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What causes long-term temporal changes in the South Atlantic?

Jürgen Holfort[1], Michael Vanicek[2], and Gerold Siedler[3]

Institut für Meereskunde, Universität Kiel

Abstract. Two zonal sections at 11°S in the South Atlantic, separated in time by 11 years, provide temperature differences in the deep ocean. The aim of this case study is to check whether intrinsic temperature changes are sufficiently large to identify long-term water mass property variations which could be related to climate change. Potential temperature differences on isobaric surfaces in the deep ocean here reach several tenths of °C. They can be caused by vertical (cross-isopycnal) or horizontal (isopycnal) advection and mixing, or by intrinsic water mass changes. The effect of vertical transport is removed by using neutral (density) surfaces. The effect of horizontal transport is determined by using a mixing parameterization for temperature and silica on neutral surfaces. The residual intrinsic temperature changes are, with a few local exceptions, within the range of the ±0.05°C uncertainty, and the temperature changes can thus be explained by advection and mixing alone.

Introduction

Although the World Ocean Circulation Experiment (WOCE) had as its primary goal the determination of a snapshot of the 'mean' circulation, it soon became obvious that information could also be gained in WOCE on the variability of fields. There are two fundamentally different approaches in observing long-term changes in the ocean. Temporal changes of the ocean are studied at near-island stations like the Bermuda Atlantic Time-Series Station (BATS)(e.g. [*Joyce and Robbins*, 1996]), the Hawaii Ocean Time Series Station (HOT) (e.g. [*Karl and Lukas*, 1996]) or the European Station for Time Series in the Ocean, Canary Islands (ESTOC) (e.g. [*Llinás et al.*, 1994]). Such observations ensure a high resolution in time, but are restricted in space to a limited region. Another approach is the comparison of two or more large-scale sections from different years with a high resolution in station distance ([*Bindoff & Church*, 1992; *Roemmich*, 1984; *Parrilla et al.*, 1994]). The latter approach is used here for two selected South Atlantic sections which are separated by eleven years. Such data do not allow the study of near-surface variability on annual or shorter time scales, and the analysis is therefore restricted here to the deep part of the ocean where the changes on short time scales can be expected to have less influence.

Changes in temperature, salinity and other properties can be considerable in the deep ocean when compared to the typical spatial variability at those depths. It is an issue of major interest in climate studies whether global warming is influencing the intrinsic temperature of deep ocean water masses. We will attempt here to quantify such intrinsic temperature changes by first assuming that such changes do not exist. In such a case, observed temporal variability at a fixed point in space can only result from vertical (cross-isopycnal) displacement or by mixing and lateral displacement along density surfaces. Any temperature changes that remain after correcting for these processes will be viewed as intrinsic change.

The two data sets used in the present study are the OCEANUS 133 section from March 1983 [*Warren and Speer*, 1991] and the WOCE A8 METEOR section from April 1994 [*Zenk and Müller*, 1995]), both at nominally 11°S. The data sets contained temperature, salinity, pressure and nutrients. In order to obtain a consistent data base, the silica data were interpolated onto the respective CTD data using a multiple regression method as described by [*Wallace*, 1995] and [*Holfort et al.*, 1998].

Temperature differences and their causes

The differences of parameter values between section pairs at a similar latitude were determined by first interpolating the more recent section onto the earlier section and then calculating the differences at the respective station locations. The following approach was used. We searched for the more recent stations that bracketed an earlier station in the zonal direction. Data from the two bracketing stations were first interpolated onto the same pressure or neutral density level (see [*McDougall*, 1987; *Jackett and McDougall*, 1997]), respectively, and were then interpolated to the longitude corresponding to the location of the corresponding earlier station. Stations with separations exceeding 1.5° of latitude or longitude were not used.

Errors in such calculations arise not only from random measurement errors, but also from systematic differences between data from both cruises. Although the measurement accuracy for salinity during one cruise will be about 0.002 (WOCE standard) relative to a certain batch of standard sea water, differences between different batches can be higher then 0.002. We use data from the deep waters in the Angola Basin for a check. The deep water in this region has a long residence time and is well mixed both horizontally and vertically (see [*Warren and Speer*, 1991] and [*Siedler et al.*, 1996]). We therefore do not expect large temporal

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[1] Now at Institut für Meereskunde, Universität Hamburg.

