N in Figure 5.

The magnitude of southward advection in the upper 850 m of the eastern basin of the North Atlantic has been recently estimated by Saunders (1982) as about  $7 \times 10^6 \text{ m}^3/\text{sec}$ . This depth range (0-850 m) encompasses the low potential vorticity layer being described here. So while direct evidence of southward advection is seen in the potential vorticity distribution, it is not in disagreement with the circulation chart of Worthington (1976, Fig. 42), which indicates a transport of less than  $10 \times 10^6 \text{ m}^3/\text{sec}$ .

## 5. Discussion

The Mode Water phenomenon is related to an older concept in physical oceanography. The importance of processes acting along isopycnals was emphasized by Montgomery (1938) in his study of property distributions in the tropical North Atlantic. For isopycnals in the upper water ( $\sigma_t \leq 27.0 \text{ mg/cm}^3$ ) he found that property distributions could be rationalized under the assumption of a lateral advective-lateral diffusive interior region on an isopycnal ["lateral" meaning along potential density surfaces]. At the edges of an isopycnal, nonisopycnal processes provide source regions for specific combinations of temperature, salinity, and other properties. He found the dominant source region for several isopycnal surfaces to be the regions of sea-surface outcropping of the isopycnals.

The Montgomery rationale of property distribution was applied by Iselin (1939) to the question of the nature of the mechanisms responsible for the quasi-linear temperature-salinity correlation of the subtropical main thermocline. In an earlier study, Iselin (1936) speculated that this quasi-linearity resulted from vertical mix-

ing between waters above and below the main thermocline. The departures from strict linearity were attributed to a mild lateral advective influence of Subarctic and Mediterranean water. In his later study, he noted the general close correspondence between the temperature-salinity correlation at the sea-surface mixed layer in late winter and that of the subtropical main thermocline. Detailed examination using the March sea-surface charts of Böhnecke (1936) led him to suggest several compact regions of the sea surface that appeared to be the origin of the thermocline correlation in other regions through the Montgomery scheme of lateral advection and lateral diffusion. A similar correspondence and interpretation was earlier noted in the South Atlantic main thermocline by Wüst (1935). Sverdrup *et al.* (1942) found similar quasi-linear temperature-salinity correlations throughout the world ocean, and coined the name "Central Water." They found the general correspondence between late winter sea-surface properties and the Central Water of a subtropical gyre to be an ubiquitous feature in the world ocean.

Mode Waters are by their very definition major contributors to regional volumetric water mass characteristics. From the unpublished regional tables used to compile Worthington's (1980) volumetric census of the temperature-salinity characteristics of the world ocean, simplified charts have been prepared for the southern Indian Ocean and South Pacific Ocean (Fig. 15). The high volume classes trending from warm-salty to cold-fresh are the volumetric manifestation of the Central Waters of these oceans. The two curves on each of these charts are the temperature-salinity correlations for the core of the Mode Water layers in Figure 7. The data points are the Subantarctic Zone observations of deep convection in winter used in Figure 8 (McCartney, 1977, and appendix of present paper). The convection data lie on the fresh side of the Central Water Curve, the poleward sections fall in the middle of the Central Water classes, while the equatorward sections fall toward the salty side of those classes.

The Mode Waters represent a particular example of the ventilation of Central Waters. As conceptualized by Montgomery (1938), Iselin (1936, 1939), Wüst (1935) and Sverdrup *et al.* (1942), certain regions of sea-surface outcropping are source regions for particular components of Central Water. All sea-surface outcroppings for a given isopycnal could conceivably act as source regions. The observations of these older studies indicated that the conditions in the late winter outcropping regions dominate over those of other seasons. This dominance remained a puzzle for quite some time, but an explanation has been recently offered by Stommel (1979). In a subtropical gyre the convergent Ekman layer at the sea-surface pumps fluid downward into the geostrophic (Sverdrup) regime beneath the Ekman layer, and it does so all year around. On an isopycnal a streamline extending southward would therefore be expected to have a spatially cyclic variation of properties corresponding to the seasonal cyclic variation of properties in the outcropping region. This is not observed. The nonwinter outcropping of a given isopycnal occurs

