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Distribution of water masses and diapycnal mixing in the Cape Verde Frontal Zone

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[1] The Cape Verde Frontal Zone separates North and South Atlantic Central Waters in the eastern North Atlantic Subtropical Gyre. CTD-O2 and shipboard ADCP data from three hydrographic sections carried out in September 2003 are used to study the structure of the front. Results show the relation between spatial variations of water masses and currents, demonstrating the importance of advection in the distribution of water masses. Diapycnal diffusivities due to double diffusion and vertical shear instabilities are also estimated. Existence of competition between the two processes through the water column is shown. Depth-averaged diffusivities suggest that salt fingering dominates diapycnal mixing, except areas of purest South Atlantic Central Water. Here, double diffusion processes are weak and, consequently, shear of the flow is the main process. Results also show that strong mixing induced by vertical shear is associated with a large intrusion found near the front. **Citation:** Martínez-Marrero, A., A. Rodríguez-Santana, A. Hernández-Guerra, E. Fraile-Nuez, F. López-Laatzen, P. Vélez-Belchí, and G. Parrilla (2008), Distribution of water masses and diapycnal mixing in the Cape Verde Frontal Zone, *Geophys. Res. Lett.*, *35*, L07609, doi:10.1029/2008GL033229.

1. Introduction

[2] The thermocline waters of the North Atlantic Subtropical Gyre flow southward to 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 the beginning of the North Equatorial Current flowing north of the Cape Verde Frontal Zone (CVFZ). This term was introduced by *Zenk et al.* [1991] to characterize the eastern part of the Central Water Boundary, which is the transition zone between North Atlantic Central Water (NACW) and South Atlantic Central Water (SACW). In the past, several surveys have taken place at the CVFZ to study the distribution and variability of water masses and its relation with the upwelling off West Africa [*Hughes and Barton*, 1974; *Manriquez and Fraga*, 1982; *Barton*, 1987; *Zenk et al.*, 1991]. The CVFZ is described as a strong meandering thermohaline front near Cape Blanc at latitudes close to 20°N. It shows sharp gradients in temperature and salinity in the upper 600 m and the presence of intrusions, produced by interleaving of NACW and SACW across the front with typical vertical scales of 10–100 m.

[3] One important aspect of the CVFZ is the compensating character of the temperature and salinity fields, which cause horizontal density gradients to be relatively small across the front. This peculiarity is an important factor in reducing the vertical shear of the horizontal velocity in some parts of the frontal region. *Klein and Tomczak* [1994] and *Klein and Siedler* [1995] have used multiparameter analysis to analyze diapycnal mixing at the CVFZ. They found significant diapycnal fluxes in the Central Water layers, with water mass composition being changed by more than 20% through diapycnal mixing. The nearly density compensated character of the front and the density ratio results, let them to suggest that double diffusion is the main cause of the observed diapycnal mixing. They conclude that double-diffusive salt flux is an important process for the salt balance in this water mass, and is balanced either by isopycnal advection or isopycnal eddy diffusion.

[4] However, the role of mixing induced by vertical shear of the current in the CVFZ has not been quantified yet. The main purpose of our study is to estimate the relative importance of vertical shear and double diffusion processes in the diapycnal mixing in different parts of the frontal zone.

2. Data and Methods

[5] The data presented here consist of 39 SeaBird 911+ CTD (Conductivity, Temperature, Depth) stations taken along three sections in the CVFZ between 20° and 26°N and between 18° and 26°W (Figure 1). Measurements were taken during the CORICA oceanographic survey carried out aboard the R/V Thalassa in September 2003. CTD-O_2 data from the western and southern sections have been already used to investigate the spatial variability of the Canary Current, by means of an inverse box model by *Hernández-Guerra et al.* [2005]. In this paper we concentrate on the upper 600 m of the three sections, adding the analysis of the shipboard ADCP (Acoustic Doppler Current Profiler) velocity data recorded during the cruise. Distance intervals between stations were approximately 0.4°, except for the African slope stations which were 0.1° apart and the eastern section where the stations had a spacing of 1°. Water samples were collected at each station for the CTD sensor calibration and the analysis of dissolved oxygen. The shipboard ADCP (a narrowband 75-kHz frequency) provided mean current profiles relative to the ship every 5 min in 16-meter bin lengths. Data were required to pass a test of the return signal (Percent Good >90%), acceptable second derivatives of horizontal and vertical velocity components with respect to depth, and reasonable error velocities as recommended by

