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Results of the research cruises of FRV 'Walther Herwig' to South America. LXXV: trans-Atlantic oceanographic measurements during South America Expeditions 1966–1976 of the Institute of Sea Fisheries, Hamburg, Germany

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Summary

During the 1960s, with the new research platform FRV 'Walther Herwig' being available for long-distance exploratory fishery and ichthyology research, the Institute of Sea Fisheries started a series of South America Expeditions. During these expeditions large-scale oceanographic sections were performed which cross major oceanic surface current systems between 40°N and 40°S. By means of historic oceanographic data, as available through the World Data Centre A, Washington, the thermohaline situation along these sections is presented and described in relation to large-scale oceanic features like the North Atlantic Subpolar Gyre System, the northern Subtropical Gyre, the Atlantic Equatorial Current System, the southern Subtropical Gyre, the Brazil Current and the Malvinas Current System. Data obtained during the 1970s reveal large-scale oceanographic properties within the Subtropical Convergence belt at 40°S, between South America and South Africa. Based on these data, an analysis on the baroclinic current velocities of the upper 1000 m is presented. This analysis documents the deep reaching influence of the two boundary currents in this region, the Brazil Current system in the west, and the Agulhas / Benguela Current system in the east of the transect along 40°S.

Also designed as large-scale ichthyology transects, the oceanographic observations performed during leg I of the Antarctic Expedition of the Federal Republic of Germany during 1975 / 1976 along 50°W and 40°W, reveal thermal properties across the Subtropical Convergence, in the sub-Antarctic surface waters and in Antarctic surface waters.

Introduction

During 1925–1927, the German RV 'Meteor' performed oceanographic observations in the South Atlantic and the tropical North Atlantic Ocean which formed the basis for classical oceanography (Merz, 1925; Defant, 1929; Wüst, 1936; Wattenberg, 1939). The oceanographic data of the legendary 'Meteor' cruise can be obtained from the World Ocean Database 2005 (see below). Thorough research in this database, and the availability of the chief scientist's records in the archives of the Institute of Sea Fisheries, Hamburg, made it possible to extract oceanographic data performed on board FRV 'Walther Herwig' during South America Expeditions of the Institute of Sea Fisheries (ISH). Another source of information on time slots of South America Expeditions of RV 'Walther Herwig' was taken from Stehmann (1997). In Table 1 of this publication, the long-distance exploratory research cruises of FRV 'Walther Herwig' in the Atlantic Ocean are listed. In the account on the ISH collection history, dedicated to the late German ichthyologist Dr. Gerhard Krefft – Dr. Krefft was member of the Institue of Sea Fisheries from 1938–1977 – Stehmann (1997) writes 'While the first expedition to South America was being planned, Krefft developed the idea to use the passage from Europe to South America not only as an opportunity for oceanic midwater fishing, but also to test a commercial-sized double-warp midwater trawl for exploratory ichthyology'. In combination with the trawl stations, sampling of oceanographic data was achieved. This approach to oceanographic sampling during a long-distance cruise followed the classical oceanographic sampling procedures as performed during the 1920s by RV 'Meteor'. According to the World Ocean Database 2005, there were no cruises done between 1928 and 1966 which are comparable with the achievements of the South America Expeditions with FRV 'Walther Herwig'. The 1966 and 1968 surveys followed the same cruise track from Bay of Biscay – Mar del Plata, which spans a distance of more than 10 000 km. While the 1966 trans-Atlantic Section was done in May, the 1968 survey covered the period mid-January to mid-February. During the 1971 South America Expedition of FRV 'Walther Herwig' two more sections were performed: '…this time the return voyage was used for a midwater transect that extended along the subtropical convergence from Mar del Plata to Cape Town and then northward along West Africa to Madeira' (Stehmann, 1997). As part of the First Antarctic Expedition 1975/76 of the Federal Republic of Germany two meridional sections were performed off the eastern South American slope, one along 40°W, the other along 50°W.

Oceanographic observations done with Nansen bottles along the 1971 long-distance sections were published by Lenz (1975). Further to this publication, a reanalysis of temperature and salinity data sampled along the 40°S section is performed in the present paper, followed by a calculation of geostrophic flows across this section to test the model assumptions given by Lenz (1975) for the current system in the southwestern South Atlantic. Of the 1968, 1975 and 1976 sections, there are some of the oceanographic results displayed in Hulley (1980). This publication, however, only presents temperature and salinity sections without any expert oceanographic interpretation.

Thus, the 1966 long-distance section, from Bay of Biscay – Mar del Plata, is not yet published. Since the repetition of this section, during 1968, is not adequately published, it seems worthwhile to enable a comparative view on both data sets which were sampled along more then 10 000 km from the Eastern North Atlantic Ocean to the Western South Atlantic Ocean, from 40°N to 40°S. Further to this, it seems adequate to present the oceanographic results in relation to large-scale

Table 1
Long-distance exploratory research cruises of FRV 'Walther Herwig' During South America Expeditions of the Institute of Sea Fisheries

Cruise	Duration	Section dates
WH015_1966	3.5.–1.9.1966	Biscay-Mar del Plata: 7.-30.5.1966
WH023_1968	10.1.–30.4.1968	Biscay-Mar del Plata: 14.1.-16.2.1968
WH036_1971	16.10.1970–29.4.1971	Mar del Plata -CapeTown 40°S: 5.3.-29.3.1971
WH036_1971	16.10.1970–29.4.1971	East Atlantic: 30.3.-18.4.1971
WH020[a]_1975	17.11.1975–16.06.1976	50°W: 17.11.-23.11.1975
WH020[a]_1975	17.11.1975–16.06.1976	40°W: 3.-10.1.1976

[a]with the new 'Walther Herwig', commissioned in 1972, counting of cruises started with cruise 1 in 1972.

oceanic features like the major surface current systems along the transect. In addition, the temperature profiles as obtained by bathythermograph during 1968–1976 are given in an extra chapter.

