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Seasonal cycle and interannual variability of the heat content on a hydrographic section off Santander (southern Bay of Biscay), 1991–2000

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A standard hydrographical section in the southwestern Bay of Biscay northward from Santander (3°47′W, 43°30′/43°54′N) was sampled monthly from 1991 by the "Instituto Español de Oceanografía". Changes were observed in the heat content and temperature at the surface in the East North Atlantic Central Water (ENACW) and also at the Mediterranean Water (MW) layers. At the surface, in addition to the typical seasonal cycle that shows rapid warming in the spring and slower cooling in the autumn, there was also a suggestion of a warming trend, but it was not statistically significant. Local and occasional sources of variability, such as coastal upwelling, were also detected. Significant warming trends were found for the shallower ENACW, where water mass characteristic changes occurred along the temperature–salinity diagram (around 0.03 to 0.06°C yr^{-1}), and also for the Mediterranean influenced water mass, where its evolution takes place along the isopycnal surface (around 0.02°C yr^{-1}).

Keywords: Bay of Biscay, heat content, seasonal cycle, warming trend.

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Introduction

A standard section northward from Santander (43°30′N 3°47′W, 43°54′N 3°47′W) has been sampled monthly since 1991 from the RV "José Rioja" of the "Instituto Español de Oceanografía". The data were collected at 7 stations, for the first period only for upper waters and from 1993 up to 1000 m depth (or to the maximum depth in the shallower stations) using a CTD profiler (see Figure 1).

Below the surface waters of the Bay of Biscay, there is a broad layer of East North Atlantic Central Water (ENACW). Its deeper part is influenced by Mediterranean Water (MW) which, after leaving the Gibraltar Strait, spreads off into the Atlantic Basin and finds its buoyancy equilibrium at this position. Below that there is a layer of East North Atlantic Deep Water formed in the Denmark Strait and Labrador Sea (OSPAR Commission, 2000).

Methods

The statistical fitting of the data from the mixing layer, where a seasonal cycle is present, was performed using annual and semi-annual harmonic terms in addition to a linear trend. Statistical significance was determined using the inverse of the statistical F cumulative distribution function, and the confidence region calculated for the six fitting parameters (independent and linear terms and amplitudes for sinusoidal and co-sinusoidal for both annual and semi-annual terms) following Jenkins and Watts (2000). Such fitting makes the confidence region an M-dimensional ellipse and, as the functions used for the fitting are not orthogonal, we could not take the confidence intervals as the ellipse semi-axes directly, so they were calculated following Chelton (1983). In regions without a seasonal cycle we have performed a simple linear fitting using the same methodology.

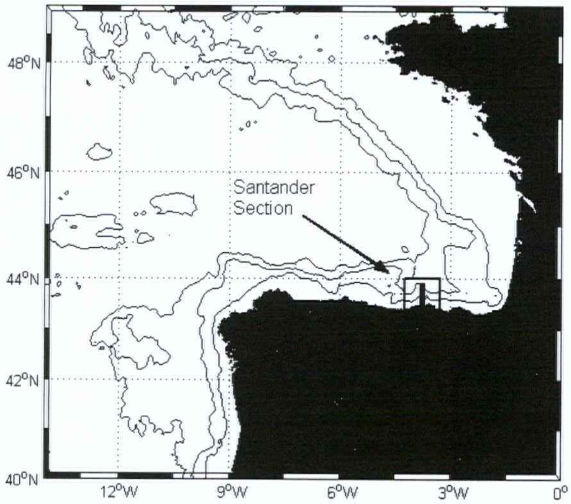

Figure 1. Chart showing location of the hydrographic section northward of Santander.

Upper water layer variability

The surface water layer depends on a seasonal cycle of solar radiation, but is also highly influenced by surface currents, wind regimes, river run-off (mainly in the Eastern part of the Bay of Biscay), and coastal upwelling events (Lavín *et al.*, 1998).