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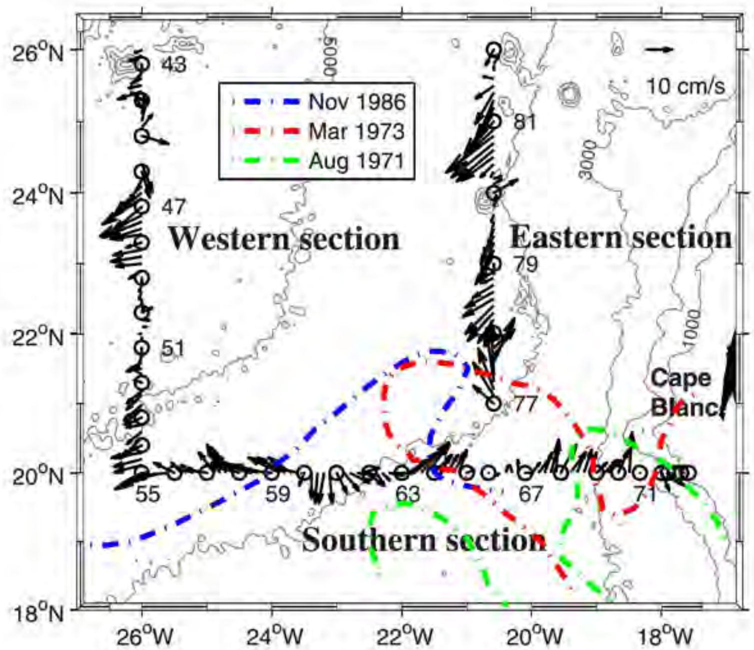

Figure 1. Sections and depth-averaged currents (150–550 m) measured by ADCP. CTD-O_2 stations are indicated by circles. For reference, the three historical westernmost positions of the CVFZ are shown. The March 1973 and August 1971 positions are from *Manriquez and Fraga* [1982], and the November 1986 position is from *Zenk et al.* [1991].

Firing et al. [1995]. The ADCP data shallower than 600-m depth usually satisfied these criteria. The velocities were calibrated for transducer misalignment and adjusted from ship relative currents to absolute currents using GPS position measurements.

[6] The density ratio, R_ρ, is the parameter that dictates a system's susceptibility to double-diffusive instability [*Thorpe*, 2005]. Density ratios were calculated from CTD data using central differences over the same depth intervals as the ADCP data. With these R_ρ we were able to estimate double diffusion diapycnal diffusivities, K_d, using the *Schmitt* [1988] parameterization for the salt-finger type, and the *Kelley* [1990] parameterization for the diffusive type. With potential densities and vertical shear from CTD and ADCP measurements respectively, buoyancy frequencies and gradient Richardson numbers (*Ri*) were calculated. Finally, the vertical shear stress diffusivities, K_s, have been estimated using the *Pacanowski and Philander* [1981] parameterization and the *Ri* values. A full description of the method can be found in the work of *Rodríguez-Santana et al.* [1999]. The scales of the instabilities induced by vertical shear are on the order of 1–10 m [*Pelegrí and Sangrá*, 1998] implying that the depth interval used in the calculation of *Ri*, should be greater than these values. The use of relatively large vertical intervals produces a smoothing effect on *Ri*, and consequently on K_s, that has been analyzed by *Miller and Evans* [1985]. Nevertheless, in this work, the K_d values have been calculated with the same averaging depth intervals (16 m) as for K_s, allowing a comparison between them to be made.

3. Results and Conclusions

3.1. Structure of the Front

[7] An accepted criterion for the position of the CVFZ is the location of the 36.0 isohaline at 150 m depth [*Barton*, 1987; *Zenk et al.*, 1991]. At the southern section, this criterion puts the front at station 64 (21°W) (Figure 2). This figure suggests that the CVFZ approaches the southern section at station 66 (20.5°W). A common characteristic observed in the vertical sections of temperature, salinity and dissolved oxygen is the fluctuation of the isolines, forming consecutive domings. The fluctuations appear to be related to the meandering of the front and the probable presence of eddies. We find upward domings around 24°W, 21°W and 18°–19°W, which are related to the penetration of SACW to the north. The 21°W doming, located at station 65, forms a core of minimum salinity (~35.6) between 100–300 m depth that coincides with a core of minimum oxygen (<60 μmole kg^{-1}), indicating the presence of a northward entrainment of SACW. A clear relation between domings and currents is observed near the front. The upward domings are found, approximately, in zones with northward currents, while downward domings are situated where currents flow to the south. These results suggest that water mass distribution is correlated with mesoscale activity at the CVFZ, illustrating the importance of horizontal advection.

