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Seasonal variability of the upper warmwatersphere in the Canary Basin*

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SUMMARY: Two years of periodic XBT data, along seven transects covering the Canary Basin, were examined to analyse the seasonal cycle of the upper layers of the warmwatersphere. This is characterised by seasonal storage/release of heat in the surface mixed layer and by the winter formation of a subsurface positive temperature anomaly. Its maximum value takes place in early winter and deepens to about 150 m in late spring, disappearing afterwards. We present a very simple argument, which illustrates how the evolution of the temperature anomaly is controlled both by the ocean-atmosphere heat exchange and by the shape of the North-Atlantic Central Water T-S relationship.

Key words: Canary Basin, surface mixed layer, heat exchange.

INTRODUCTION

The warmwatersphere is the relatively shallow (always less than 1 km) pool of warm water in the subtropical Atlantic, comprising both North Atlantic and South Atlantic Central Waters (NACW, SACW). North of the Canary Archipelago the NACW is the predominant water mass in the warmwatersphere. It is a relatively salty water mass that has its origin in the Canary Current flowing from northern regions. Its saltiness makes it relatively unstable and liable to be a source of vertical convection and water mass formation. Siedler *et al.* (1987) concluded that the eastern North Atlantic basin near Madeira is indeed a region for “mode water” formation, the water mass being formed at the sea surface and left under the seasonal thermocline (McCartney, 1977).

During the last decade the National Oceanographic and Atmospheric Administration and other institutions have made a very great effort to take routine ocean temperature measurements from opportunity ships. Such programme have helped to obtain a much better view of the dominant temporal cycles in the upper ocean and the data set that is being obtained will be of critical importance to understand long-term changes in the ocean. These programme, however, usually look at very large-scale features and lack the necessary spatial resolution to examine in detail regional processes such as the formation of Madeira mode water. This gap is partially filled with regional projects such as the CANIGO one, funded by the European Commission, which covered the Azores-Canary Islands-Strait of Gibraltar region between 1996 and 1999.

In this paper we will present a set of XBT sections done in the easternmost portion of the North

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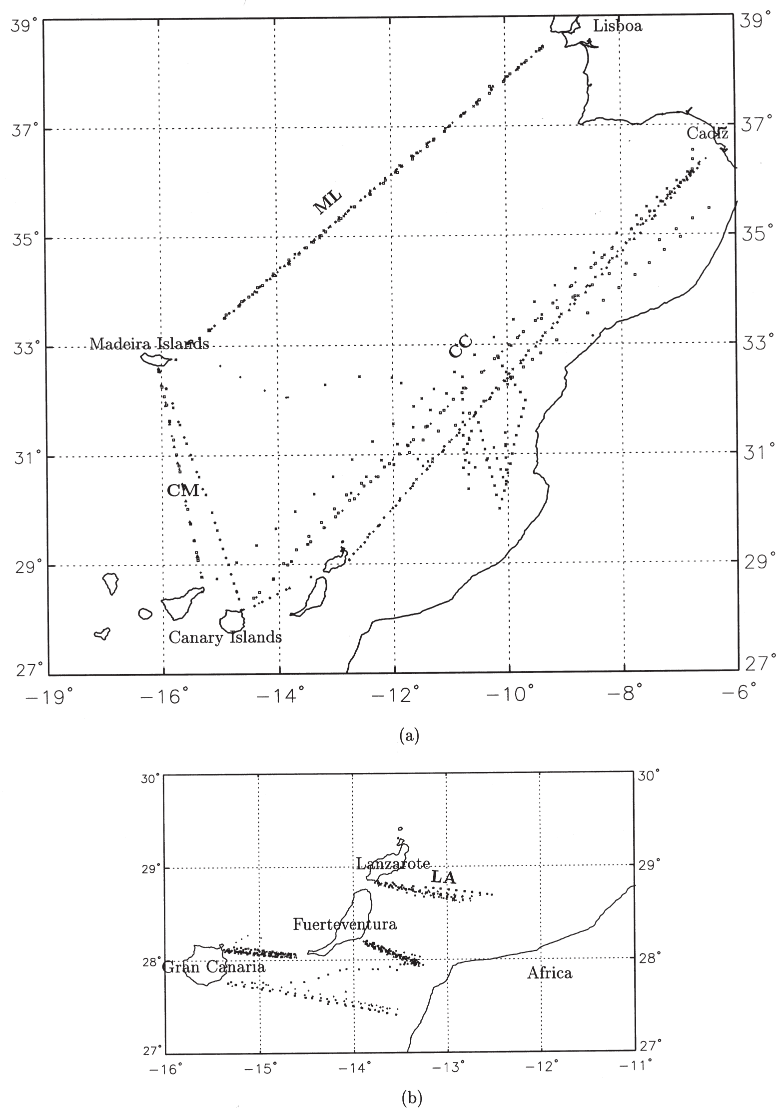

FIG. 1. – Location of all XBT stations collected under CANIGO project. (a) Long sections between the Canary Islands, the Iberian Peninsula, and the Madeira Islands and (b) short sections between the Canary Islands and the northwestern African continental shelf.