Data and methods

Oceanographic data were downloaded from the World Ocean Database 2005 (http://www.nodc.noaa.gov/OC5/WOD05/data05geo.html). Following the track of FRV 'Walther Herwig' during her first cruise to South America, from Bay of Biscay to the approaches of Mar del Plata/Argentina, the corresponding bottle data were imported to the Ocean Data View software (Schlitzer, 2008) environment. The data are organized by World Meteorological Organization (WMO) 10 degree squares. Within each WMO square, data are separated by dataset and depth. About 113 500 bottle data from 47 WMO squares were downloaded for the area from Bay of Biscay (WMO square 7400) to Mar del Plata (WMO square 5305), the Atlantic sector of the Southern Ocean between 70°W, 70°S and 20°E, 70°S (WMO squares 5606–5602), off Cape Town (WMO square 3301) to Madeira (WMO square 7301). A similar geographic coverage with WMO squares was taken for the bathythermograph data of which 124 500 stations were downloaded. With the information derived from the cruise reports of cruises WH015_1966 and WH023_1968, as well as for the cruises during the 1970s, it was possible to formulate the selection criteria in time and space for both trans-Atlantic Sections (bottle data, Fig. 1), and the bathythermograph stations (MBT data, Fig. 10). Positions of hydrographic and pelagic trawl stations during WH023_1968, and superimposed a schematic identifying the location and nomenclature for many of the major upper ocean current systems of the Atlantic Ocean, and the connections between these flow patterns is given in Fig. 2. Presentation of oceanographic data was achieved by means of the Ocean Data View (ODV) software (Schlitzer, 2008). To indicate the bathymetry along the 1966, 1968 and 1971 transects, the GEBCO 1-minute global bathymetric grid data were selected in ODV (Figs 3, 4 and 8). To facilitate comparing of vertical fields of temperature and salinity along the transects, the 'Overlay Window' feature was taken. The respective graphs show potential temperature (reference level 0 dbar) in colour, and salinity as 'Overlay' in isohalines (Figs 5 and 6). To reveal distribution of geostrophic currents along 40°S the 'Geostrophic Flows' feature of ODV was used. Since the depth of 1000 m is the deepest depth of

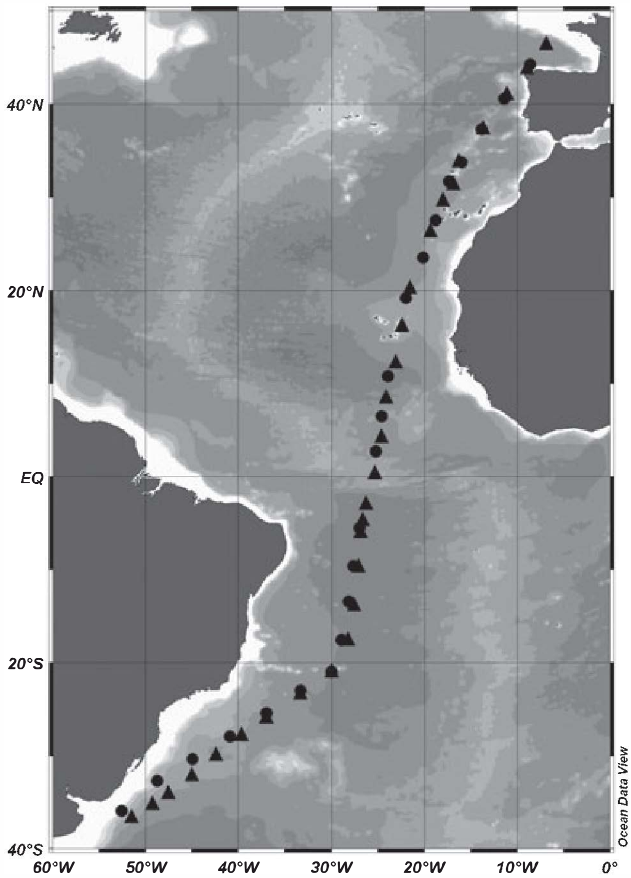

Fig. 1. Positions of hydrographic and pelagic trawl stations during WH015 (7 – 30 May 1966, dots), and WH023 (14 January – 16 February 1968, triangles)

most Nansen casts, as performed during WH036_1971 along this transect, a reference level of 'no motion' at 1000 m depth was taken (Fig. 9). Due to the accuracy of the input data temperature and salinity, as well as the accuracy of the position determination in those days, it seems adequate to expect an error of ± 5 cm s^{-1} incorporated in the geostrophic current computations (Fig. 9).

Results

Nansen bottles

Starting in the Bay of Biscay in both years, the long-distance transects 1966 and 1968 as displayed in Fig. 1, head towards west off the Canary Islands, continue to the Cape Verde Islands, and cross the equator at about 26°W. After reaching longitude 30°W, the heading of transects changes to the southwest, and the final station is reached off the South American continental slope at about 450 m depth. The inter-station distance is in the range of 230 nautical miles, allowing a resolution of only large-scale oceanographic features. A large-scale schematic, identifying the location and nomenclature for many of the major upper ocean current systems of the Atlantic Ocean, and the connections between these flow patterns is given in Fig. 2 as overlay on the positions of hydrographic and pelagic trawl stations performed during WH023_1968. Accordingly, the transects during 1966 and 1968 crossed parts of the North Atlantic Subpolar Gyre (NASG), the eastern parts of the Subtropical Gyre of the North Atlantic (STG-N), the Atlantic Equatorial Current System (AEC), the

