INTRODUCTION

The upper thermocline waters of the North Atlantic Subtropical Gyre (NASG) off West Africa flow south until latitudes near Cape Blanc, where they turn west, away from the coast. The southward flow is commonly identified with the Canary Current, while the westward turn is thought to be the beginning of the North Equatorial Current. The separation from the African coast and slope takes place rather abruptly, at the Cape Verde frontal system. It prevents southward advection of the NASG thermocline waters, leaving behind what has been called the shadow zone (Luyten et al., 1983; Sarmiento et al., 1982; Kawase and Sarmiento, 1985; Láiz et al., 2001). This dynamically very complex region separates, and merges, two rather distinct water masses: North Atlantic Central Water (NACW) and South Atlantic Central Water (SACW) (Fraga, 1974; Hughes and Barton, 1974; Barton et al., 1977; Manríquez and Fraga, 1982; Barton and Hughes, 1982; Hagen, 1985; Zenk et al., 1991).

Fraga (1974) and Manríquez and Fraga (1982) (hereafter F and MF respectively) examined the water mass distributions in the Cape Verde frontal system off Cape Blanc between 16ºN and 24ºN, using data collected in three different months. Their hydrographic data, which goes down to 1000 m, illustrate the vertical and horizontal distribution of the NACW and SACW. Their results show rather sharp gradients in temperature and salinity in the upper 400 to 600 m, reflecting the transition between these two water types, while the lower half of the water column (600 to 1000 m) was occupied...
by NACW. In the upper 100 m they found an even
er larger contrast in temperature and salinity, with
high-salinity and low-temperature northern waters
separated from very low-salinity and high-tempera-
ture southern waters. The temperature of this surface
water, however, varies seasonally, with temperatures
5 or 6°C higher in November than in March.

One important aspect of the Cape Verde frontal
region is the compensating character of the tempera-
ture and salinity fields, which causes the horizontal
density gradients to be relatively small across the
front. This peculiarity is probably an important fac-
tor in reducing the vertical shear of the horizontal
velocity in the frontal region (Rodríguez-Santana et
al., 1999). As a result, the frontal region is likely to
be rather stable in the vertical, with low diapycnal
exchange of water properties, which in turn is
responsible for the maintained gradients in other
properties such as temperature, salinity and nutrients.

From the above point of view the Cape Verde
frontal system is an effective barrier between different
water masses (rather than a blender: for a nice
discussion see Bower et al., 1985) and water
exchange has to take place mainly as the result of
large-scale horizontal instabilities. Such instabili-
ties, expressed as major interleaving of water mass-
es across the system, have been clearly reported in
previous studies of this region and are responsible for
the high temporal variability in the frontal posi-
tion. Satellite images of sea surface temperature pro-
vide a vivid illustration of this variability but, away
from the coastal upwelling region, these have to be
seen with caution because of the masking by the surfac-
exchange layer. In any case, the surface tempera-
ture field patterns associated with the giant Cape
Blanc filament expelled towards the interior ocean
(Gabric et al., 1993), precisely as a result of the con-
vergence of NACW and SACW at the frontal
region, is a clear indicator of the variability.

Several authors have studied the distribution and
variability of water masses in the Cape Verde front
during different seasons (F and MF; Hughes and
Barton, 1974; Barton and Hughes, 1982; Fraga et
al., 1985). All prior dynamic studies, however, have
either dealt with a single hydrographic cruise (Zenk
et al., 1991) or have used rather limited spatial res-
olution (Barton, 1987). In this work we will analyse
the wonderful data sets used by F and MF, in an
attempt to investigate the relation between the
frontal structure and the flow patterns at the end of
the winter and summer seasons. Additionally, since
water exchange has to take place principally along
isopycnals, we will examine the distribution of
salinity and nutrients using isopycnic coordinates.
The frontal position will be where these properties
show maximum epipycnic gradients. Finally, we
will use infrared images of the water surface (Van
Camp and Jewell, 1990) to help us locate the inter-
leaving of south surface and north surface waters
(SS and NS respectively) in both seasons.

DATA REPRESENTATION ON ISOPYCNIC
COORDINATES

Fraga and Manríquez (1974) and Manríquez and
Fraga (1978) originally published the data used in
this work. The hydrographic data correspond to
cruises Atlor 2 (March 1973) and Atlor 7 (Novem-
ber 1975), and hence may be considered as repre-
sentative of the conditions at the end of winter and
summer respectively. The location of the stations
was almost the same for both cruises and is present-
ed in Figure 1. The data cover a region about 200 km
wide along some 500 km of coastline, but there are
two hydrographic sections normal to the coast of
nearly 450 km length. These sections, indicated as

![Image](image-url)
FIG. 2. – Salinity and density distributions, as a function of depth, along H1 and H2 during Atlor 2 (March 1973). The arrows on top show the position of the front as where the 36.0 ‰ isohaline intersects the 150 m depth.