Atlantic Subtropical gyre with rather good temporal and spatial resolution. This is a region where a warm water mass is formed thanks to the presence of relatively cool surface waters prone to warming, which are advected southward by the Azores-Canary Current or raised to the surface through coastal upwelling (Pelegrí *et al.*, 1997). The XBT sections form a closed box initially aimed at calculating geostrophic water transports through the region, but they may also illustrate the temporal evolution of the upper ocean thermal structure. We will see that the evolution of the temperature anomaly in the top 200 m follows a seasonal cycle as the result of atmosphere-ocean heat exchange, and is indicative of the history of winter vertical convection and mixing.

DATA SET

The two-year temperature data set consists of three relatively long sections (Canary Is.-Cádiz, CC; Canary Is.-Madeira, CM; Madeira-Lisbon, ML) carried out approximately every three months, and three short sections between the eastern islands of the Canary Archipelago and the African coastline carried out with bimonthly periodicity. Expendable bathythermographs (XBTs) that go down to 760 m were launched from opportunity ships, and the mean distance between stations was 35 km for the long sections and 8 km for the short ones. Figure 1 shows the location of all XBT stations.

The data were horizontally and vertically interpolated to obtain the mean temperature distribution

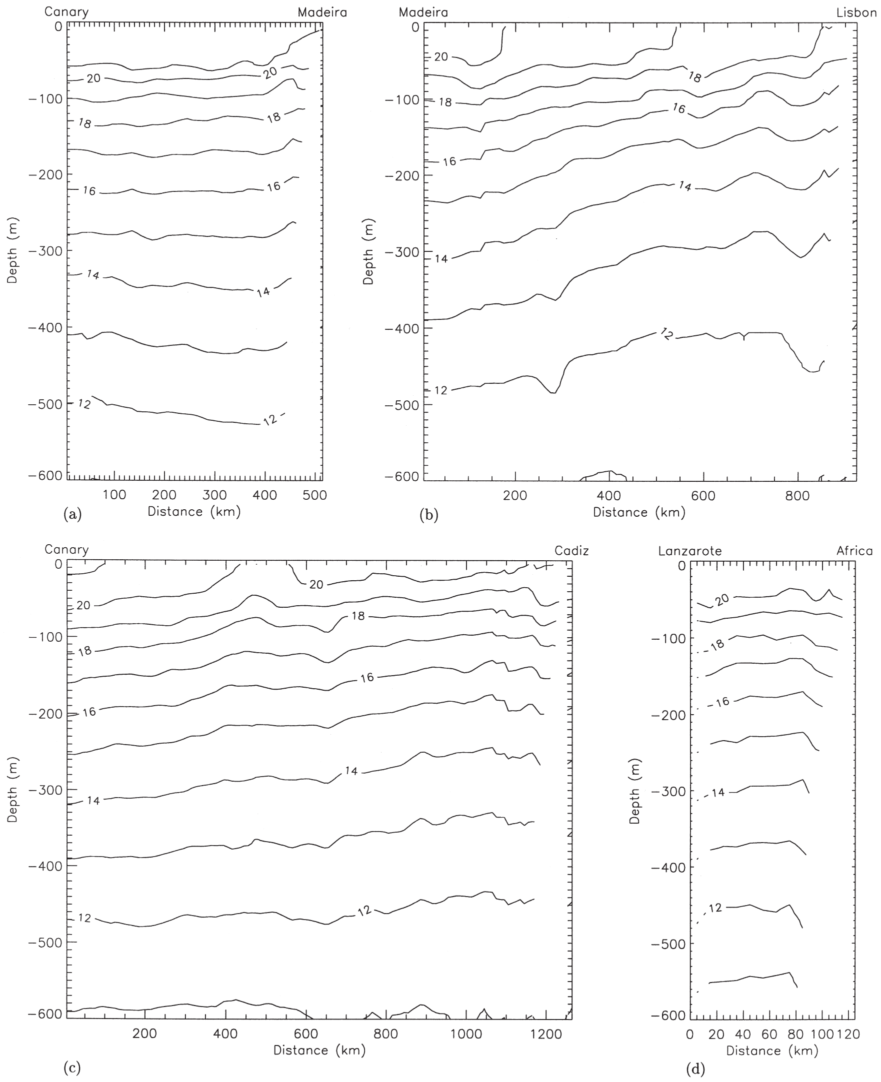

FIG. 2. – Mean temperature sections for the (a) Canary Is.-Madeira (CM), (b) Madeira-Lisbon (ML), Canary Is.-Cádiz (CC), and Lanzarote-Africa (LA) lines. The vertical axis represents depth in meter and horizontal axis distance in kilometers. Isolines are every 1ºC.

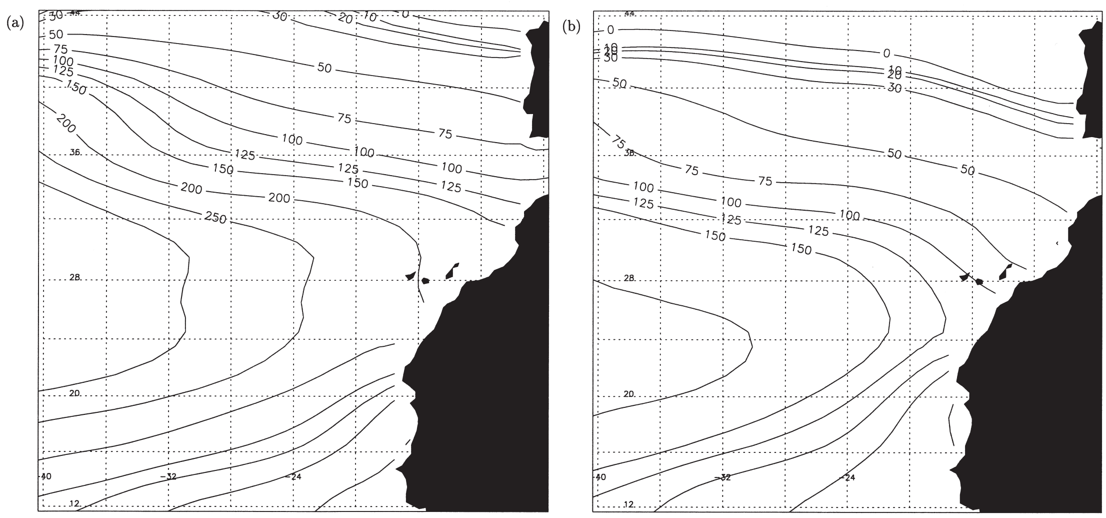

FIG. 3. – Topography in metres of (a) the 16ºC and (b) the 18ºC isotherms as obtained from the Levitus data set.