[8] The second column of Figure 2 shows the results for the eastern section. This section also shows mesoscale variability with alternating westward and eastward flowing currents. However, the currents reveal essentially a net westward flow along the section that is coherent with the presence of the southwest extension of the Canary Current north of the CVFZ. The front is found between stations 77 (21°N) and 78 (22°N). The results show a meander or eddy structure that produces a SACW penetration centred at station 77. Oxygen values <60 and 100 μmole kg^{-1} are observed again in the purest SACW, and at the front position, respectively. The position of the front coincides with a change of velocity direction: station 77 (21°N) shows a northwestward current that is advecting the tongue of

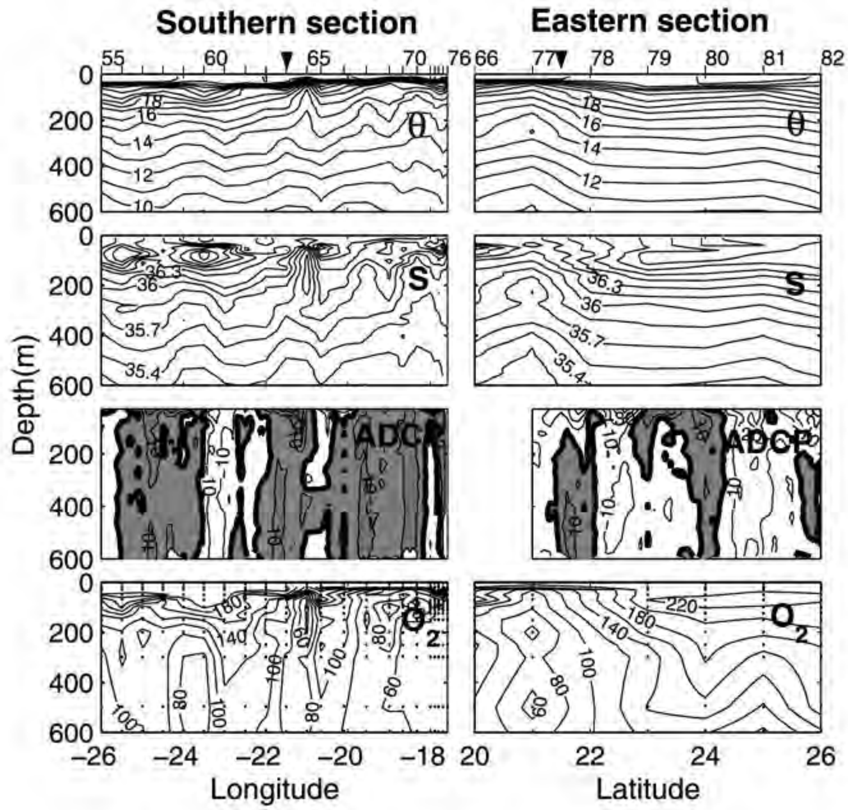

Figure 2. Vertical distributions of potential temperature, salinity, velocity normal to the section measured by ADCP, and dissolved oxygen. Dots in the oxygen contours indicate the locations of the sample bottles. Station positions are shown at the top. The velocity contours are constructed with a horizontal resolution of 0.1°, and grey contours mean eastward (northward) velocity in the eastern (southern) section. Arrows depict locations of the front as obtained by the position of the 36.0 isohaline at 150 m depth.

SACW. At the western section (not shown), the 36.0 isoline does not reach 150 meters depth, indicating that the section does not cross the CVFZ. However, the salinity, temperature and oxygen values at station 55 reveal the nearness of the front at the southern extreme of this section. The current vectors of Figure 1 evidence a mean westward flow along this section as well as in the eastern section.

3.2. Diapycnal Mixing

[9] Figure 3 shows depth averaged values and standard deviations of the diffusivities obtained for the 150–600 m depth layer (approximately the Central Water layer). The results show that K_s are of the order of $10^{-5} \pm 10^{-6}$ m^2 s^{-1} and vary little along the sections, except at station 65 where we obtain the highest mean value and standard deviation ($\sim 3\times10^{-5} \pm 4.5 \times 10^{-5}$ m^2 s^{-1}). The mean values of K_d suggest that double diffusion dominates the diapycnal mixing in the studied region, except where purer SACW is found (i.e. the eastern border of the southern section). Here, the diffusivity coefficients due to double diffusion are clearly small ($<10^{-5}$ m^2 s^{-1}) and, consequently, diapycnal mixing induced by the vertical shear of the flow is the