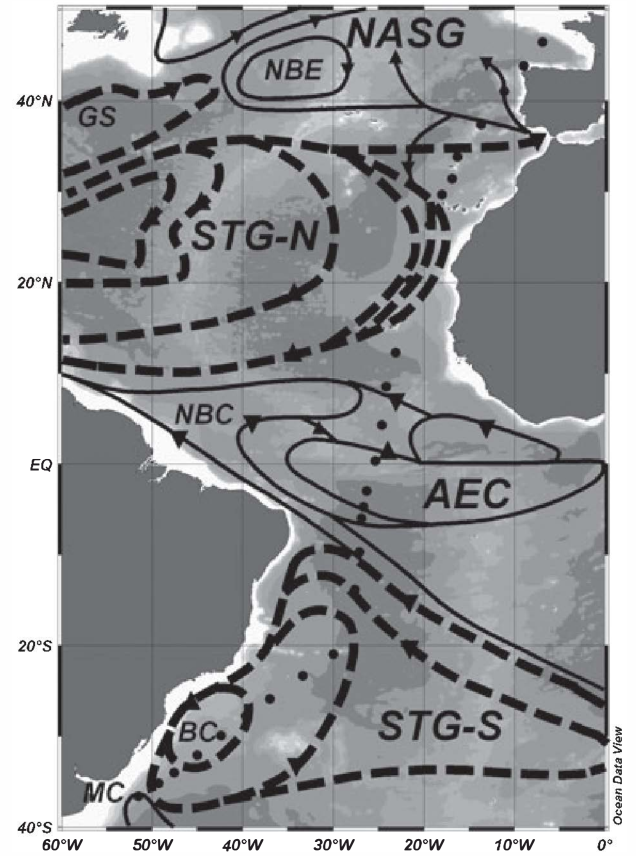

Fig. 2. Positions of hydrographic and pelagic trawl stations during WH023_1968 (dots); overlayed: schematic identifying the location and nomenclature for many of the major upper ocean current systems of the Atlantic Ocean, and the connections between these flow patterns (redrawn after Schmitz, 1996a); NASG = North Atlantic Subpolar Gyre System, GS = Gulfstream System, STG-N / STG-S = Subtropical Gyre North / South, NBC = North Brazil Current System, AEC = Atlantic Equatorial Current System, BC = Brazil Current System, MC = Malvinas Current

Subtropical Gyre of the South Atlantic (STG-S), the Brazil Current System (BC), and the Malvinas Current (MC). The bottom topography along the sections is given in Figs 3 and 4. It is based on the GEBCO 1-minute global bathymetric grid. Major topographic features which are crossed by the transects and are visible in the figures, are the Cape Verde Seamount (15.3°N, 22.2°W), the Sierra Leone Rise (about 6°N), the Pernambuco and the Brasilian Abyssal Plain (about 7°S and 10°S). The points of observation depth given in the upper parts of Figs 3 and 4, indicate major differences in sampling during the 1966 and 1968 cruises. Accordingly, during 1966 only the upper 600 m of the water column were covered, while during 1968 the upper 1000 m were sampled, and there are occasional measurements at 2000 m depth during this cruise. The thermohaline conditions along the transects indicate similar temperature and salinity fields in the upper 200 m of the water column (Figs 5 and 6). A clearly emerging feature is the Subtropical Gyre (STG-N) in the northern hemisphere. Delineated by the 36 psu isohaline during both observation periods, northern spring 1966 and winter 1968, the winter observations suggest a northward shift of the STG-N as revealed by the surface expression of the 36 psu isohaline. Whether the vertical extension of the 36 psu isohaline during spring 1966 is real, or whether it represents erroneous data, cannot be answered here. However, when comparing the salinity profile as measured on 13 May 1966, with recently acquired ARGO-float profiles (2006–2008), the 1966 salinity profile below 250 m depth appears to be questionable. To the south of the STG-N, warm surface waters are observed in the top 200 m during spring 1966. The area of the Atlantic Equatorial Current System (AEC) is characterized by temperatures well above 26°C and above 27°C, and salinities > 36 psu. The thermohaline conditions during May 1966 and during mid-January to mid-February 1968, as delineated in Figs 5 and 6, reveal similar features in the top 200 m of the water column. There are two regions north and south of the equator which are characterized by high salinities and temperatures (> 36 psu and temperatures in the range of > 26°C). During 1968, salinities > 36 psu were found southward from the equator, and when reaching the southern STG, salinities increased to > 37 psu (Fig. 6). The data obtained during 1966 (southern autumn), reveal salinities > 36.75 psu at the same position. Unfortunately, the vertical spacing of the Nansen bottle data does not allow a scrutinised analysis of thermohaline conditions of the upper layers. The bathythermograph data, however, as obtained along the same section during 1968, give a better resolution of the thermal field in the 0–275 m layer (Fig. 6, bottom panel). Accordingly, the 20°C isotherm which reaches down to 200 m depth at 20°S, is at

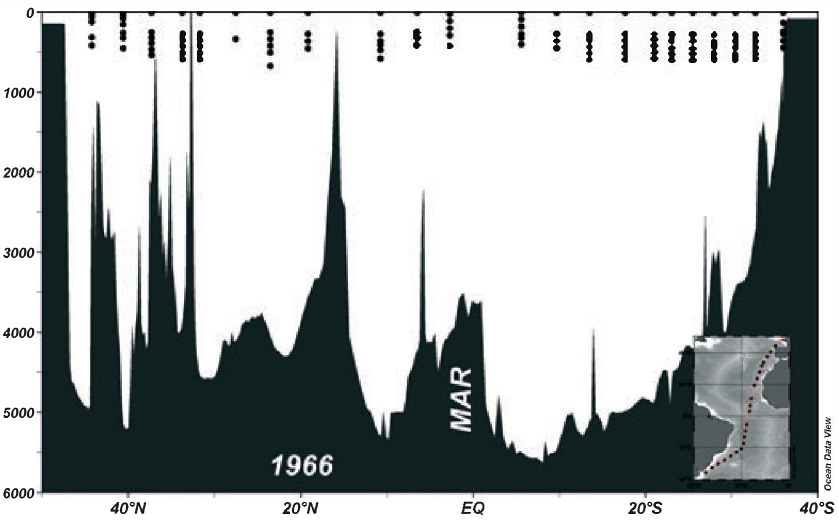

Fig. 3. Positions and maximum depth [m] of hydrographic stations during WH015_1966; bottom topography: GEBCO 1; MAR = Mid-Atlantic Ridge