Upper layer water temperature does not follow a sinusoidal seasonal cycle but experiences a rapid warming period in late spring while the autumn cooling process is usually less abrupt, so the semi-annual term is needed to achieve a correct fitting. Our data set reveals a positive warming trend for upper water at all stations (around 0.06°C yr^{-1} for external stations and less at shelf stations where coastal variability is higher), but at none of the stations was the trend statically significant at the 95% level. This is similar to the warming trend found by Koutsicopoulos *et al.* (1998) in the Southern Bay of Biscay, derived from SST images (0.06°C yr^{-1}) from 1973 to 1993, and is also in accord with the winter warming trend shown by Pingree (1994) in the slope region in the same area. On the other hand there is a clear reduction in trends when comparing with previous analysis of the data for a shorter period (Lavín *et al.*, 1998).

Central water evolution in the 1990s

Heat content stored in the water column was calculated for 100 m layers from the limit of the seasonal cycle (200 m) down to 1000 m and fit with a linear trend line. At station 8 (the more oceanic and best sampled deep station), there was increasing heat content through the 1990s in all layers. The increases in the 200 to 500 m layers and also the 700 to 900 m layers (from 100 to 300 kJ m^{-3} yr^{-1}) were significantly different from zero.

From the heat content, we calculated the average rate of increase in temperature for each depth layer assuming standard (35, 10, 0) seawater (Figure 2). They ranged from 0.02°C yr^{-1} to 0.06°C yr^{-1} in such regions with statistical significance, with the largest increase in the shallowest (200–300 m) layer and almost no trend in the 600–700 m layer. Unfortunately, the lack of data at deeper depths prevents us from determining whether there were significant trends in other water masses.

For the shallower part of the ENACW there was an increase of warmer water quantity. This change occurred along the T–S relationship defined by the historic water mass characteristics. As reported by Pérez *et al.* (2000), analysing the $\sigma_0 = 27.1$ kg m^{-3} (corresponding to around our 200 to 300 m depth branch) ENACW of the eastern North Atlantic responds quickly to climatological forcing and hence these variations are highly correlated with the NAO index; an especially warm decade at the North Atlantic could have caused the observed trends for this water mass at the southern Bay of Biscay.

In the case of the deeper layer (Mediterranean influenced seawater) the T–S was in fact transformed, showing a clear displacement towards warmer and salty regions. Changes were along constant, locally defined, density surfaces (Pingree, 1972).

This surprising behaviour may be explained by an increase in outflow of MW at Gibraltar, a stronger northward transport of MW, a variation in the characteristics of the MW – or the Atlantic waters that mixed with it – in the mixing rate between these water masses, or perhaps a combination of all of these possibilities. In fact the warming and the increasing salinity of the Mediterranean intermediate and deep layers have been reported (Rohling and Bryden, 1992). Variations in Mediterranean water

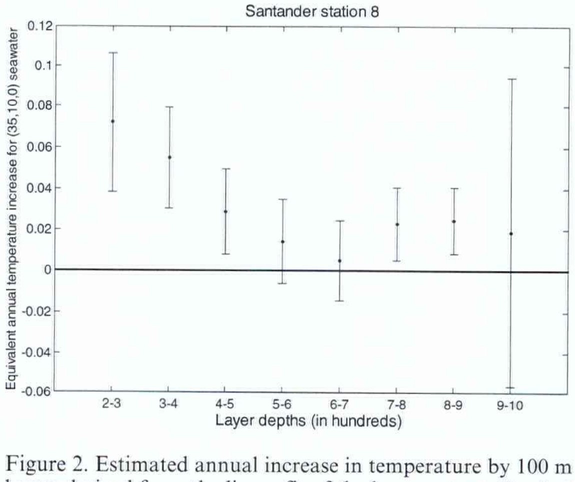

Figure 2. Estimated annual increase in temperature by 100 m layers derived from the linear fit of the heat content. Vertical lines indicate the 95% confidence limits.

mass in the Eastern North Atlantic have not yet been reported, perhaps because the intense diapycnal mixing which occurs during spreading, and the lack of homogenization of the branch until it reaches the southern Bay of Biscay renders analysis, such as the one performed by Rohling and Bryden (1992), difficult, since it involved compiling data from several stations from different cruises over a wide area.

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