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Origin and ages of mode waters in the Brazil-Malvinas Confluence region during austral winter 1994

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Abstract. The ventilation of the main thermocline associated with the formation of Subtropical Mode Water (STMW) and Subantarctic Mode Water (SAMW) within the Brazil/Malvinas Confluence region is investigated using satellite data, hydrographic data, and dissolved CFCs as transient tracers. During the winter of 1994, two types of STMW were observed. Both types, 26.24 σ_θ and 26.46 σ_θ were formed within the warm pool of the South Atlantic Central Water (SACW). The SAMW is found on the 27.10 σ_θ density surface. This surface lies in the minimum salinity layer of the Antarctic Intermediate Water (AAIW). The mode waters are dated using CFC ratios. To our knowledge, this is the first estimate of the age of the mode waters in the region using the CFC-113:CFC-11 ratio method. The lighter STMW was being formed during the cruise. The heavier STMW was found to be 6 ± 3 years old and is thought to have circulated in the subtropical gyre without losing its primary properties. The SAMW, or the lightest AAIW has an age of 3 ± 2 years. This water is very young compared with the oldest (10 ± 5 years) and heaviest component of the AAIW, which circulates within the subtropical gyre. The formation of the STMW in the confluence region is dependent on the southward extension of the Brazil Current.

1. Introduction

The upper level circulation of the Brazil-Malvinas Confluence region at 38°S on the continental slope of South America is characterized by the encounter of the warm and salty South Atlantic Central Water (SACW) carried poleward by the Brazil Current (BC) and the cool and fresh Subantarctic Surface Water (SASW) carried northward by the Malvinas Current (MC). The MC turns southward after meeting the BC at 38°S. However, the BC continues beyond 38°S before retroflecting northward in the interior of the basin, resulting in meanders. The southward extension of warm water exposed to relatively harsh climatic conditions favors the formation by convection of Subtropical Mode Water (STMW), while the northward flow of the MC transports Subantarctic Mode Water (SAMW) toward the confluence region.

The SAMWs were identified by *McCartney* [1977, 1982]. He distinguishes two types of SAMWs, the heavier one on the density surface 27.1 σ_θ and the lighter one on the density surface 26.5 σ_θ. Both have various regions of formation: the heavier SAMW is formed mainly in the subantarctic region, and the lighter one is formed mostly within the Subtropical Gyre [*Provost et al.*, this issue]. Because of their different regions of formation, we decided to follow *Provost et al.*'s mode water nomenclature, which classifies as STMW mode waters lighter than 27.0 σ_θ and as SAMW mode waters heavier than 27.0 σ_θ.

The STMW is found north of the Subtropical Front or north of the southward extension of the BC. *Provost et al.* [this issue] describe the characteristics, extent, thickness, and region of formation of the Subtropical Mode Waters in the South Atlantic. In the confluence region, three varieties of STMWs with densities lower than 27.0 σ_θ are found. We shall subsequently refer to the three types of STMW as $STMW_1$, $STMW_2$, and $STMW_3$ in the order of lightest to heaviest. The lightest is found on the 26.24 σ_θ density surface with a potential temperature between 17°C and 18°C and salinity greater than 36.0. This type is observed mainly at 30°-35°S and may be advected southward in the confluence region [*Arhan and Mercier*, submitted manuscript, 1999; *Provost et al.*, this issue]. $STMW_2$ is found near the 26.46 σ_θ density surface with a potential temperature between 14°C and 16°C and salinity varying from 35.5 to 35.9. This is the most common type found in the confluence region, and it is active in the ventilation of

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the main thermocline because the convected layer can reach a depth of 400 m [*Gordon*, 1981; *Provost et al.*, this issue]. The heaviest type, $STMW_3$, is observed around the 26.70 σ_θ density surface with a potential temperature between 12°C and 14°C and salinity less than 35.5. $STMW_3$ is found more often in the interior of the Argentine Basin and is a mixture of the SASW and the SACW. In general, convective overturning can occur on any isopycnal but the quantity of water formed depends on the extent of the outcrop of the isopycnal at the surface, which is larger for $STMW_2$ [*Provost et al.*, this issue]. $STMW_2$ corresponds to the lightest SAMW defined by *McCartney* [1977, 1982].

SAMW is formed in the Subantarctic Zone of the northern Drake Passage and is advected northward along the continental slope by the MC as part of the SASW where its properties are modified [*McCartney*, 1977, 1982; *Piola and Gordon*, 1989; *Talley*, 1996]. SAMW is the primary precursor of the Antarctic Intermediate Water (AAIW) in the South Atlantic Ocean. The SAMW is found within the density range 27.05-27.15 σ_θ, while the AAIW has a density of 27.05-27.25 σ_θ. The SAMW (or the lightest AAIW, as we shall refer to it) is detectable by its relatively high concentration of dissolved oxygen (about 6 mL L^{-1} [*McCartney*, 1982]). The spreading of the SAMW in the South Atlantic Ocean is linked to the AAIW circulation scheme. South of the confluence region, the SAMW, or the lightest AAIW, follows the path of the MC [*Piola and Gordon*, 1989; *Talley*, 1996]. North of the confluence region, the AAIW flows with the Subtropical Gyre [*Reid*, 1989; *Suga and Talley*, 1995; *Boebel et al.*, 1997; *Maamaatuaiahutapu et al.*, 1998]. Exchange between north and south components of AAIW is possibly achieved through ring formation and mixing [*Davis et al.*, 1996; *Talley*, 1996].