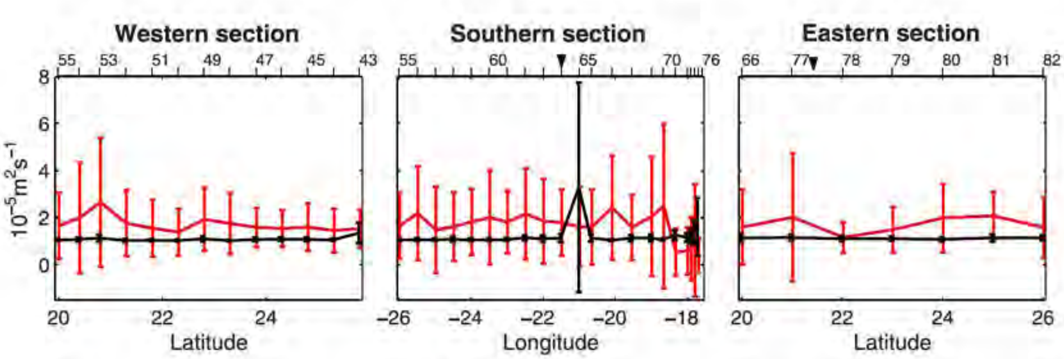

Figure 3. Mean values and standard deviations of the diffusivity coefficients due to shear instability (black line) and double diffusion (red line), calculated for the 150–600 meter depth layer. Arrows depict locations of the front as obtained by the position of the 36.0 isohaline at 150 m depth.