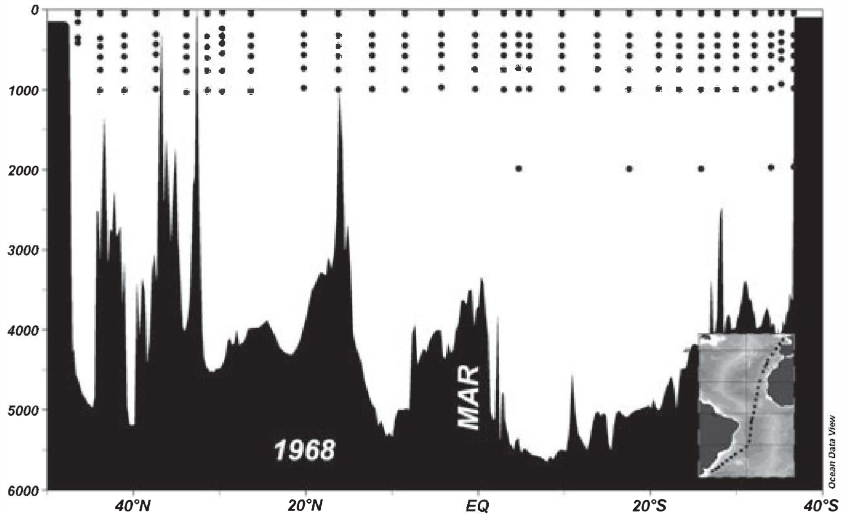

Fig. 4. Positions and maximum depth [m] of hydrographic stations during WH023_1968; bottom topography: GEBCO 1; MAR = Mid-Atlantic Ridge

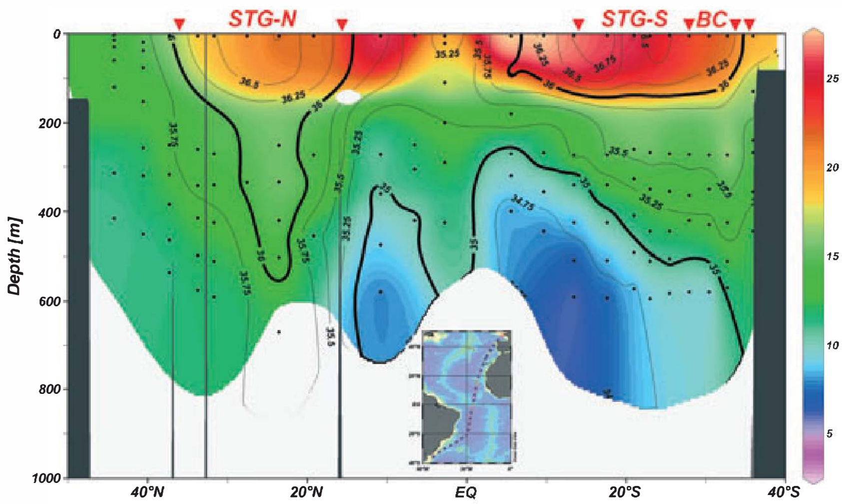

Fig. 5. Vertical distribution of potential temperature [°C] and salinity [psu] along transect from Bay of Biscay to Mar del Plata during WH015_1966 (7 – 30 May 1966); bottom topography: GEBCO 1; triangles denote major upper ocean current systems of the Atlantic Ocean (acc. Fig. 2).

about the same depth (180 m) as the 36 psu isohaline at the same position in Fig. 6, top panel. The 20°C isotherm reveals a significant slope from north to south, from eastern tropical North Atlantic, to western tropical South Atlantic, starting at the sea surface at 20°N, and reaching 200 m depth at 20°S. Responsible for this downward sloping is the average wind pattern, the easterly trade wind flow. As a result, the thermocline is deep in the west (near-surface layer convergence) and significantly shallower in the east (near-surface layer divergence).

The water mass analysis performed for the Nansen bottle data along the transect from Bay of Biscay to Mar del Plata during the 1966 and 1968 cruises (Fig. 7), reveals a broad scatter of θ,S dots which spans a range of 3.25°C – 27.14°C, and 34.239 psu – 37.134 psu. The θ,S-profiles outline northern spring (austral autumn) 1966 and winter (austral summer) 1968 conditions in the area. Accordingly, the surface water conditions as given by rectangles in Fig. 7, indicate northern STG waters (16.91°C – 21.03°C, 36.37 psu – 36.96 psu), AEC waters (23.63°C – 27.13 °C, 36.99 psu – 35.71 psu), southern STG waters (24.89°C – 27.51°C, 36.99 psu – 37.25 psu), and Brazil Current System water (22.72 °C – 25.31°C, 35.88 psu – 36.49 psu). West off Spain and to the Northwest off Africa, the θ,S diagram reveals Mediterranean Water, found during both cruises, and representing the outflow of this water mass from the Mediterranean Sea at depths of about 1000 m.