Temperature, salinity, and dissolved oxygen are traditionally used to detect and trace the evolution of the mode waters. For instance, the recently formed mode waters generally have a relatively high level of dissolved oxygen compared with neighboring water. A number of authors have investigated the ventilation of the thermocline by analysing the concentrations of dissolved CFCs [e.g., *Warner and Weiss*, 1992; *Haine et al.*, 1995]. The CFCs (specifically CFC-11, CFC-12, and CFC-113) have the advantage, in addition to their role as tracer, of providing the ventilation age, the time when the water left the surface. The ventilation age of a water mass can be determined by using either the CFC concentrations or the CFC concentration ratios [*Pickart et al.*, 1989; *Smethie*, 1993; *Warner and Weiss*, 1992]. The ratio method is preferred, however, because the inferred water mass age is independent of the effect of dilution by mixing with CFC-free water. The CFC-11:CFC-12 ratio is adequate for determining the age of a water mass that was at the surface before 1980. After this time the atmospheric CFC-11:CFC-12 ratio became constant as a result of a change in the use of CFC-producing goods. The CFC-113:CFC-11 or CFC-113:CFC-12 ratio can be used to age water that was at the surface after the time when the CFC-11:CFC-12 ratio became obsolete [*Wisegarver and Gammon*, 1988; *Haine et al.*, 1995; *Smythe-Wright et al.*, 1996]. The CFC-113:CFC-11 or CFC-113:CFC-12 ratio allows the determination of the age of water with a precision of less than a year [*Haine et al.*, 1995; *Smythe-Wright et al.*, 1996]. Such precision is appropriate in the detection of newly formed water parcels such as the mode waters in the confluence region. Very few investigations based on CFCs have been carried out to study the ventilation of the thermocline by mode water formation in the South Atlantic Ocean because of the difficulty of measuring CFCs. *Warner and Weiss* [1992] and *Weiss et al.* [1993] investigated the AAIW by analysis of CFC-11 and CFC-12 compounds during the South Atlantic Ventilation Experiment (SAVE), including a transect in the confluence region in March 1989. CFC-11 and CFC-12 data have been collected during the Confluence 4 cruise in the austral summer (January 1994) by *Takahashi et al.* [1997].

This study focuses on the conditions and mechanisms related to the formation of mode waters within the confluence region during the Confluence 5 cruise in September 1994. Satellite, hydrographic, and CFC data are combined to describe the upper level circulation and its variability.

2. Data and Methods

Various data sets were used to detect the mode waters and describe their formations. Sea surface temperature (SST) data were used to provide the large-scale picture of the surface circulation near the time of the Confluence 5 cruise. The SST images were obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory (California Institute of Technology) and have a resolution of 9 x 9 km^2. However, because of an intense cloud cover, there were no images (even composite) corresponding to the cruise period itself and the following 3 weeks. The images of the confluence region 14 days before the cruise show particularly cloud free conditions (Figure 1a). A composite image of sea surface temperature over the confluence region corresponding to September 12-15, i.e., 3 days before the beginning of the cruise, is shown in Figure 1b.

Maps of sea level anomaly from the TOPEX/POSEIDON altimeter were produced by the CLS Space Oceanography Division in Toulouse, France. These maps have a temporal resolution of 10 days and were created from values on a 1/4° grid. Three maps, two before and one after the cruise, were used to quantify the mesoscale activity and its evolution (Figure 2).

Hydrographic and tracer data were collected during the Confluence 5 cruise (September 17-23, 1994), in the west of the Argentine Basin on board the R/V *Holm-*