FIG. 3. – Salinity and density distributions, as a function of depth, along H1 and H2 during Atlor 7 (November 1975). The arrows on top show the position of the front as where the 36.0 ‰ isohaline intersects the 150 m depth.
H1 and H2 in Figure 1, are of key importance to examine the water structure and flow of the boundary region.

**Distributions on sections normal to the coast**

The arrows on top of Figures 2 and 3 show the position of the front, defined as where the 36.0‰ isohaline intersects the 150 m depth (Barton, 1987; Zenk et al., 1991). In the 0-400 m layer the regions of relatively salty (fresh) water correspond to NACW (SACW); in the top 100 m salinity values close to 36.5‰ (35.4‰) are indicative of NS (SS).

Figure 2 illustrates the conditions during Atlor 2 (March 1973; see also Fig. 4 in F). In the top 400 m there is SACW in the central and easternmost portions of H1 and in all but the westernmost portion of H2; the very salty surface water at the western end of H1 is indicative of NS. The compensating character of temperature and salinity is clear in this figure, where the isopycnals appear rather flat, except in the western surface layer of H1 due to the presence of NS. From Figure 2 alone it is not possible to differentiate between NACW and NS near the surface at Station 13 (Section H1), and the homogeneous salinity layer between 200 and 450 m disguises the usual character of the frontal region.

Figure 3 shows the conditions during Atlor 7 (November 1975; see also Fig. 29 in MF). In the top 200 m there is SACW in the eastern portion of H1 and in the mid-western and eastern portions of H2; the very salty surface water in most of H1 is indicative of NS. Again, the density is compensated over most of the sections and the maximum gradients are at the surface due to the contrast between NS and SS.

A comparison of the 36.0‰ -150 m intersection criterion with the percentages of NACW and SACW (as obtained by F and MF) suggests that the presence of NS and SS may indeed misrepresent the existence of a boundary or front. A different alternative is to plot the salinity and nutrient distributions in Sections H1 and H2 against density, as in Figures 4 and 5. Any strong salinity/nitrate gradient at constant density is indicative of a frontal region where epipycnal exchange is inhibited. When looking at each of these distributions we must keep in mind that their upper portion, for sigma-t less than 26.5, roughly corresponds to the top 150 m, where NS and SS are usually found. Hence, the actual boundary between NACW and SACW will correspond to those places with strong epipycnal gradients for densities of 26.5 sigma-t or larger. Taking this into account, we may appreciate that the position of the front according to the 36.0‰ -150 m intersection criterion may not always be correct. This is particularly true for the Atlor 7 (November) sections: according to the criterion of maximum epipycnal gradients the front crosses H1 at about 220 and 350 km and H2 at about 180 km, 360 km and 480 km.

**Distributions on isopycnic surfaces**

Figures 6 and 7 show the salinity and nitrate distributions over three different isopycnals (sigma-t equal to 26.5, 26.8 and 27.1) during Atlor 2 and Atlor 7 respectively. The 26.5 sigma-t surface corresponds to near surface water and it should illustrate changes between NACW, SACW and the warm surface waters. The 26.8 sigma-t surface is located deep enough that no surface water is found here, so any strong gradient on this surface should be indicative of a boundary between NACW and SACW. The 27.1 sigma-t surface is located at depths of more than 500 m, where F and MF found little gradients in water-mass composition.

Figure 6, corresponding to the Atlor 2 cruise, illustrates the existence of strong interleaving between NACW and SACW in the northern region at all three surfaces, and a predominance of SACW in the southeastern region (see Figs. 5 to 8 in F). Figure 7, which corresponds to the Atlor 7 cruise, shows a predominance of NACW, with SACW found only in a band near the African slope (see Figs. 25 to 29 in MF). In particular, the NACW signal is very intense around Station 39 at all three surfaces and around Station 18 at the upper surface.

**VELOCITY FIELDS**

In this section we will examine the north-south geostrophic velocity field, as calculated referred either to 1000 m or to the bottom floor (whichever is shallower). The meridional orientation of the coast will allow us to integrate the velocity transport from the coast and to plot the streamlines of water transport in the top 400 and 800 m.