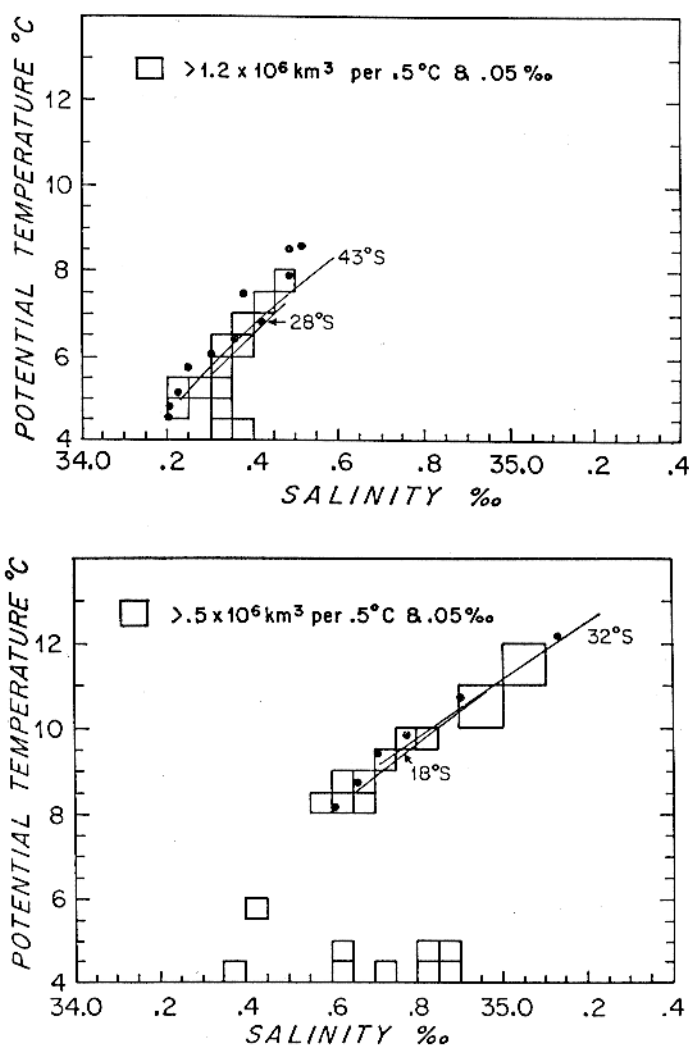


Figure 15. Largest volume potential temperature-salinity classes of the warm water ( $\theta \geq 4^\circ\text{C}$ ), from unpublished tables used to construct the world ocean census (Worthington, 1980). The curves on the  $\theta$ - $S$  correlations for the core (potential vorticity minimum) of the low potential vorticity layers in the four sections of Figure 7. The dots are the  $\theta$ - $S$  values of the winter deep convection observations indicated on Figure 8 and tabulated in McCartney (1977) and the appendix to the present paper. (a) South Pacific; (b) Southern Indian.

farther poleward than its winter outcropping. The water pumped downward at these higher latitude sites moves equatorward in the geostrophic regime beneath the surface layer, but not fast enough to avoid being overtaken in fall and winter by the location of the outcropping of an isopycnal shifting southward. The nonwinter mixed

layer products are then stirred into the winter mixed layer of that isopycnal. Hence, only the late winter and early spring outcropping characteristics survive the annual cycle and escape to advect around the anticyclonic gyre.

The older studies used the tendency toward conservation of temperature, salinity and oxygen to deduce likely advection paths from outcropping source regions. The present study uses the tendency toward conservation of another property, potential vorticity. In the case of a Mode Water, the outcropping is deep convection rather than shallow. This outcropping source, like all winter outcroppings, contributes particular temperature, salinity and oxygen correlations to the regional Central Water. But it is the low potential vorticity due to its deep convective origin that makes the Mode Water contribution to the regional Central Water so visually and volumetrically dramatic.