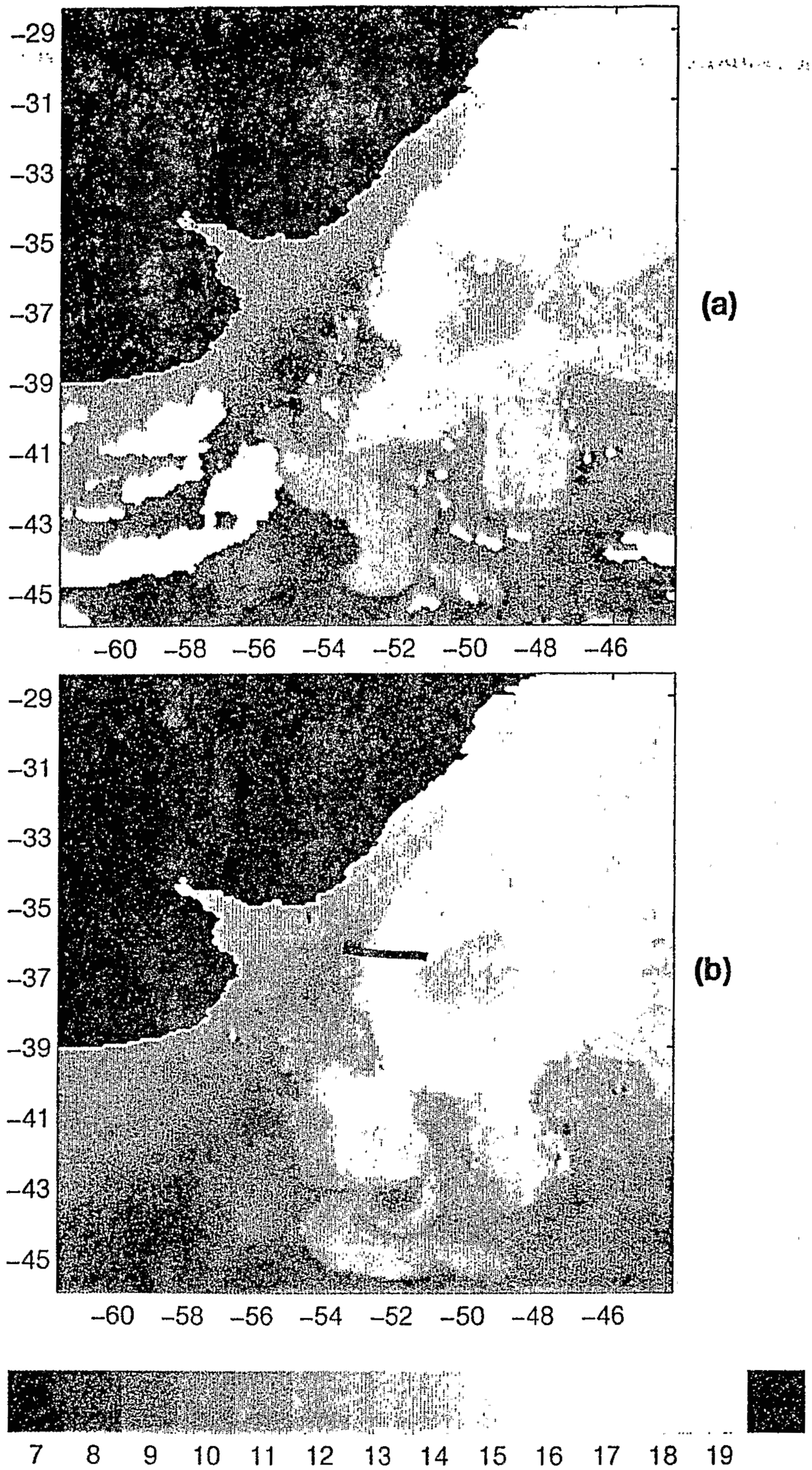


Figure 1. (a). Sea surface temperature in the confluence region on September 4, 1994 (i.e., 14 days before the cruise) showing particularly cloud free conditions. This 9 x 9 km^2 resolution image was provided by the NASA Physical Oceanography Distributed Active Archive Center (Jet Propulsion Laboratory). (b). Composite image of sea surface temperature over the confluence region corresponding to September 12-15, 1994, i.e. 3 days before the cruise. Resolution and source are same as figure 1a. The solid line is the section along which the conductivity-temperature-depth-oxygen (CTD-O^2) stations are located.

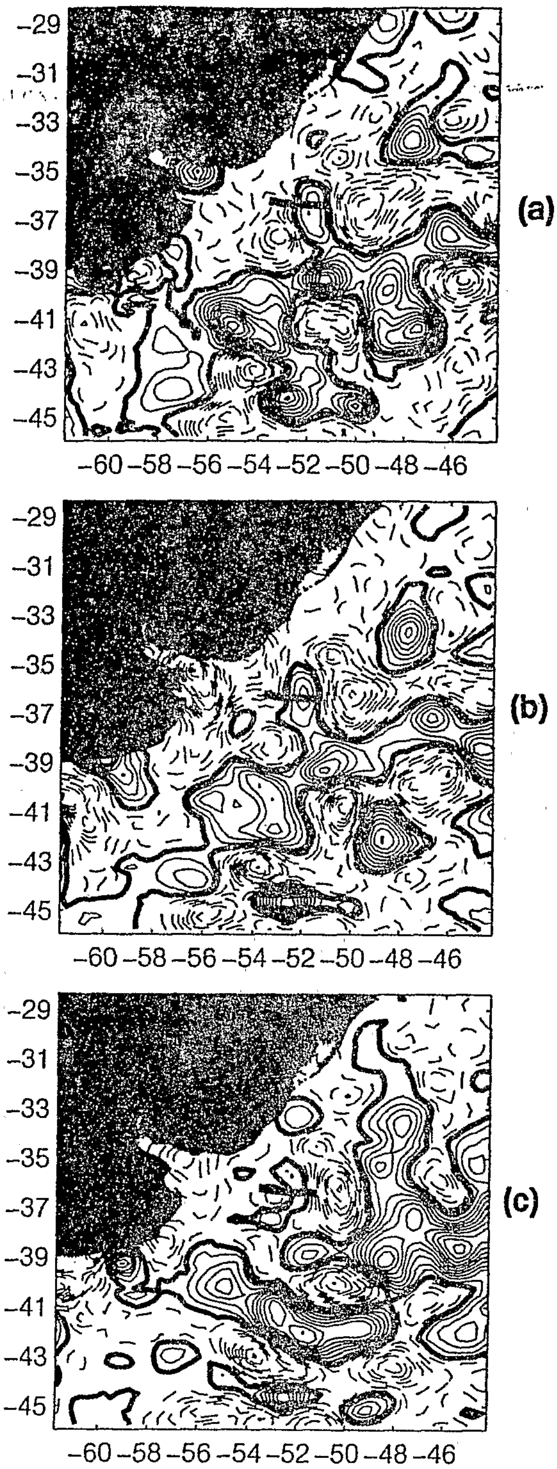


Figure 2. Sea level anomaly on (a) September 2, (b) September 12, and (c) September 22, 1994 (14 days before the cruise). The isoline interval is 5 dynamic centimeters (dyn cm). Dashed isolines correspond to negative anomalies. The zero isoline is bold. Source is P-Y. LeTraon, CLS-Argos.

berg. An east-west transect (Figure 1) was made at ~36.3°S, on the continental slope offshore from the Rio de la Plata. The section, perpendicular to the contours of the continental slope, catches the signal of the MC and the southward flowing portion of the BC as described by the sea surface temperature. Conductivity, temperature, depth, and oxygen data were obtained with a Sea-Bird SBE 9-11 instrument. The CTD-O^2 calibrations are detailed by *Kartavtseff* [1995]. When mode water is recently formed, the best tracer for detecting its presence is potential vorticity. A relative minimum in its vertical profile is the characteristic signature of a mode water. The potential vorticity q is determined from the conductivity-temperature-depth (CTD) data as $q = (f/\rho)\,(\Delta\sigma_\theta/h)$, where f is the Coriolis parameter, ρ is the density, $\Delta\sigma_\theta$ is the fixed potential density increment (here taken as 0.02 kg m^{-3}), and h is the distance between adjacent potential density surfaces. The quantity plotted is the magnitude of the potential vorticity which is negative in the Southern Hemisphere.

The concentrations of CFC-12, CFC-11, and CFC-113 were determined on board the ship using a classical purge and trap system [*Bullister and Weiss*, 1988] interfaced to a Shimadzu GC14 gas chromatograph with an electron capture detector. The analytical procedure was modified in order to separate CFC-12, CFC-11, and CFC-113 using a unibeads trap (at -45°C) and a chromatographic Quadrex capillary column of 75 m length [*Haine et al.*, 1995; *Happell et al.*, 1996]. The CFC data were calibrated using an air standard prepared in the Brookhaven Laboratory [*Happell and Wallace*, 1997], using the Scipps Institution of Oceanography (SIO) 1986 calibration scale [*Bullister and Weiss*, 1988] for CFC-11 and CFC-12, and a Climate Monotoring and Diagnostics Laboratory (NOAA, Boulder, Colorado) (CMDL) scale for CFC-113. For each station, calibrations were performed by injections of different standard aliquots. The CFC-12 data are of lower quality than the CFC-11 because of an inferior N_2O/CFC-12 peak separation. The peak separation of CFC-113 is satisfactory. However, the blank level determined from the concentrations of CFC-113 in deep samples (0.01 pmol kg^{-1}) is relatively high (but reproducible). Surface concentrations of all three CFCs are consistent with the expected solubility equilibrium values [*Warner and Weiss*, [1985] for CFC-12 and CFC-11 and *Bu and Warner*, [1995] for CFC-113). Age computations have been performed using the time evolution of CFC atmospheric mixing ratios from *S. Walker et al.* (personal communication, 1998) shown in Figure 3, assuming the water mass was in equilibrium with the atmosphere. According to the limits defined by the blank level on CFC-113 concentrations, CFC-113:CFC-11 ages are estimated with a precision of ±1 year in the upper layer and ±3 years below 1000 m, the latter being larger owing to the decreasing CFC values. We discuss the respective water mass "vintages" i.e., the year when the water mass was in equilibrium with the atmosphere.