Figure 8 outlines positions and maximum depth of hydrographic stations obtained during WH036_1971 along 40°S section, as well as the vertical distribution of temperature [°C] and salinity [psu] along a transect from Mar del Plata to Cape Town performed during March 1971. Results of this section are published by Lenz (1975). The section was done along a great circle, the shortest connection between Mar del Plata/Argentina and Cape Town/South Africa. Fifty-three hydrographic stations (Nansen bottles and bathythermograph) form the transect, the inter-station distance being about 60 nautical miles. The transect is located in the region of the Subtropical Convergence. Between 55°W and 30°W, the thermal fields are characterized by isotherm amplitudes of several hundreds of metres. The 10°C isotherm declines from 50 m depth at the Argentine continental slope, to more than 600 m depth in the oceanic region. The thermal expression at the sea surface indicates temperatures >20°C. This narrow, deep reaching thermal structure represents the Brazil Current which influences the water column down to 1000 m (Lenz, 1975). To the west of the Brazil Current, the cold waters of the Malvinas Current emerge. The frontal system established between both current systems, reveals horizontal temperature contrasts of >10°C. These gradients are in the range of 0.08°C km^{-1}. Further to the east, the depth of the 10°C isotherm increases to 200 m at 33°W which is followed by a downward slope to about 350 m. This depth is maintained to

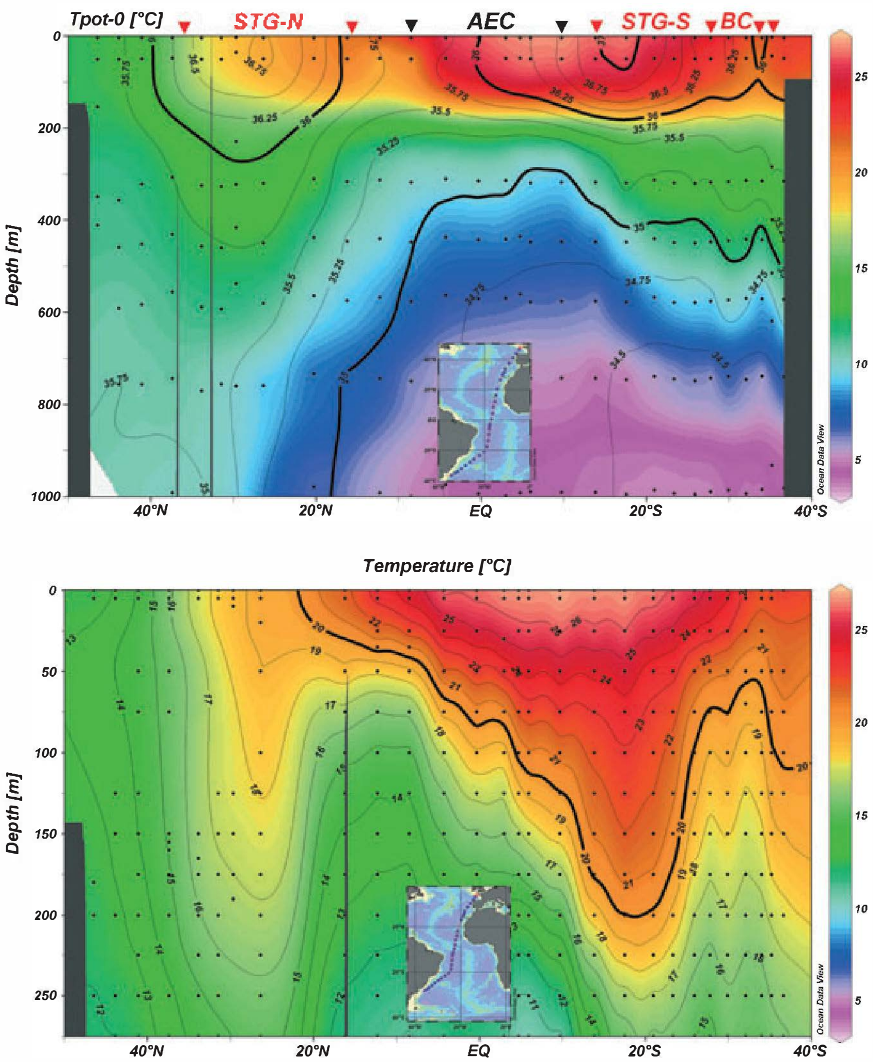

Fig. 6. Top panel: Vertical distribution of potential temperature, given in colour [°C] and salinity given with isohalines [psu] along a transect from the Bay of Biscay to Mar del Plata during WH023_1968 (14 January – 16 February 1968); bottom topography: GEBCO 1; triangles denote major upper ocean current systems of the Atlantic Ocean (acc. Fig. 2). Bottom panel: Vertical distribution of temperature, given in colour and isotherms [°C] (bathythermograph stations) along a transect from the Bay of Biscay to Mar del Plata during WH023_1968 (14 January – 16 February 1968); bottom topography: GEBCO 1

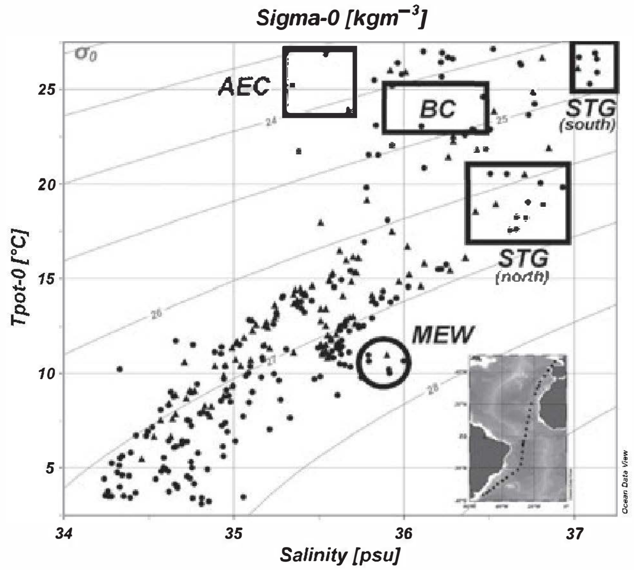

Fig. 7. θ,S diagram along transect from Bay of Biscay to Mar del Plata during WH015_1966 (red triangles) and WH023_1968 (asterisks); MEW = Mediterranean Water, and surface waters of: STG = Subtropical Gyre, AEC = Atlantic Equatorial Current System, BC = Brazil Current System