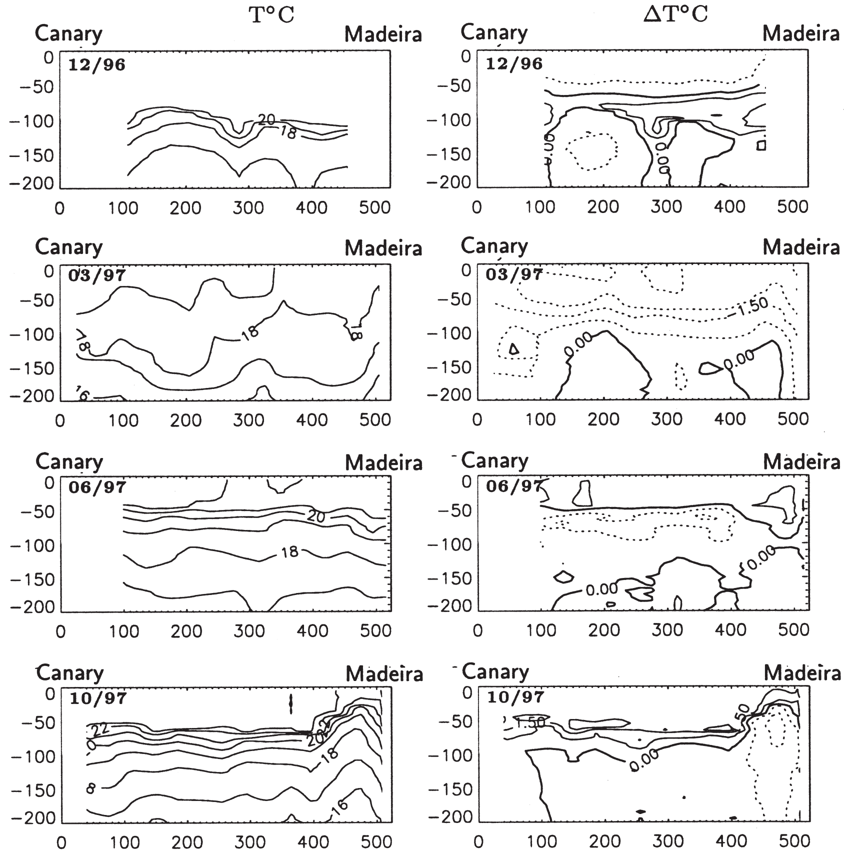

FIG. 4. – Temperature and temperature anomaly distributions along the CM line in December 1996, March 1997, June 1997 and October 1997. Regions of positive and negative anomalies are represented respectively with continous and dotted lines, with isolines separated by 0.75ºC.

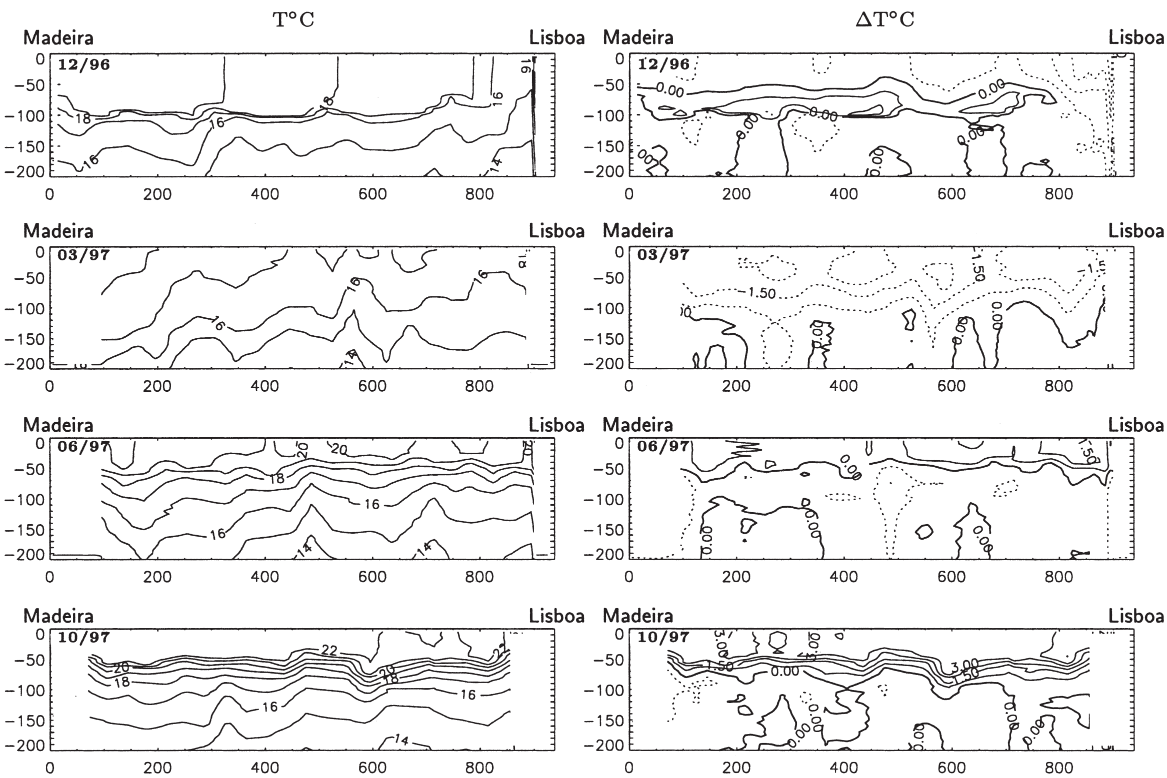

FIG. 5. – As in Figure 4 but along the ML line.