3. Upper Layer Circulation

In the confluence region the poleward flowing BC, which carries the warm and salty water of the SACW,

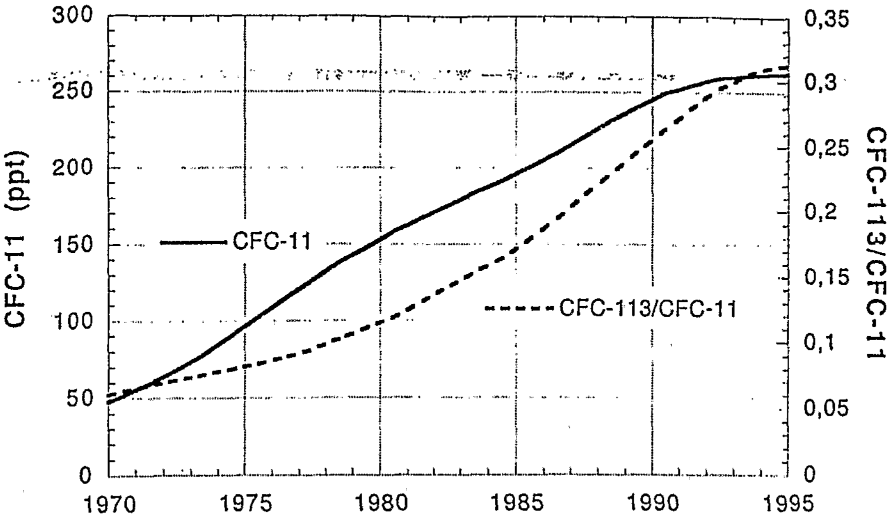


Figure 3. Evolution of the CFC-11 atmospheric content (solid line) and the CFC-113:CFC-11 atmospheric ratio (dashed line) for the Southern Hemisphere (S. Walker et al., personal communication, 1998).

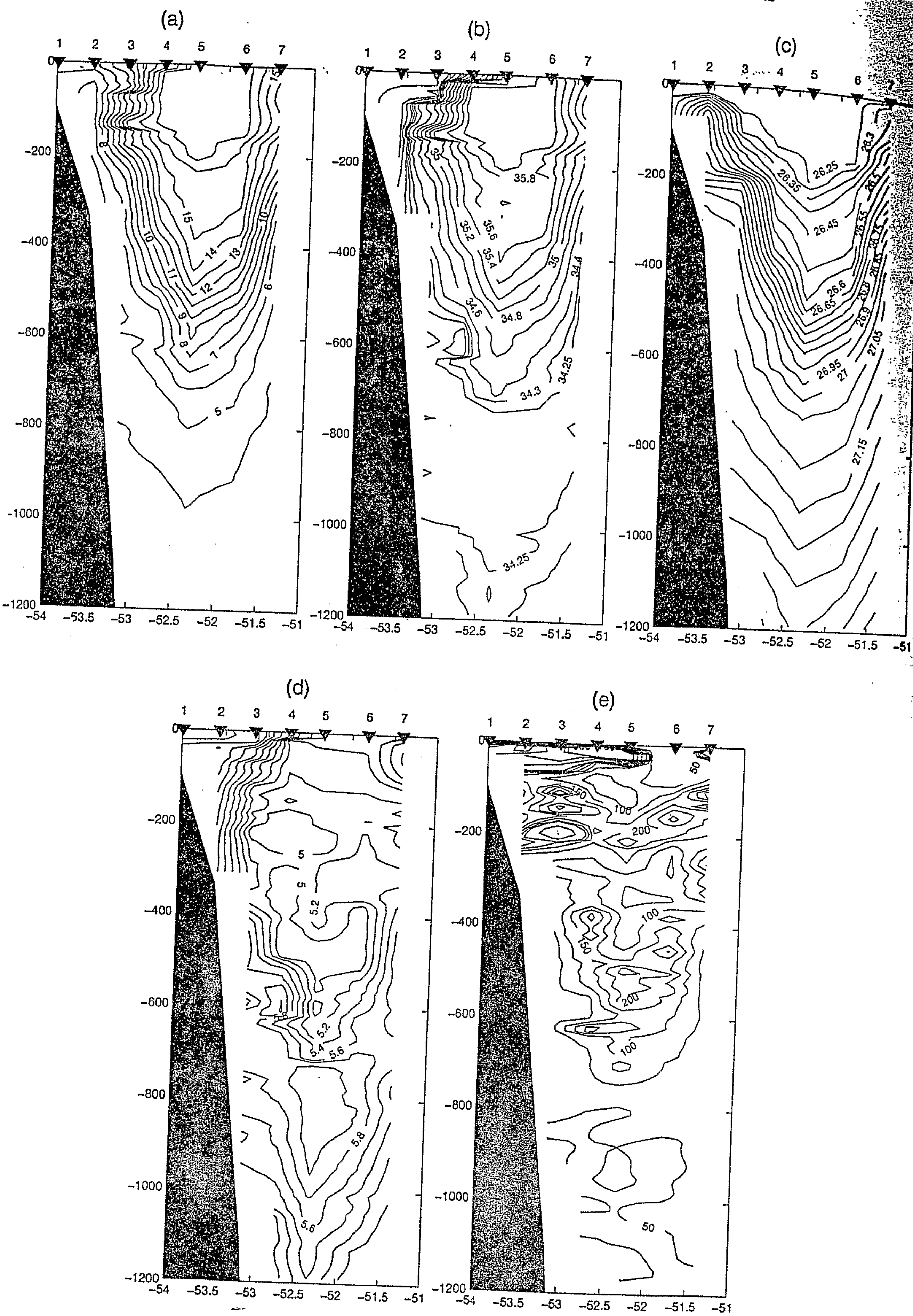
encounters the northward flowing MC, which transports the cooler and fresher water of the SASW (Figures 1 and 4). SST images depict the general situation 14 days (Figure 1a) and 3 days (Figure 1b) before the cruise. After meeting the MC at 38°S, the BC overshoot extends as far south as 45°S. Surface temperature in the BC decreases poleward, from about 19°C at 30°S to 14°C at 45°S. The SST images reveal numerous mesoscale structures and an intrusion of a cold-core ring at about 37°S, 50°W. The maps of sea level anomaly, 15 and 5 days before the beginning of the cruise (Figures 2a and 2b) and 1 day after the cruise was completed (Figure 2c), reveal the intensity of the mesoscale activity and the rapid evolution of the BC extension. The signature of the cold-core ring visible 15 days before the cruise is still well marked 1 day after the cruise, while the signal of the BC west of the cold eddy has changed. This change could be due to the movement of the front between the SACW and the SASW.