[2] Now at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

[3] Presently at Instituto Canario de Ciencias Marinas, Telde, Gran Canaria, Spain.

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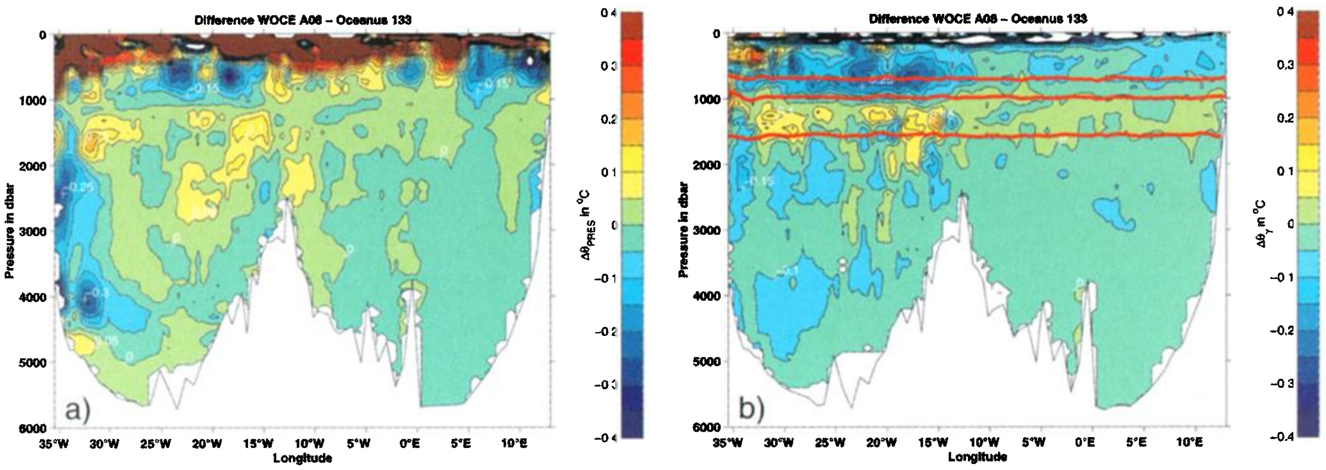

Figure 1. Potential temperature differences at 11°S between WOCE A08 (1994) and Oceanus 133 (1983), where blue colors represents cooling and red warming. a) on isobars. b) on neutral surfaces (marked in red are the locations of the neutral surfaces $\gamma = 27.4$, 27.6 and 27.9).

and spatial variability there, and the differences found in the eastern basin can be taken as a measure of the systematic differences between both cruises. The comparison on pressure surfaces leads to differences in the deep part of the eastern basin that are generally smaller then 0.01 °C in temperature (Figure 1a) and 0.005 in salinity.

The silica values of WOCE A8 are about 2μmol/kg lower than the values from Oceanus 133. The A8 line also has lower silica values in comparison with other cruises in the region ([*Gouretski & Jancke*, 1998]).

The observed property changes between sections can have different causes. They can be due to changes of intrinsic properties of the water masses. On the other hand changes in the oceanic circulation and also in mixing can lead to a lateral displacement of water, with the same point in space therefore representing different water masses at different times. Also, a vertical displacement of water masses, particularly due to internal waves and mesoscale eddies on shorter time scales, will appear as a property change on isobars.

In order to remove the influence of vertical displacements, we use temperature differences on neutral (density) surfaces instead of pressure surfaces. The results for 11°S are shown in Figure 1b. In general, the temperature changes are smaller when using neutral surfaces. A distinct temperature increase is recognized in the depth range between about 1100 and 1700dbar. The largest signal is found in the Brazil Basin in the west, and a smaller signal range stretches to the African coast in the east. A temperature decrease by more then 0.05°C is found in the region of the deep western boundary current and in a large part of the deep western basin below 2000 dbar.