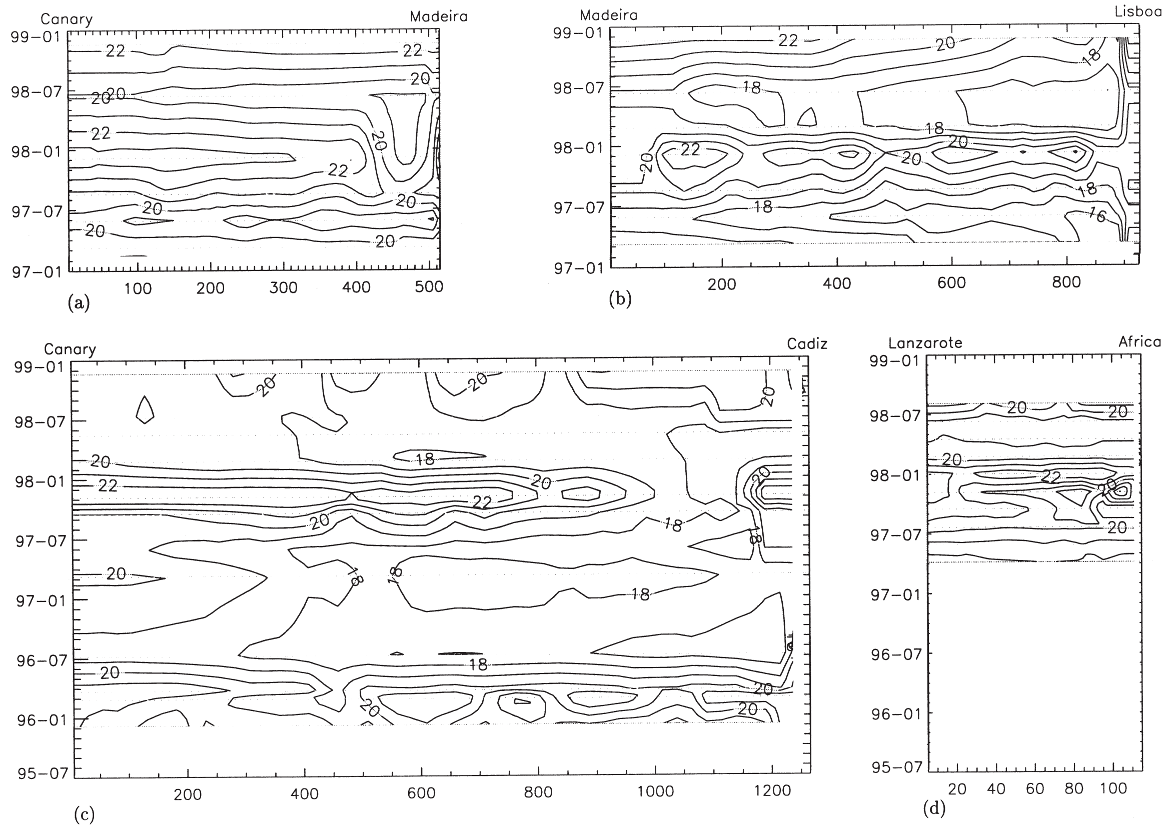

FIG. 6. – Space-time plot of the temperature distribution at 50 m along (a) CM, (b) ML, (c) CC and (d) LA lines. Isolines are every 1ºC.

for the different sections. In total we processed eight transects for the CM line, seven for ML, thirteen for CC, and ten for the Lanzarote-African coast (LA) line. Figure 2 shows these mean sections for the CC, CM, ML and LA lines. Along CM the isotherms are rather flat, along both CC and ML they show a substantial rise with latitude, and along LA they rise slightly towards the east except close to the African coast. These data are coherent with the topography of isotherms presented in Figure 3, as obtained from the Levitus data set (Levitus and Boyer, 1994). The seasonal changes in temperature structure and heat content take place (within the accuracy of the XBT probes, about 0.2ºC) in the top 200 m and this is the portion of the water column that will be examined in the following sections.

SPATIAL AND TEMPORAL VARIABILITY

Figures 4 and 5 show the vertical distributions of temperature and temperature anomaly, relative to the previously computed mean, along the CM and ML lines, corresponding to four different sections taken in different seasons (December 1996, March 1997, June 1997 and October 1997). The mixed layer is relatively cold and deep in December and March, and warm and shallow in June and October. The maximum depth and minimum temperature of the mixed layer correspond to the early spring section (March), the minimum depth corresponds to the early summer section (June), and the maximum temperatures occur after ocean heating during the whole summer (October). The temperature anomaly sections illustrate the relatively cold/warm situations that are reached after cooling/warming during the whole winter/summer. A striking feature is the positive subsurface temperature anomaly in winter found at the lower part of the mixed layer.

Figure 6 presents a space-time plot of the temperature at 50 m along four lines (CM, ML, CC and LA) using all available casts. We may observe that heating starts earlier and lasts longer in the southern regions, in accordance with heat flux estimates for the North Atlantic (e.g., Bunker, 1976; Schmitt et al., 1989). In the CC line a relatively cool region is observed at about 500 km, which corresponds to the location of the Cape Ghir filament.