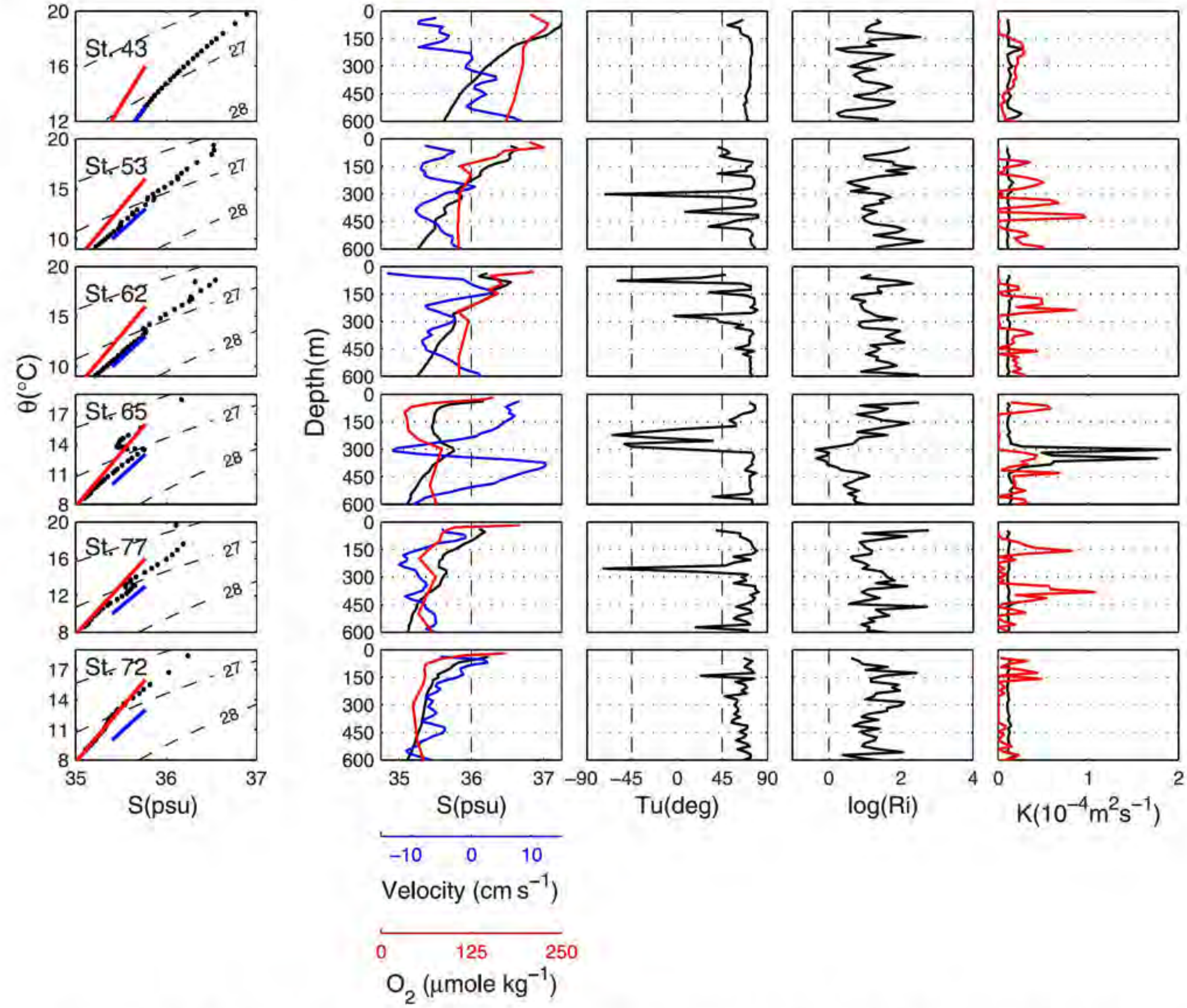

Figure 4. The θ-S diagrams and vertical profiles of salinity (S), current velocity normal to the section, dissolved oxygen (O_2), Turner angle (Tu), Richardson number (Ri), and diffusivity coefficients (K) due to shear instabilities (black line) and double diffusion (red line) in six stations. Station 43 shows NACW properties, station 72 is characteristic of SACW, and the remaining stations show mixed properties. Straight lines as proposed by *Tomczak* [1981] and *Harvey* [1982] for the θ-S relationship for SACW (red line) and NACW (blue line), respectively, are shown.

dominant process. The standard deviations of K_d show a tendency to increase toward the front, indicating that in the frontal area both processes compete through mixing in the water column.

[10] Figure 4 shows potential temperature-salinity (θ-S) diagrams and vertical distributions of different variables at six stations. Station 43 is far from the front and shows typical NACW salinity and temperature values. Station 72 shows SACW properties, and the remaining stations have intermediate values, indicating a mixture of the two water masses. An inspection of the results shows that the complex variation of currents in the vertical direction governs most of the distribution of water masses at the places situated close the front (stations 62, 65, 77). This can be seen especially at station 65, where the cores of minimum salinity and minimum oxygen (mentioned in the previous section) are in fact caused by a large intrusion of highly saline NACW that flows to the south at 300 m depth between northward-flowing SACW layers.

[11] Since the dependence of the strength of double diffusive mixing on R_ρ is complex, the Turner angle, Tu, [*Ruddick*, 1983] is used in Figure 4 instead of R_ρ. Turner angles between -90 and -45° indicate that that portion of the profile is unstable to diffusive layering, whereas Turner angles up to 45° indicate that the portion of the profile is unstable to salt fingering, with the strongest activity near 90°. The Turner angles for the selected stations are shown in the third column of Figure 4. The regime of nearly constant Tu over the depth range 150–600 m in the region of undisturbed NACW (station 43) is in contrast with the situation in the frontal zone. Here, the vertical profiles of Tu show a high variability and the presence of diffusive layering regions generated by intrusions. The results for Tu also illustrate that salt fingering in NACW is stronger than

in SACW. In the SACW the values for K_d (Figure 4, sixth column) decrease strongly, especially between 200 and 400 m depth, where the salt-fingering decrease due to the lower vertical gradients of salinity and temperature. This result is probably a consequence of enhanced mixing in the SACW during its journey through the equatorial current system.

[12] Within a thermohaline front, the boundary area between two water masses increases through the occurrence of intrusions. These features, which are visible as large fluctuations or inversions in the profiles, are thought to enhance double diffusive diapycnal mixing [*Barton*, 1987; *Klein and Siedler*, 1995]. The calculated diffusivity coefficients shown in Figure 4 indicate that the presence of intrusions at the front increases the fluctuation of the diapycnal mixing due to double diffusion along the water column. This effect is due to the generation of layers of enhanced double diffusion: salt fingering under warm, salty intrusions and diffusive convection above; diffusive convection under cold, fresh intrusions and salt fingering above. Between these two layer types, layers of diffusive stability appear that produce the minima of K_d. The results also show that large intrusions can generate important enough velocity gradients to produce gradient Richardson numbers less than one, implying strong mixing. Station 65 shows such behaviour, where maximum values of K_s of about 2×10^{-4} m^2 s^{-1} are obtained. Therefore, large intrusions, often observed in the past at the CVFZ, may favour diapycnal mixing induced by vertical shear in the water column to the detriment of double diffusion. The obtained results in this study suggest that estimations of diapycnal mixing in the CVFZ should include instabilities due to vertical shear, as well as double diffusive processes.

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