The Confluence 5 hydrographic section extends across the warm southward flowing BC (Figure 1). In the west, the data show the presence of a strong density front detached from the continental slope at ~53.2°W (Figure 4c). This front represents the western boundary of the BC. Between the continental slope and the front is the slope water [*Gordon*, 1981]. This water is a mixture of SASW and shelf water. The western front has a complex thermohaline structure, whereas the density structure is smooth (Figures 4a-4c). Two small features stand out in Figure 4: a fresh and cool layer 15 m thick between stations 3 and 5 and a 20-m-thick intrusion of salty and warm water into the front at a depth of ~150 m (Figures 4a, 4b and 5). The subsurface intrusion is perfectly density compensated whereas the surface one is not (Figures 4c and 5). The fresh and light surface layer, likely to be Rio de la Plata water, is transported offshore by Ekman drift (a southward wind of speed of ~ 10 m s^{-1} was recorded during the cruise) and is squeezed between the northward flowing MC and the southward flowing BC. It is then entrained along the BC/MC front farther offshore [*Provost et al.*, 1996]. Subsurface intrusions are frequently observed along the western boundary of the BC [*Provost et al.*, 1995]. The subsurface intrusion of warm, salty water is also observed at a depth of 150 m at station 7. These subsurface intrusions provide an active mixing mechanism in transferring heat and salt to cooler and fresher water [*Provost et al.*, 1995].

Oxygen and CFC surface data collected during Confluence 5 are close to equilibrium with the atmosphere or slightly over saturated (100 to 110% saturation values). As discussed in the modeling approach of *Haine and Richards* [1995], this is principally due to the temporal variability of physical processes. The difference between the CFC-11 values at station 5 (2.5 pmol kg^{-1}) and station 3 (3.8 pmol kg^{-1}) is a result of the different temperatures of the water masses, the warm SACW and the cold SASW, respectively. Similarly, *Takahashi et al.* [1997] reported, for the Confluence 4 cruise (January 1994), CFC-11 values varying from 2 to 2.6 pmol kg^{-1} for the SACW and from 3.5 to 4.1 pmol kg^{-1} for the SASW.

4. Subtropical Mode Waters

As mentioned above, the STMWs are detected by relative minima in potential vorticity. Layers of relatively low potential vorticity (less than 10010^{-14} m^{-1} s^{-1}) are detected between stations 4 and 7 (Figure 4e), within the warm pool of the SACW. One patch of low potential vorticity, extending from the surface to ~150 m and between 51.5°W and 53.2°W, defines the $STMW_1$. A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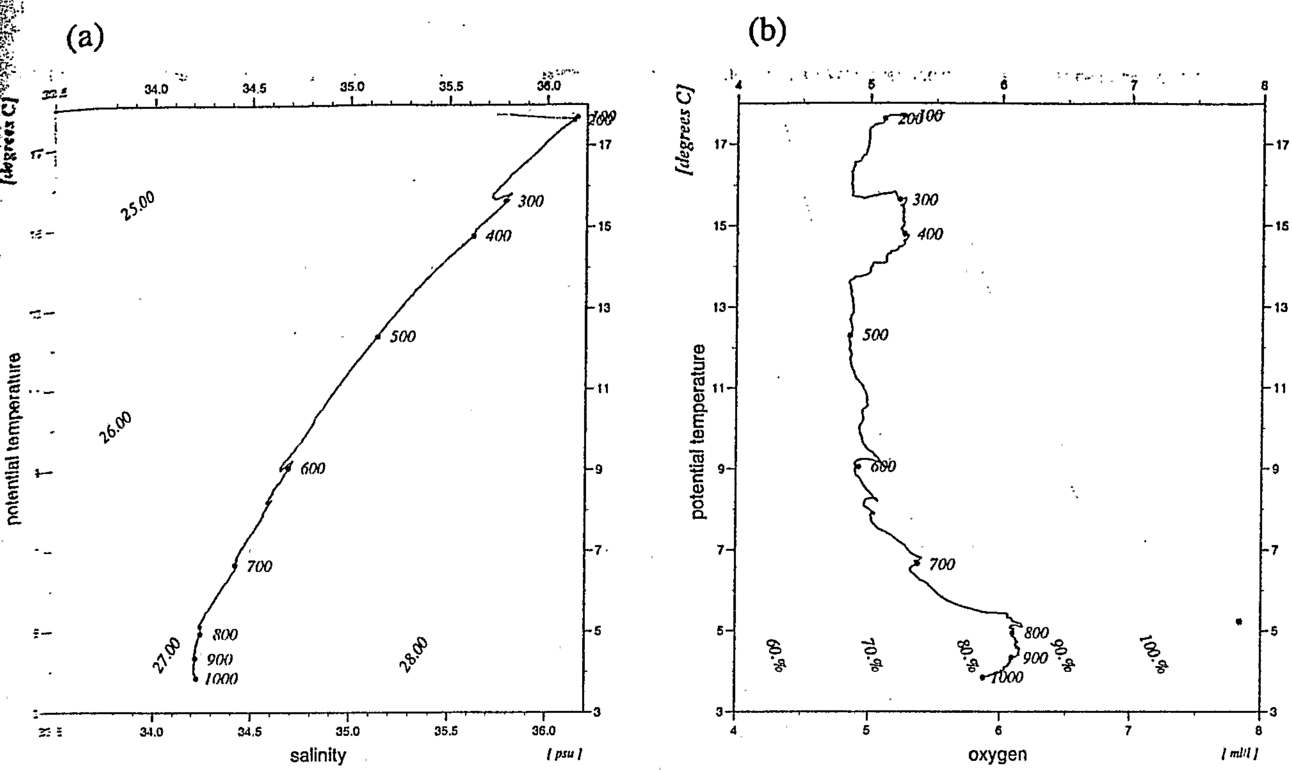