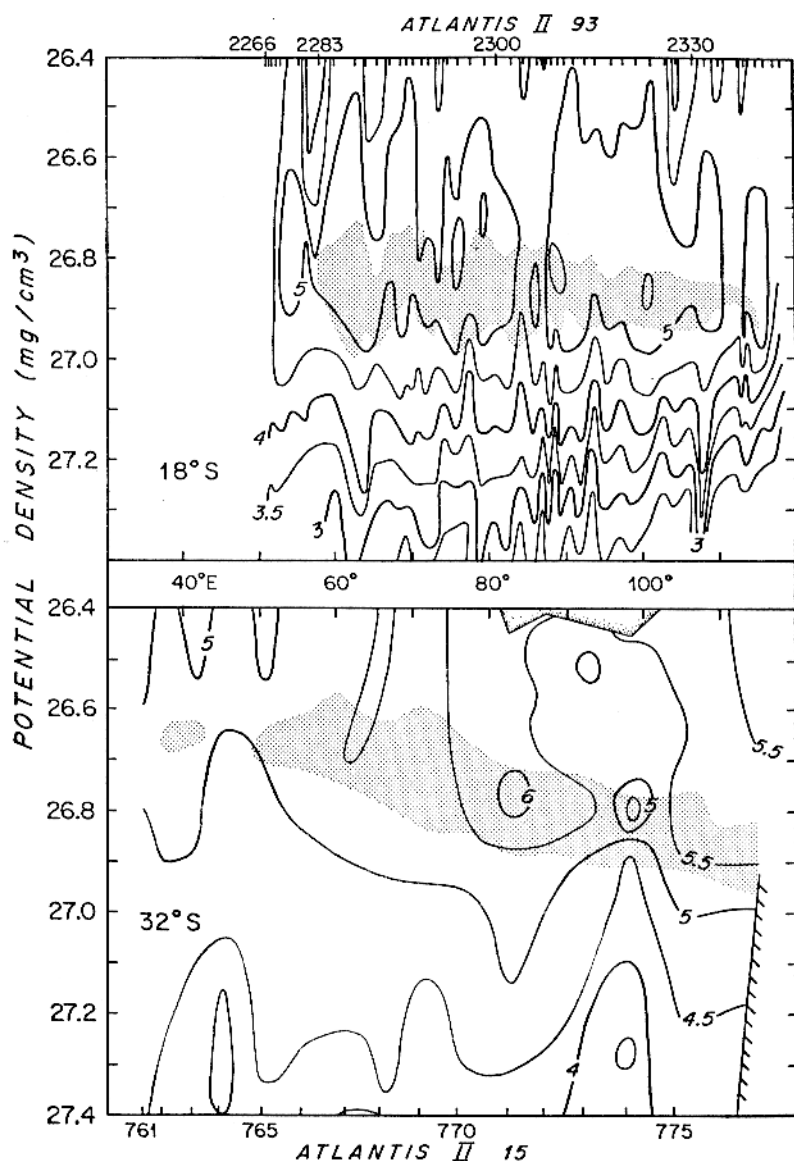
The strong influence of low potential vorticity at subtropical latitudes is certainly indicative of advection from high latitudes. However, it is clear that mixing does affect the Mode Water distribution. For example, potential vorticity is consistently higher on the equatorward sections or ends of sections than on the poleward sections or ends of sections (Figs. 3b, 5, 6, 7, 9 and 10). The temperature-salinity relationship is not constant (Fig. 15). Finally, the oxygen level of the Mode Water seems lower at low latitudes. This is illustrated in Figure 16, which shows oxygen sections for the same data set used in Figure 7. The Mode Water is a high oxygen layer, consistent with its convective origin, but the levels are lower on the equatorward sections than on the poleward sections.

Montgomery's (1938) lateral advective/lateral diffusive balance is not the only process scheme in which the Mode Water distributions in the subtropical gyres can be rationalized. Schmitt (1981) discussed the possible role of double-diffusive mixing in determining the shape of the Central Water temperature-salinity correlation. Along this line, one could conceive of a lateral advective/cross-isopycnal diffusive balance as an alternate to the pure lateral balance. In such a scheme, temperature, salinity and potential density would increase following an advective path away from a convective source region, given a pycnocline with a warm-salty over cold-fresh Central Water. The density increase results from the contribution of the layer down-gradient salt, as opposed to heat, flux. The trend of temperature-salinity changes in Figure 15 fits this scheme, but evidence of significant density change following an advection path is difficult to find due to the breadth of density range associated with the Mode Water of a given ocean. The long time scale variability of convective source density further complicates the search for systematic spatial changes (Talley and Raymer, 1982; Talley and McCartney, 1982).

It takes more than the mere existence of deep convection at a given density somewhere within an ocean to result in a Mode Water influence of that density within the subtropical gyre of that ocean. Included on the chart in Figure 12 is the zero wind stress curl curve from Leetmaa and Bunker (1978). South of this line, the







within the cyclonic regime, that near  $\sigma_\theta = 27.8 \text{ mg/cm}^3$  in the Labrador Sea, shows evidence of a low latitude influence (Talley and McCartney, 1982). As discussed in section 4b, this influence occurs indirectly via a deep western boundary current rather than directly through the interior anticyclonic circulation.

The mid-latitude zero windstress curl contours for the rest of the world ocean are included in Figure 1. In general, the Mode Water formation and circulation regions

lie equatorward of this zero curl curve. Two exceptions occur, the major one being the subpolar North Atlantic just discussed. There is a lesser one around the tip of South America. Here as described in section 4a, the communication from the convection region in the southeastern Pacific and Drake Passage poleward of the zero curl line occurs indirectly as a western boundary current: the northward flowing Falkland Current.