Figures 7 and 8 are a space-time representations of the temperature anomaly distribution at four different depths (10 m, 50 m, 100 m and 200 m), along lines ML and LA, as obtained using all available data. The sea-

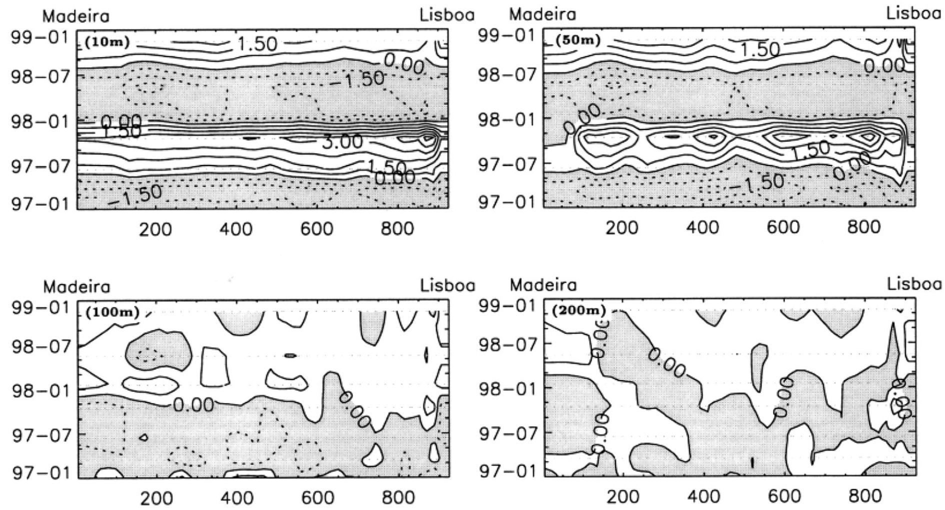

FIG. 7. – Space-time plot of the temperature anomaly distribution at four different depths (10 m, 50 m, 100 m and 200 m) along the ML line.

sonal cycle is quite striking in the two top levels (10 and 50 m) while below 100 m depth the temperature anomaly distribution does not show any seasonal cycle. In the LA lines there is some spatial variability, probably due to upwelling filaments emanating from the coast.

Figure 9 illustrates the evolution of a temperature profile in the top 200 m at a location about 100 km north of Madeira (Fig. 9a) and at a location about 20 km east of Lanzarote (Fig. 9b). In both cases the thick line corresponds to the mean profile as obtained from all available XBT casts at the respective location. For the location north of Madeira we present the temperature profiles corresponding to December 1996, March 1997, June 1997, and October 1997. For the location east of Lanzarote we present bimonthly profiles starting in January 1997 and ending in July 1998. The seasonal evolution of the surface mixed layer and the vertical location and extension of the subsurface temperature maximum may be appreciated from these individual casts.

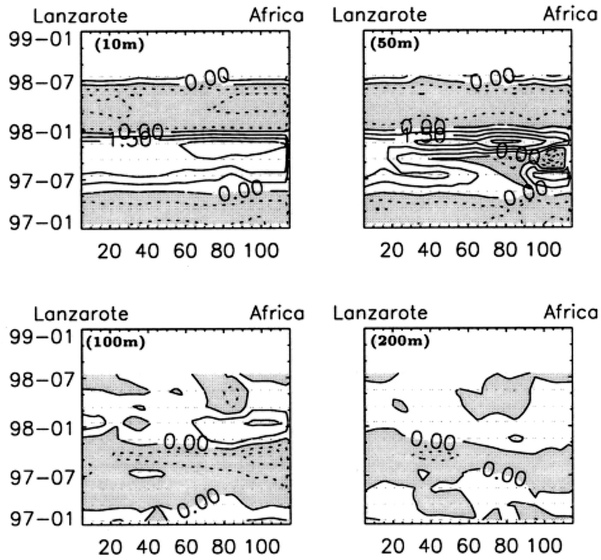

FIG. 8. – As in Figure 7 but along the LA line.