Figure 5. (a). Potential temperature (°C) and salinity diagram for station 5. Density contours are drawn every 0.5 σ unit. (b). Potential temperature (°C) and dissolved oxygen (mL L^{-1}) diagram for station 5. Saturation curves are drawn every 10%.

second patch of low potential vorticity but of smaller extent, between 300 and 400 m and between 51.5°W and 53.2°W, defines the $STMW_2$. The $STMW_1$ and $STMW_2$ are separated by a layer of high potential vorticity which is associated with the thermohalocline as found at lower latitudes [*Arhan and Mercier*, submitted manuscript, 1999; *Provost et al.*, this issue]. No $STMW_3$ is encountered during the Confluence 5 cruise.

The $STMW_1$ is located mostly on the eastern part of the section between stations 4 and 6 (Figure 4e). The $STMW_1$ lies within the density range 26.23-26.25 σ_θ. At station 6, $STMW_1$ is a homogeneous layer with a temperature of 17.5°C and salinity of 36.12 which extends from the surface to a depth of 120 m (Figures 4a and 4b). It is clear from Figure 4e that the water around station 6 is still in a convection phase. At station 5, $STMW_1$ has a slightly higher temperature (17.8°C) and salinity (36.15) and is located at depths between 30 and 150 m (Figure 5a). The dissolved oxygen content of the $STMW_1$ varies between 5.2 and 5.4 mL L^{-1} (Figure 5b) which corresponds to between 97% and 100% saturation. At station 4 a small amount of $STMW_1$ is found. The CFC data located within the $STMW_1$ are only available at station 5. The dissolved CFC concentrations for the $STMW_1$ vary from 0.18 to 0.22 pmol kg^{-1} for CFC-113 and from 2.56 to 2.75 pmol kg^{-1} for CFC-11, which are around the solubility equilibrium values (Figure 6). The CFC-11 values are slightly higher than those measured during summer 1994 [*Takahashi et al.*, 1997] within the SACW, owing to the different atmospheric conditions. The CFC-113:CFC-11 ratio gives an age of less than a year for the $STMW_1$. The SACW has therefore convected during the current winter to form the $STMW_1$.

The $STMW_2$, which is detected by a minimum in potential vorticity between 300 and 400 m and between stations 5 and 6 (Figure 4e), can also be identified by a relative maximum in dissolved oxygen (Figures 4d and 5). This layer is quite homogeneous in dissolved oxygen with values $\sim$ 5.2 mL L^{-1} (i.e., 93% saturation) (Figure 5). The average temperature and salinity of the $STMW_2$ are 15.4°C and 35.73, respectively (Figures 4a and 4b). Owing to isopycnal mixing, the $\theta - S$ properties of the $STMW_2$ expand over a larger portion of

Figure 4. Vertical section of data from the Confluence 5 cruise for (a) temperature (°C), (b) salinity (practical salinity units), (c) density (σ units), (d) dissolved oxygen (mL L^{-1}), and (e) potential vorticity (10^{-14} cm^{-1} s^{-1}).

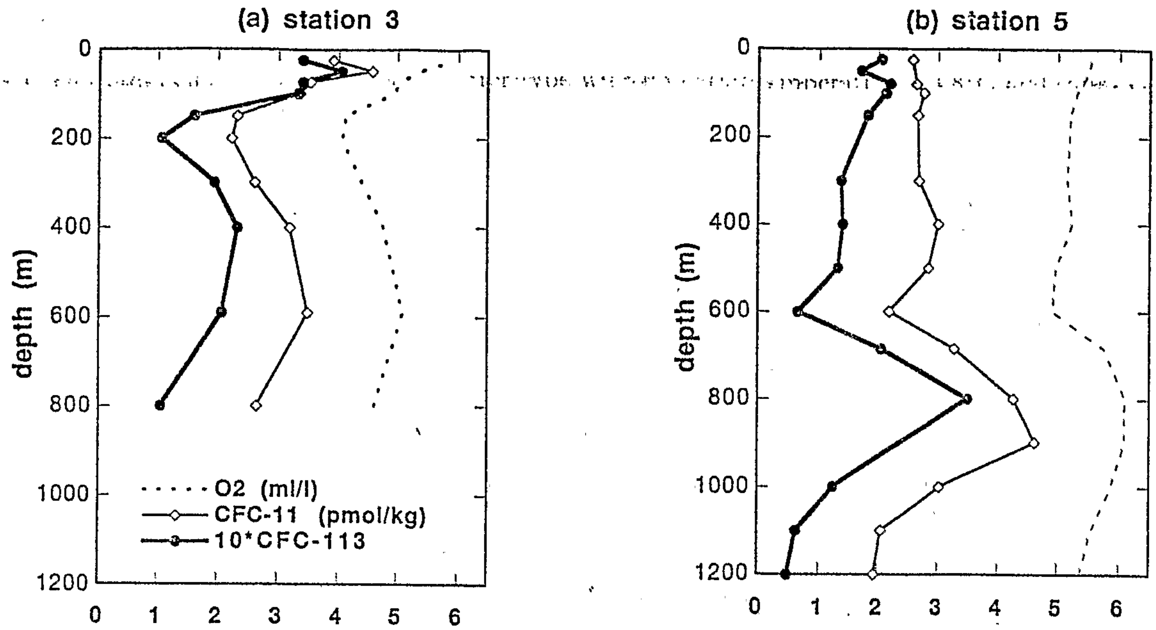

Figure 6. (a). Concentration of dissolved CFC-11, CFC-113 (pmol kg^{-1}) and oxygen (mL L^{-1}) at station 3 and (b) station 5.