about 15°W where another sharp upward increase by about 200 m is observed. At 1°E the 10°C isotherm slopes downward, and the deep reaching influence of the Agulhas Current becomes visible. Here, the transect runs well north of the Agulhas Ridge, a topographic feature where the Agulhas Current is characterized by retroflection and the formation of Agulhas rings (Lutjeharms, 1996). This area is considered as the southern boundary of the Benguela system (Shannon and Nelson, 1996). In this southern Agulhas / Benguela system region, water mass characteristics for the Surface Water are given as $16.0°C < t < 26.0°C$, and $s > 35.5$ (Valentine et al., 1993). The surface T,S-values measured during 29 March 1971 at the eastern margin of the transect, meet theses characteristics in the top-100 m ($16.66°C < t < 17.91°C$; $35.519 < s < 35.589$). The temperature (BT) exceeds 18°C at the sea surface and resulting warm intermediate waters dominate the upper 800 m layer. Consequently, the thermal stratification in the east of this latitude is similar to that controlled by the Brazil Current in the west. Nevertheless, the zonal extension of this 'warm-water-layer' is much larger in the east than in the west. It amounts to about 360 nautical miles when taking the horizontal extension of the 12°C isotherm at 400 m depth.

Since for the computation of geostrophic currents (Fig. 9) only Nansen bottle data were used, the inter station distance is

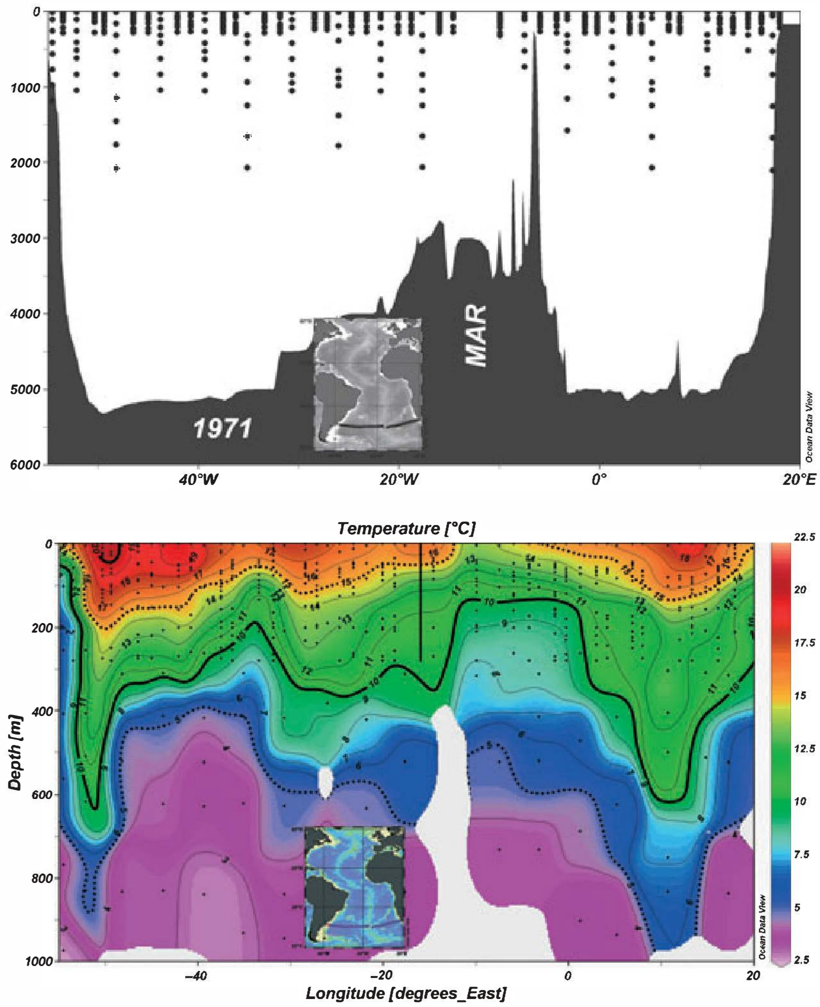

Fig. 8. Top panel: Positions and maximum depth [m] of hydrographic stations (Nansen bottles and BT) during WH036_1971 along 40°S section; bottom topography: GEBCO 1; MAR = Mid-Atlantic Ridge. Bottom panel: Vertical distribution of temperature, given in colour and isotherms [°C] along a transect from Mar del Plata to Cape Town during WH036_1971 (05 March – 29 March 1971)

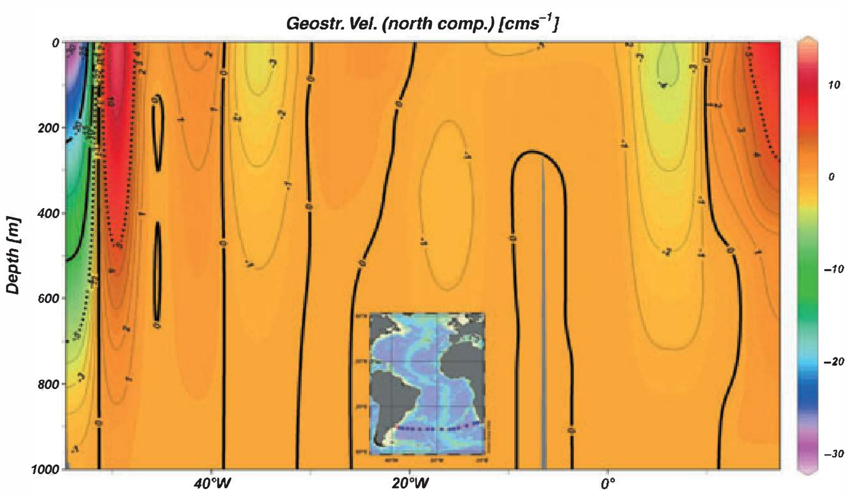

Fig. 9. Vertical distribution of geostrophic velocity (north comp.) cm s^{-1}] along a transect from Mar del Plata to Cape Town during WH036_1971 (05 March – 29 March 1971)