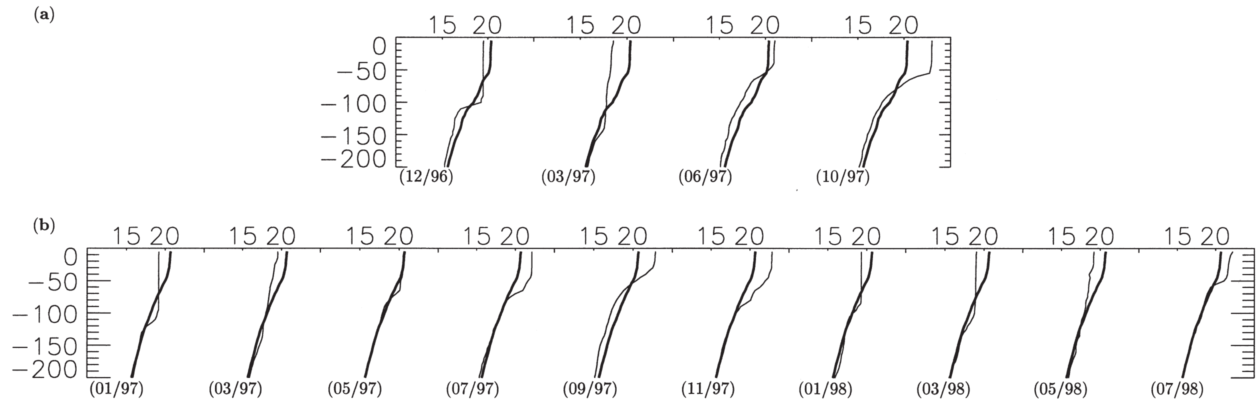

FIG. 9. – Temporal evolution of the top 200 m temperature profile at (a) 100 km north of Madeira and (b) 20 km east of Lanzarote. Thick lines represent the mean temperature profile.

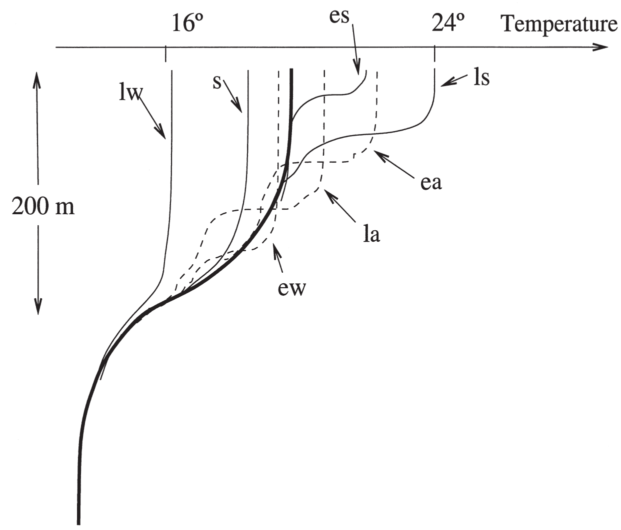

FIG. 10. – Idealized sketch of the mixed-layer temporal evolution (see text for explanation). The thick line corresponds to the annual mean profile.

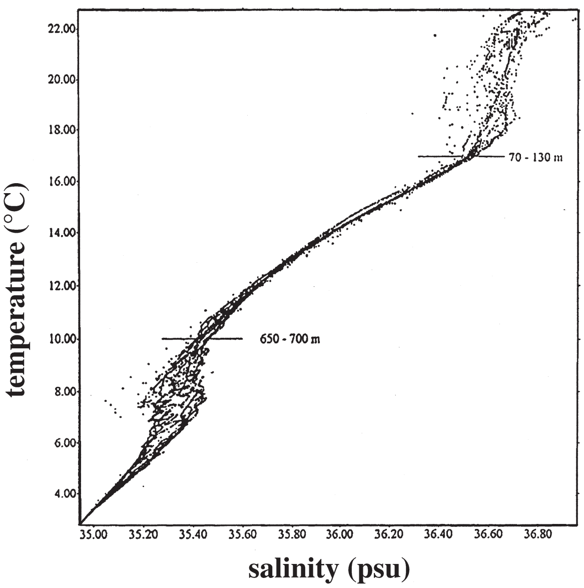

FIG. 11. – Temperature-Salinity diagram in the 26-28ºN, 15-17ºW square box.

THE SUBSURFACE WINTER TEMPERATURE ANOMALY

A remarkable feature in all time-space temperature anomaly plots is the presence of a subsurface temperature maximum in winter. This maximum corresponds to the lower portion of the surface layer formed by vertical convection/mixing in winter, which turns out to be warmer than the mean annual temperature at this depth. Throughout spring and summer the mixed layer is capped by a shallow surface layer, under which remain the relics of the deep wintertime mixed layer. This water left under the new mixed layer is thought to spread horizontally over long distances and to form what has been called the Madeira mode water (Siedler *et al.*, 1987).