We now want to separate the effects of lateral displacement and mixing from the intrinsic property changes of water masses. For example a longitudinal displacement of the core of NADW can lead to a dipole with a positive anomaly at the longitude where the core was located at the newer section and a negative anomaly where the core was located at the earlier section. Along a neutral surface the effects of displacement and mixing lead to changes in properties on this

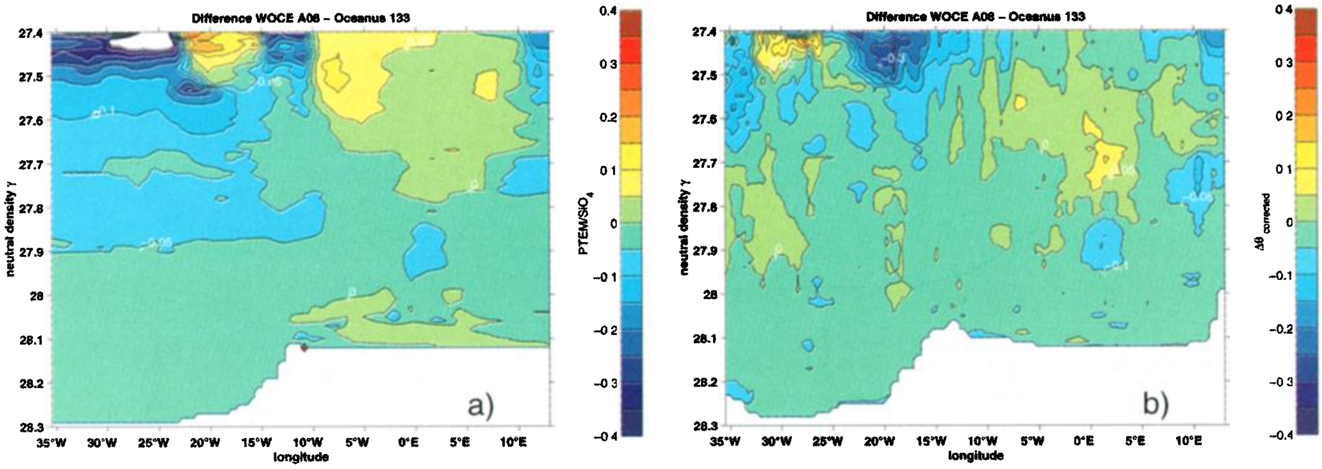

Figure 2. 11°S sections. a) The linear term a_1 of the local correlation between potential temperature and silica ($\theta = a_0 + a_1 * SiO_4$ in °C μmol^{-1}kg). b) Corrected temperature differences showing the intrinsic changes in water mass characteristics at 11°S.