much wider than in the previous temperature section at 40°S (Fig. 8). It amounts to about 180 nautical miles. The vertical distribution of geostrophic velocity along the transect from Mar del Plata to Cape Town is calculated with the 'reference level of no motion' set at 1000 m (see under Data and methods, and Fig. 9). Due to the error incorporated in the computation of geostrophic currents (see above), the velocity structures < 5 cm s^{-1} as given in Fig. 9, have to be taken with caution. Accordingly, only velocity structures > 5 cm s^{-1} are discussed here. Starting at the westernmost side of the transect, a narrow band of southward (negative sign) flowing current is detectable. The surface expression of this current indicates velocities > 30 cm s^{-1}. The vertical extension of this current is documented by the 5 cm s^{-1} isoline which is found at 700 m depth. To the east of this narrow current band, a region of northward flow is observed which reaches until 38°W. This broad northward flowing system consists of two discrete current bands, one with core speeds > 10 cm s^{-1} at the western

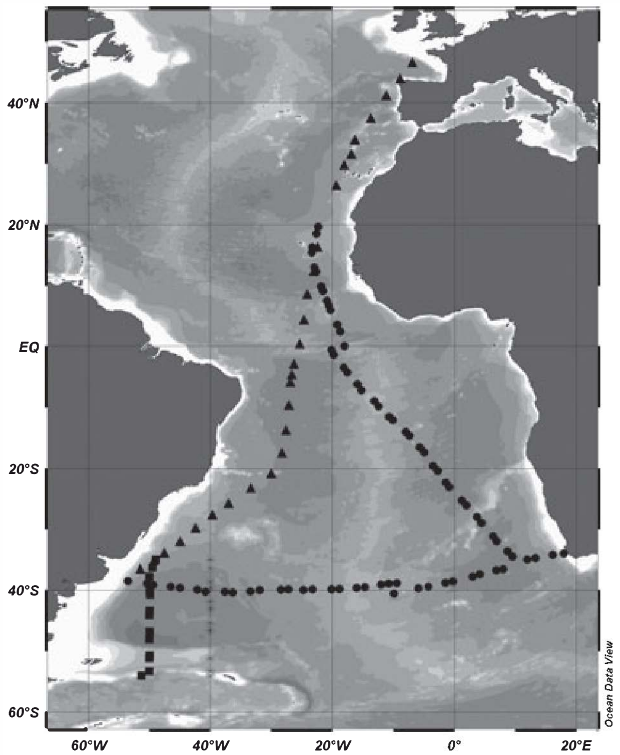

Fig. 10. Positions of bathythermograph stations during WH023_1968 (triangles), WH036_1971 (dots), WH020_1975 (squares), and WH020_1976 (asterisks); cruise dates: see Table 1

boundary, another with lower speeds at the eastern boundary. Between 38°W and 10°E, there are no salient current structures. The indicated velocities are within the given error range. At the eastern margin of the section, a northward flowing current band characterizes this portion of the 40°S transect. This broad current band has core speeds of >5 cm s^{-1}. Whereas the prominent current bands at the western and eastern margins of the transect mark the Brazil Current and the Agulhas / Benguela Current systems, the different orientation of the current bands between these boundary currents seem to represent the meandering path of surface currents in the Subtropical Convergence (STC) which is located at about 40°S. Based on mean surface current maps for the month of March, Lenz (1975) suggests that the steep slopes as seen in the distribution of the isotherms (Fig. 8, lower panel) represent dynamically forced cyclonic gyres in the Southwest Atlantic. The distribution of geostrophic currents along the western portion of the transect (55°W to 30°W) seems to corroborate this assumption. This could explain the high biological productivity in this part of the STC: In their centres the cyclonic gyres 'pump' nutrient rich intermediate waters to the surface waters.

Bathythermograph data (BT)

The positions of bathythermograph stations during 1968, 1971, 1975 and 1976 are given in Fig. 10. For the temperature measurements performed during the 1968 and March 1971 cruises see above (Figs 6 and 8).

Starting in the Cape Basin, the BT-transect as performed from 30 March to 18 April 1971, crosses the Walvis Ridge at 28°S, passes the equator at the Romanche Gap, and ends in the vicinity of the Cape Verde Islands (Fig. 11). At the southernmost end of the transect, the source region of the Benguela Current is crossed (Lutjeharms, 1996). In the vicinity of the Walvis Ridge, the 20°C isotherm reveals a downward slope from south to north. At 7°S the maximum depth of this isotherm was found at 98 m. Towards the equator, and further north the 20°C isotherm performs wave-like up and down movements, reaching 35 m depth at 6°N, followed by a gradual downward sloping towards the Cape Verde Islands region. At the equator, surface temperatures >28°C are observed, and the region of the Inter-Tropical Convergence Zone (ITCZ) is delineated by the >27°C surface water domain, from 9°S to 4°N.

The BT-transects as performed during the first Antarctic Expedition of the Federal Republic of Germany, are given in Figs 12 and 13. Starting in the warm waters of the Brazil Current, the 50°W transect (Fig. 12) runs from 35°S towards the southwest. Off the Rio de la Plata Canyon it follows 50°W, crossing the Argentine Basin, the Falkland Plateau, and ends at the North Scotia Ridge. The 40°W transect (Fig. 13) starts in the surface waters of the southern STG (see Fig. 2) at 35°S, follows the 40°W meridian across the Argentine Basin, and ends above the North Scotia Ridge, off Northwest South Georgia.