the diagram than the $\theta - S$ properties of the $STMW_1$ (Figure 5). The σ_θ density range of $STMW_2$ is 26.45-26.47. Within the $STMW_2$ the CFC-11 concentrations are 2.67 pmol kg^{-1} at 300 m and 3.0 pmol kg^{-1} at 400 m (Figure 6). CFC-113 values are 0.14 pmol kg^{-1} at 300 and 400 m. According to the CFC-113 "age," the CFC-113:CFC-11 ratio and the CFC-11 age (Figure 7), the $STMW_2$ was formed 6 ± 3 years before the time of the observations. Once formed, the $STMW_2$ recirculates within the BC recirculation loop or within the subtropical gyre [*Provost et al.*, this issue] and conserves its initial potential vorticity for a long time.

5. Antarctic Intermediate Water and Subantarctic Mode Water

The presence of the AAIW is marked by a salinity minimum (lower than 34.3) that extends along the whole section (Figure 4b). The thickness of the layer of salinity lower than 34.3 varies with the position relative to the warm pool. On the edge of the warm pool the AAIW layer reaches a thickness of 550 m, while underneath the pool the thickness is reduced to 350 m (Figure 4b). The salinity minimum is located at an average depth of 800 m underneath the warm pool. The density in the 34.3 salinity layer varies from 27.05 to 27.25 σ_θ. A recently ventilated water parcel can be detected by high values of dissolved oxygen and CFCs. A relative maximum for the dissolved oxygen data is observed between 700 and 900 m at stations 5 and 6 (Figure 4d and 5). The layer is quite homogeneous, with oxygen values close to 6 mL L^{-1} (85% saturation). The salinity in this layer is in the range 34.20-34.24. The potential temperature varies from 4.2° to 5.2°C, and the density ranges from 27.05 to 27.15 σ_θ (Figure 4). The ventilation of the AAIW at the confluence region is achieved by SAMW within the density range 27.05-27.15 σ_θ. In the Subant-

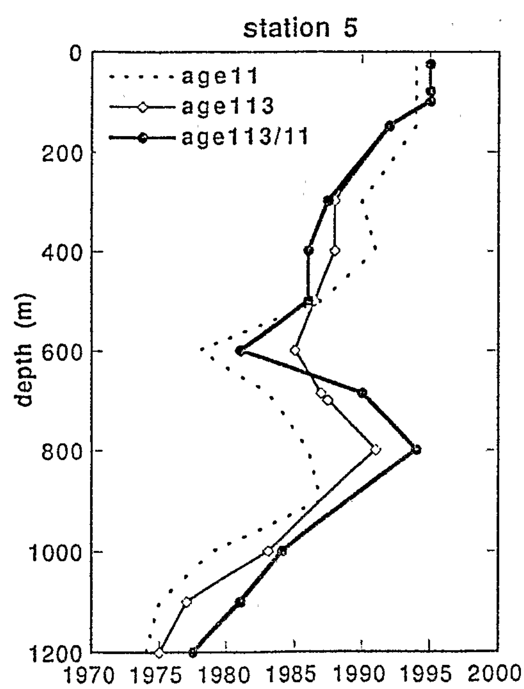

Figure 7. CFC-113:CFC-11 ratio age (thick solid line), pCFC-113 concentration age (thin solid line) and pCFC-11 concentration age (dotted line) profiles for station 5. Ages are expressed as water mass "vintages" i.e., the year when the water mass and atmosphere were in equilibrium.

arctic Zone and the northern Drake Passage the SAMW has been identified by *Piola and Gordon* [1989] as a water type with potential temperature ~4.8°C and salinity higher than 34.20. Figure 6 shows that the largest values of CFCs are obtained within this layer (700-900 m), coinciding with the oxygen maximum. The largest CFC-113 concentration measured is 0.35 pmol kg^{-1} at station 5 (80% saturation) at around 800 m depth (no data at 900 m). The maximum CFC-11 content is greater than 4.5 pmol kg^{-1} (83% saturation). On a similar density level, *Weiss et al.* [1993] found CFC-11 concentrations to be around 2.6 pmol kg^{-1} (~63% saturation) in the confluence region during March 1989. *Takahashi et al.* [1997] report CFC-11 concentrations of ~ 3.9 pmol kg^{-1} (about 75% saturation) at 40°S within a 400-m-thick layer close to the surface along the shelf break of South America during Confluence 4 in austral summer (January 1994). The CFC-11 saturation values increase from 1989 to 1994. This increase in saturation values also results from the decrease or slowing of the rate of increase in the atmospheric concentrations of the CFC-11. During Confluence 5 (September 1994) the CFC-113:CFC-11 ratio at 800 m shows that this component of the AAIW was formed in 1992 (Figure 7). The *p*CFC-113 ventilation year, calculated from the only CFC-113 concentration, is 1991. Similarly, the CFC-113:CFC-12 ventilation year evaluated at 700 m (no CFC-12 data are available at 800 m) is also 1991. The estimation of the AAIW ventilation age from the mean of the CFC-113 ratio ages within the 700-800 m depth range is 3 ± 2 years. This evaluation should be considered with caution when compared with the 8- and 9-year *p*CFC-11 apparent ages in 1994 and 1989, respectively [*Weiss et al.*, 1993] (Figure 7). However, *Haine and Richards* [1995] demonstrate that the spatial and temporal variability of the processes in the upper ocean limit the validity of *p*CFC-11 and -12 ventilation ages compared with the CFC-113:CFC-11 ratio age, especially in regions where great water volumes are ventilated. Mixing by dilution with surrounding waters is also a reason why estimates of ventilation age of the AAIW using CFC-11 or CFC-12 alone can be too large. The important result here is that strong signals in CFCs have been observed within the core of the AAIW, and they reveal that the water is quite young compared with neighboring water. The AAIW within the density range 27.15 to 27.25 σ_θ has lower CFC contents (Figure 6). The ventilation for this layer occurred between 1980 and 1985.