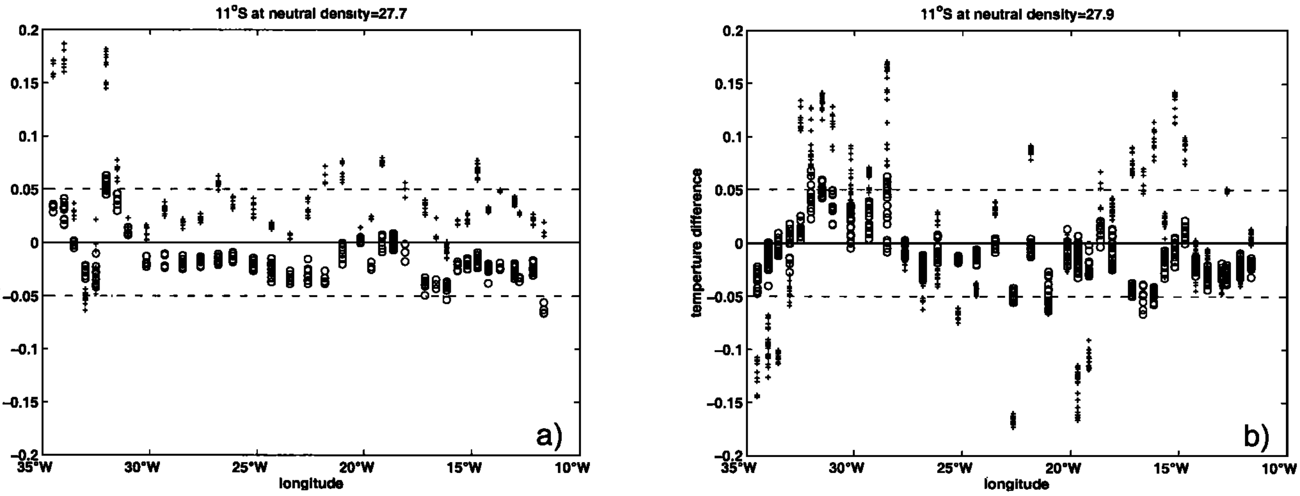

Figure 3. Potential temperature differences on neutral density $\gamma = 27.7$ (a) and $\gamma = 27.9$ (b) between WOCE A8 and Oceanus 133 at 11°S. Crosses are without, circles with correction for lateral displacement and mixing.

surface. Assuming that only two water masses are involved, a linear correlation can be expected to exist between two conservative tracers. Lateral displacement and mixing are therefore identified by using the temperature-silica correlation on neutral surfaces resulting from a simple two-member mixing parameterization. Changes in one property (temperature) can then be determined from changes in the other property (silica). We cannot use salinity for this purpose because salinity is a function of temperature along an isopycnal surface. Silica is not truly a conservative tracer, but in general the sources are so small, that it takes at least 100 years before this source term becomes significant (see [*van Bennekom*, 1996]). We are also not trying to infer the complete mixing history of the water parcel but just want to infer the local correlation of temperature and silica on a isopycnal surface.

For each data point we calculated the linear correlation between silica and potential temperature on neutral density surfaces, using data within ±5° of longitude around each data point. Using the obtained linear term (Figure 2a) we calculated the change in temperature which corresponds to the observed silica difference. Subtracting these temperature changes from the total observed temperature difference between the sections, we obtain as a residual the difference which is due to intrinsic property changes of water masses (Figure 2b). With a relative uncertainty of 1 μmol kg^{-1} in SiO$_4$ the value of the linear term of Figure 2a expresses the uncertainty in the intrinsic temperature change. In the deep ocean below about 1000dbar, corresponding to neutral densities $\gamma > 27.6$, the uncertainty is of order 0.05°C. Results are similar when using the actual data points instead of the gridded fields.

The non-gridded temperature differences on neutral surfaces in Figure 3 show a strong variability from station to station. The corrected temperature differences are much smoother. This could be the effect of eddies and/or meandering current bands. An eddy of 'fresh' North Atlantic Deep Water (NADW) at one station of the more recent section shows up as a positive temperature anomaly (e.g. at 22°W), but it also has a negative SiO$_4$ anomaly. The displacement/mixing correction takes this into account, and the result is a much smoother curve of corrected temperature differences.

The resulting intrinsic temperature changes are small and, with the exception of a few small-scale features (e.g. at about 2°E in the range of the upper Circumpolar Deep Water and the upper NADW), they are within the uncertainty of 0.05°C. Thus although intrinsic changes in water mass characteristics were observed at or in the vicinity of the formation regions (see [*Bersch et al.*, 1999], [*Joyce et al.*, 1999], [*Sy et al.*, 1997] and others) no such changes can be seen at 11°S. Most probably these changes have been *diluted*, due to mixing with other water masses, to such a degree that the remaining signals are smaller than the error of our calculation. Similarly [*Joyce and Robbins*, 1996] found that changes at Bermuda and 65°W at depths from 500 to 2500 dbar could be explained by vertical excursions of isopycnals or meridional excursions without a change in the T/S relation of the upstream sources. We conclude that in the case studied here in the South Atlantic, the deep water temperature changes observed below 1000m can be explained by vertical or lateral advection and mixing alone. Any possibly existing intrinsic property changes affecting temperature and silicate in a different way are too small to be detectable with the available observational accuracy.

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J. Holfort, Institut für Meereskunde, Universität Hamburg, Troplowitzstr.7, 22529 Hamburg, Germany (email: holfort@ifm.uni-hamburg.de)

M. Vanicek, Woods Hole Oceanographic Institution 360 Woods Hole Road Woods Hole, MA 02543, USA (email: mvanicek@whoi.edu)

G. Siedler, Institut für Meereskunde, Universität Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany (email: gsiedler@ifm.uni-kiel.de)

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