Both sections cross the STC at about 40°S. The STC is marked by pronounced surface temperature gradients which amount to 14–18°C during summer, and 11–15°C during winter (Longhurst, 1998). Separated by a steep vertical front (see e.g. Fig. 13 at depths below 100 m), ocean water

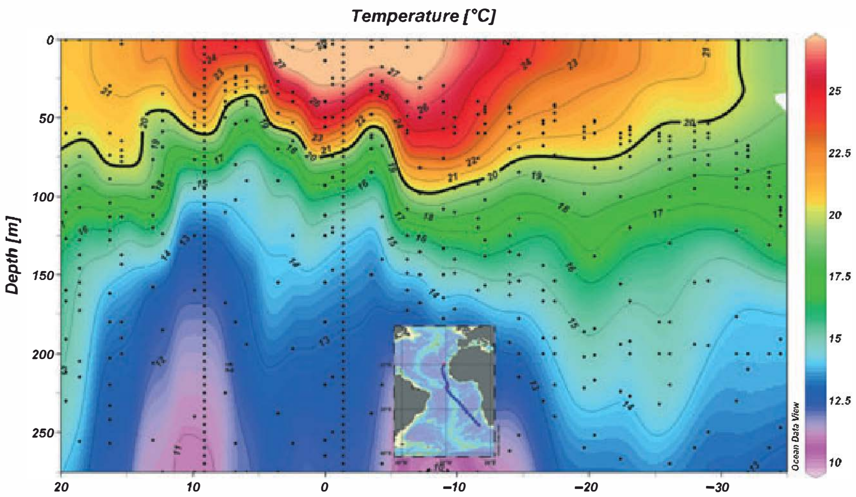

Fig. 11. Vertical distribution of temperature, given in colour and isotherms [°C] (bathythermograph stations) along transect from Cape Town to Cape Verde Islands during WH036_1971 (30 March – 18 April 1971); bottom topography: GEBCO 1

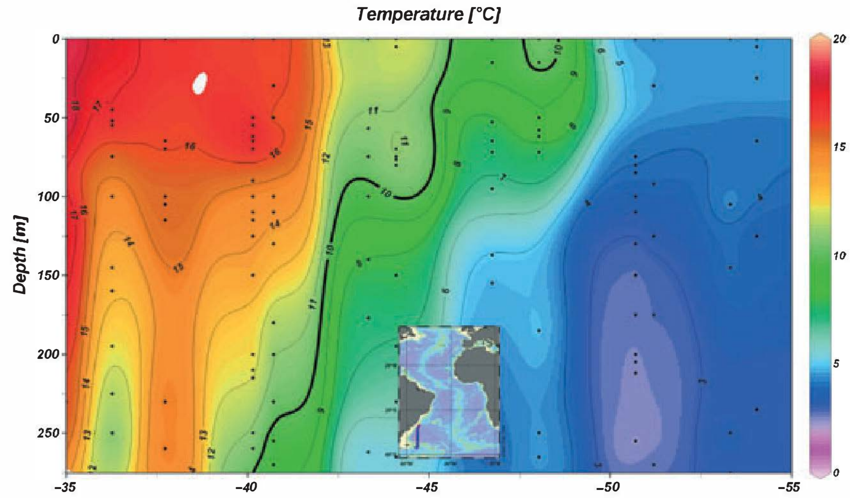

Fig. 12. Vertical distribution of temperature, given in colour and isotherms [°C] (bathythermograph stations) along 50°W transect during 17 – 23 November 1975

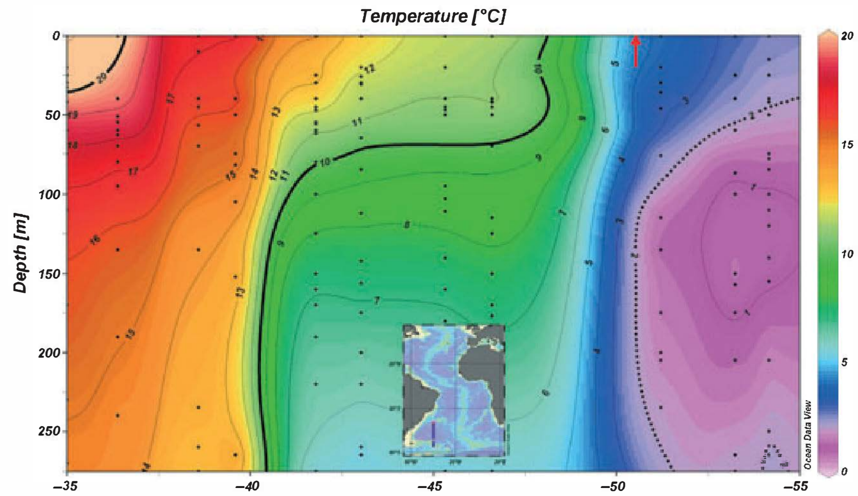

Fig. 13. Vertical distribution of temperature, given in colour and isotherms [°C] (bathythermograph stations) along a 40°W transect during 3 – 10 January 1976; red arrow denotes location of the Antarctic Polarfront (position of 2 °C isotherm at 200 m depth)

properties change from warm and saline subtropical conditions in the north of the STC to colder and fresher conditions in the south of the STC. Figs 12 and 13 indicate that the denser surface waters of subantarctic origin move under the lighter subtropical surface waters. The 10°C isotherm given in bold in Fig. 13, points at seasonal warming of the surface waters during summer. At about 50°30′S the 40°W transect crosses the Antarctic Convergence or the Antarctic Polar Front which is *per definitionem* the position of the 2°C isotherm at 200 m depth. As indicated in Fig. 13 (dotted 2°C isotherm), during the time of observation the Polar Front was masked, i.e. the surface expression of the 2°C isotherm was shifted by more than 5° latitude to the south. Seasonal warming of Antarctic surface waters during austral summer, and possibly the local wind fields have lead to this masking effect. Within the Antarctic domain, at depths around 100 m, a cold water core is visible in Fig. 13. This < 1°C water mass is the so-called winter water originating from intense downward convection released by extreme cooling at the sea surface during the whole winter season, cf. (Stein, 1981).

Acknowledgements

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