An aspect of the Mode Water process that is poorly understood is the nature of the low latitude closure. Another way of thinking of a Mode Water convection region is as a source of mass for a density layer: air-sea cooling of the upper water column converts light water into a given heavier density at some annual average rate. As a result, somewhere else in that density layer, there must be a sink in which mass is removed from the density surface. Otherwise the volume of the density layer would increase with time. One type of sink is to make yet another denser variety of Mode Water out of a lighter Mode Water by further air-sea modification. This indeed does happen: the systematic progressions of the Subpolar Mode Waters. Another way is the Schmitt double-diffusive mixing process, which again would act to increase the density of a fluid parcel. Neither of these processes really helps, for they just transfer the mass flux to a denser level. Somewhere upwelling from dense to light water must occur, and generally this has been assumed to be small in magnitude but geographically distributed over large areas. This notion of concentrated sources and distributed sinks was developed for the abyssal waters beneath the main pycnocline [Stommel (1958) and Stommel and Arons (1960)]. The Mode Waters represent the same sort of process acting at intermediate depths rather than abyssal depths. This analogy between the abyssal situation and the pycnocline was first made by Worthington (1959) in connection with Eighteen Degree Water, but seems applicable to the general Mode Water case.

*Acknowledgments.* The author's participation in the R/V *Atlantis II* 18S cruise (July-August, 1976) and the OSS *Researcher* (April, 1977) cruise was funded by the Office of Naval Research under contract N00014-74-C-0262, NR 083-004. The New Zealand sector R/V *Knorr* cruise was funded by the National Science Foundation under grant OCE77-22885. The South American sector R/V *Atlantis II* cruise was funded by the National Science Foundation under grant OCE 78-22223. The R/V *Thomas Washington* data utilized in Figure 6 was kindly provided to the author by Peter Niiler. The analysis leading to this paper was jointly sponsored by the above contracts and grants, and by the Office of Naval Research under contract N00014-79-C-0071, NR 083-004.

This is contribution number 4379 of the Woods Hole Oceanographic Institution.

Mary Raymer's assistance with and perseverance through the four-year analysis of the material contained in this paper is greatly appreciated, as is the careful work of Karin Bohr and Doris Haight in preparing typescript. Conversations with many colleagues helped in the development of the ideas in this paper, with the comments and advice of Ray Schmitt, Lynne Talley, George Veronis and Val Worthington being particularly constructive and useful.

I would like to express my thanks and indebtedness to Val Worthington for his continued support and encouragement during all my years in oceanography, for providing me with open

access to all his fine data sets and his stimulating interpretations of them, for opening the door to my participation in numerous cruises, and for helping me keep track of my corks.

## APPENDIX

**Additional winter observations of deep convection in the Subantarctic Zone, and a comment on conditions in 1978.**

Ship/Investigator	Region	Date	Latitude	Longitude	Typical			
					Depth	Temp	Salinity	$\sigma_\theta$
<i>Sprightly</i> R.O.R.Y. Thompson	Extreme SE Indian	IX 78	48°S	145E	300-500	8.6	34.51	26.82
	Extreme SW Pacific	X 78	48°S	152E	300-500	8.6	34.51	26.82
<i>Knorr</i> M. S. McCartney	South of New Zealand	X 78	52°S	174E	400	7.5	34.39	26.89
<i>Atlantis II</i> M. S. McCartney	SE Pacific	IX 80	57°S	89W	500	5.1	34.22	27.06
			57°S	78W	500	4.8	34.21	27.09
			57°S	71W	500	4.5	34.20	27.12

**Comment:** The 1978 observations appear anomalously fresh and light. This freshness is relative to older observations of the Mode Water of the western South Pacific. It is also relative to the water column structure at the time of the 1978 observations: the mixed layer lies above warmer, saltier, heavier water that has the characteristics closer to the older observations of the regional Mode Water. It appears there that convective formation was incomplete in 1978. As cooling proceeds through the winter, it convectively mixes down the fresh surface layer of the Subantarctic Zone—a product of the excess of precipitation over evaporation for the Zone. In this year, this local convection reached only to the top of the local pycnostad, the core of which was about .01-.02 mg/cm<sup>3</sup> denser. See Thompson and Edwards (1981) for a discussion of the *Sprightly* data and the 1978 situation.

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Printed in U.S.A. for the Sears Foundation for Marine Research,  
Yale University, New Haven, Connecticut, 06520, U.S.A.  
Van Dyck Printing Company, North Haven, Connecticut, 06473, U.S.A.

Received: 6 June, 1979; revised: 10 March, 1982.