Figure 10 shows an idealized sketch of the mixed-layer temporal evolution, the thick line indicating the annual mean profile, which may be summarized as follows. In late winter (lw) the mixed layer reaches its minimum temperature and maximum depth, which slowly shifts along the mean profile in spring (s) as the upper ocean starts gaining heat. By early summer (es) a shallow mixed layer has formed which warms up and thickens until late summer (ls), due to the combined effect of intense heating and stirring by the intense summer easterly winds. By early autumn (ea) the upper ocean slowly starts losing heat, a process which increases during late autumn (la) and early winter (ew).

The loss of heat to the atmosphere in the salty upper layer makes it unstable, thus allowing progressive vertical convection and mixing to take place. This evolution may be understood with the help of temperature-salinity (T-S) diagrams for the region, such as the one shown in Figure 11. This diagram has been constructed using data from over 50 CTD casts in a 2 by 2º square box (26-28ºN, 15-17ºW), obtained from NODC historical data. In this particular T-S diagram we may see that the surface mixed layer reaches values above 22ºC and its maximum depth is about 130 m. The T-S diagram clearly shows the position of the mixed layer as where the data points spread and the temperature increases rapidly. Figure 12 hypothesises a sequence in the evolution of the uppermost ocean during autumn/winter (Fig. 12a) and spring/summer (Fig. 12b). During autumn/winter cooling takes place and vertical convection develops until the mixed layer becomes nearly homogeneous in temperature, with an intermediate salinity value. At the initial vertical location reached by convection, the T-S slope will follow an equal density line (ρ_1). Mixing will smooth the vertical gradients and continued vertical convection will tend to homogenise the temperature by following another constant density line (ρ_2) in the T-S diagram. This process will continue as illustrated in Figure 12a, with the data points spanning a T-S band. Figure 12b illustrates the opposite situation as spring progresses: the temperature increases due to net heating and the salinity decreases due to fresh water flux (Schmitt *et al.*, 1989).

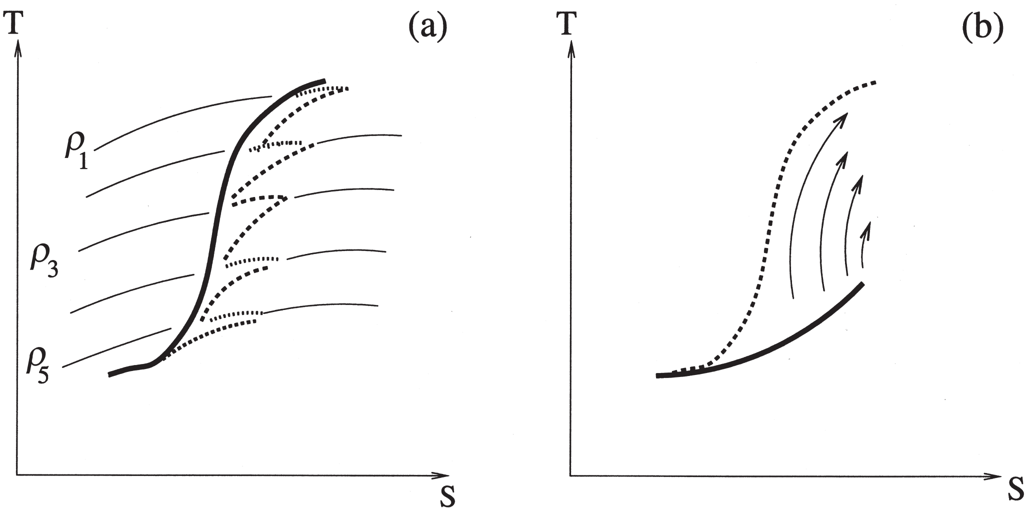

FIG. 12. – Hypothesised T-S sequence in the evolution of the uppermost ocean during (a) Autumn/Winter and (b) Spring/Summer.

CONCLUSIONS

We have analysed the temperature variation in the warmwatersphere of the Canary Basin as obtained from two years of XBT casts along seven lines. The main changes take place in the upper 200 m due to seasonal heating/cooling. A subsurface negative temperature anomaly in winter, centered at about 100 m, is a very ubiquitous feature in the region. This anomaly has its origin in vertical advection and mixing during the cooling season, which results in a mixed layer that progressively deepens as it cools. Close to the African coast there is more spatial and temporal variability, apparently related to upwelling.

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