**Geostrophic velocity field**

Figure 8 illustrates the meridional velocity field relative to 1000 m for both Atlor 2 and Atlor 7 across H1 and H2, but plotted against density rather than depth; northward velocities are taken as posi-
Fig. 4. – Salinity distributions, as a function of density, along H1 and H2, during Atlor 2 and Atlor 7.

Fig. 5. – Nitrate distributions, as a function of density, along H1 and H2, during Atlor 2 and Atlor 7.
FIG. 6. – Salinity and nitrate distributions over three different isopycnals during Atlor 2.

FIG. 7. – Salinity and nitrate distributions over three different isopycnals during Atlor 7.
tive. During Atlor 2 the velocities across both sections are dominantly negative, but there is northward flow across H2 at both the eastern and western ends. The speed is maximum negative across H1, precisely where NACW is found, and it is positive across H2 near the coast, where SACW is found. During Atlor 7 the north-south velocity alternates across both sections, maintaining little correspondence to the water-mass distribution, which suggests that it is undergoing rapid deformation.

**Depth integrated streamlines**

Figure 9 presents the water transport integrated down to 400 and 800 m for both cruises. These depths were chosen based on the water mass distribution found by F and MF, where NACW was always predominant below 400 m. The integration assumes zero flow at the location of the easternmost station and moves zonally towards the interior ocean (a right-hand coordinate system is maintained, with the x axis pointing into the African continent and the y axis pointing north).

A striking feature of the water flow referred to 400 m is the strong meridional convergence that forces the flux to turn westward between H1 and H2. This convergence is still quite clear for the water flow referred to 800 m during Atlor 2 but not so during Atlor 7, in which case the water flows north over most of the domain. The intense water interleaving found by F and MF, and also reported by Barton and Hughes (1982) and Barton (1987), has the form of pronounced north-south meanders immersed in the westward flow.

**Surface mixed layer**

A result that may be inferred from the distribution of south surface and north surface waters, as presented by F and MF, is that surface interleaving is less pronounced by the end of the summer season, with SS well located south of the frontal region. The intensity of surface water interleaving may also be determined from the monthly maximum sea surface temperature distribution, as obtained from infrared satellite observations between 1982 and 1985 (Van
Camp and Jewell, 1990). These maps allow us to obtain the position of the 21.5°C and 25°C surface isothermals in March and November (Fig. 10). This figure shows very large latitudinal movements of the isothermals, mainly due to water heating and cooling during the summer and winter seasons. The positions of the 21.5°C isotherm in March and the 25°C isotherm in November are of particular relevance because these isotherms represent the typical values of SS and NS as shown in F and MF. Close to the African coast the isotherms show larger interleaving in March than in November.

CONCLUSIONS

Isopycnic coordinates may be of valuable help in identifying frontal boundaries in regions where the temperature and salinity fields are compensating, such as in the Cape Verde frontal region. Here we have shown that the 36.0‰ – 150 m intersection criterion may not always be the best choice to locate the Cape Verde front. Instead, we have illustrated that the representation of the salinity and nutrient fields in isopycnic coordinates shows the presence of actual fronts as the place where the exchange of properties along isopycnals is inhibited.

The distribution of salinity, nutrients and meridional velocity in the region is very complex, illustrating strong interleaving between different water masses. Some correspondence between NACW (SACW) and southward (northward) flow may be found, although this association is often unclear, which suggests that the water flow is continuously deforming the density field. During Atlor 7, for example, the dominant flow was north although the prevalent water mass was NACW, possibly indicating that the whole frontal zone had been displaced south beyond its mean position and had to shift north. In general we may conclude that the water flow shows strong convergence between NACW and SACW, which causes the flux to turn westward. This zonal flow is characterised by the presence of unstable meanders, which are probably the origin of the observed interleaving.

The surface temperature field shows very large meridional excursions as the result of warming and cooling during the summer and winter seasons.
respectively. These movements are clearly not associated with water advection. Nevertheless, near the coast, where the surface mixed layer is almost absent, the variability of surface water temperature as observed from satellite images may be indicative of spatial variability in the region. Both the hydrographic measurements and the satellite-derived surface water temperature suggest that the zonal gradients are less intense in November than in March.

ACKNOWLEDGEMENTS

This work was supported by the Spanish government through CICYT’s project MAR96-1893. The
principal author, PPR, wishes to thank the Ministerio de Educación y Cultura of the Spanish government for funding during this work. The authors wish to thank Angel Rodríguez-Santana and three reviewers for a number of useful comments.

REFERENCES