The hydrological sections (Figure 4) show that the water mass characteristics are constant along the 27.10 isopycnal. The comparison of CFC and oxygen profiles (Figure 6) confirms this continuity between station 5 (maximum concentrations at 800 m) and station 3 (maximum concentrations at 400-600 m). The tracer concentrations seem to indicate that ventilation of the main core of the AAIW is not efficient along the continental slope at 36°S.

6. Discussion

The mode waters in the confluence area, STMWs and SAMWs, were identified during winter 1994 by their minimum in potential vorticity. Their ages were determined using the ratios of dissolved atmospheric CFC-113 and CFC-11. This technique of determining water sample ages has been proved to be effective in detecting newly formed water [*Haine et al.*, 1995; *Smythe-Wright et al.*, 1996]. The two types of STMW ($STMW_1$ and $STMW_2$) are located within the warm pool of the SACW and transported within the confluence region by the Brazil Current. The SAMW is found within the bulk of the AAIW.

The estimated age of the $STMW_1$ is less than a year. This component is being formed during the Confluence 5 cruise. The formation process of this water is convection. The southward extension of the BC is in a region where the heat lost from the ocean to the atmosphere is important [*Escoffier and Provost*, 1998]. Thus the warm water is exposed to cooling atmospheric conditions when transported southward within the BC. The $STMW_1$ could have been formed either in the confluence area, as suggested by the late winter Confluence 5 data set, or farther north, before being advected farther south [*Provost et al.*, this issue; *Arhan and Mercier*, submitted manuscript, 1999].

The $STMW_2$ is located within the depth interval 300-400 m and has an estimated age of 6 ± 3 years. The $STMW_2$ is formed in great quantity farther in the interior of the basin [see *Provost et al.*, this issue], and what is observed during the Confluence 5 cruise is a remnant that has recirculated within the interior of the Argentine Basin. *Provost et al.* [1998] show that the $STMW_2$ barely reaches the eastern side of the Subtropical Gyre and is more likely to be found within the recirculation cell of the BC or within a larger recirculation loop within the Argentine basin as suggested by *McCartney* [1982].

The SAMW, or the lightest AAIW, essential to the ventilation of the AAIW, is detected at a depth of 800 m under the warm pool of the SACW within a density range of 27.05-27.15 σ_θ. According to the CFC data, the SAMW detected during Confluence 5 is estimated to be 3 ± 2 years old. The Subantarctic Water has therefore been rapidly advected underneath the thermocline water. The present data set shows that the SAMW along the continental slope (station 3) cannot efficiently ventilate the AAIW. *Maamaatuaiahutapu et al.* [1992, 1994] and *Provost et al.* [1995], using a multiparameter analysis and data collected during spring, summer, and winter, show that most of the SASW carried northward along the continental slope by the MC comes back southward within the return branch of the MC and an insignificant quantity of SASW sinks along the slope under the SACW north of 38°S. The sinking or subduction of the SASW or SAMW must occur along the BC and MC front as both currents flow alternately southward and northward farther into the interior of the Argentine Basin. Hydrographic data [*Gordon*, 1981; *Kartavtseff et al.*, 1994; *Maamaatuaiahutapu et al.*, 1992, 1994; *Provost et al.*, 1995] hint at a sinking of SAMW around the meander generated by the extension of the BC or around the cold-core ring that is frequently observed at this latitude [*Legeckis and Gordon*, 1982; *Provost et al.*, 1992]. *Davis et al.* [1996] report that their floats show no evidence for intermediate-depth flow northward across the confluence region that might feed the AAIW located under the subtropical gyre. However, they do not exclude a possibility of a net water transport or water exchange from the Antarctic Circumpolar Current to the South Atlantic Current through stirring or mixing processes due to strong eddy variability. Our data set shows that the water patch corresponding to the SAMW as detected by high oxygen values has a zonal extension of 100 km underneath the northward flow of the BC. Water patches with a zonal extension of ~200 km have been observed by *Gordon* [1981] at 38°S in the return branch of the BC. Undoubtedly, the exchange between water of Antarctic origin and water of subtropical origin at the AAIW level does occur on scales of the order of 100 km, and the patchiness of the oxygen-rich core found under the SACW suggests an intermittent or spatially uneven process. The ventilation age for the SAMW does not contradict the possibility that SAMW comes from the Drake Passage. With an age of 3 years, a speed of 3 cm s^{-1} is needed for the SAMW to travel directly from the Drake Passage to the confluence region. This speed should, however, be regarded as a minimum value since a direct path is unlikely. *Vivier and Provost* [this issue] give an average speed of 13 cm s^{-1} for the AAIW within the MC. *Davis et al.* [1996] give an estimate of 13 cm s^{-1} onto the Falkland Plateau. The heaviest component of the AAIW (density range of 27.15-27.25 σ_θ) present within the subtropical gyre has an age varying from 9 to 14 years.

7. Conclusions

The mode waters and their relation to the ventilation of the thermocline in the Brazil/Malvinas Confluence have been studied by analysis of various types of data. The dissolved CFC data provide, for the first time, estimates of the dates of formation of the mode waters, the STMWs lying on the density surfaces 26.24 σ_θ and of 26.46 σ_θ and the SAMW lying on a density surface of 27.10 σ_θ. The lightest STMW is in the process of formation at the time of the cruise. The heavier STMW has circulated for 6 ± 3 years within the subtropical gyre and, surprisingly, has retained a low value of potential vorticity, even in the presence of the strong mesoscale activity within the gyre reported by *Escoffier* [1998]. The SAMW responsible for the ventilation of the AAIW is 3 ± 2 years old. The mechanism by which the SAMW reaches a depth of 800 m in such a short time is thought to be a strong mesoscale process dependent on the BC/MC front intensity instead of a simple subduction such as what occurs at a convergence zone.

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