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# Water and nutrient fluxes off Northwest Africa

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**Abstract**

A historical data set is used to describe the coastal transition zone off Northwest Africa during spring 1973 and fall 1975, from 17° to 26°N, with special emphasis on the interaction between subtropical (North Atlantic Central Waters) and tropical (South Atlantic Central Waters) gyres. The near-surface geostrophic circulation, relative to 300 m, is quite complex. Major features are a large cyclonic pattern north of Cape Blanc (21°N) and offshore flow at the Cape Verde front. The large cyclone occurs in the region of most intense winds, and resembles a large meander of the baroclinic southward upwelling jet. The Cape Verde frontal system displays substantial interleaving that may partly originate as mesoscale features at the coastal upwelling front. Property–property diagrams show that the front is an effective barrier to all properties except temperature. The analysis of the Turner angle suggests that the frontal system is characterized by large heat horizontal diffusion as a result of intense double diffusion, which results in the smoothing of the temperature horizontal gradients. Nine cross-shore sections are used to calculate along-shore geostrophic water-mass and nutrient transports and to infer exchanges between the coastal transition zone and the deep ocean (import: deep ocean to transition zone; export: transition zone to deep ocean). These exchanges compare well with mean wind-induced transports and actual geostrophic cross-shore transport estimates. The region is divided into three areas: southern (18–21°N), central (21–23.5°N), and northern (23.5–26°N). In the northern area geostrophic import is roughly compensated with wind-induced export during both seasons. In the central area geostrophic import is greater than wind-induced export during spring, resulting in net import of both water (0.8 Sv) and nitrate (14 kmol $s^{-1}$), but during fall both factors again roughly cancel. In the southern area geostrophy and wind join to export water and nutrients during both seasons, they increase from 0.6 Sv and 3 kmol $s^{-1}$ during fall to 2.9 Sv and 53 kmol $s^{-1}$ during spring.


*Keywords:* Coastal upwelling; Central waters; Frontal features; Double diffusion; Transport processes; Interleaving; Cape Verde; Geographic bounding coordinates (17–26°N) (22–14°W)

## 1. Introduction

The 1970s was the International Decade for Ocean Exploration. This interest in international cooperation was combined with the relevance of fisheries off Northwest Africa to impulse a major program, the Cooperative Investigation of the Northern Part of the Eastern Central Atlantic (CINECA), aimed at understanding the ocean environment of this highly productive region. The program involved near 100 scientific cruises from many nations (Hempel, 1982), mainly focusing in the continental shelf and slope. As part of this program the Institut de Ciències del Mar together with other CSIC research teams (at that time Instituto de Investigaciones Pesqueras, IIP) participated with eight cruises. Despite some of these cruises were consecutive in time and had good coverage of the upper ocean in adjacent areas, so far they have always been analyzed separately. A first objective of our work has been to produce synoptic data sets, of good quality and large-scale coverage, from these old data sets.

Our region of interest is the upper ocean between the Canary Islands (28°N) and Cape Verde (15°N). This is a

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very complex oceanographic region, with the top 700 or 800 m occupied by surface and central waters of either northern (North Atlantic Central Waters, NACW) or southern (South Atlantic Central Waters, SACW) origin (Fraga, 1974; Tomczak, 1981, 1984; Zenk et al., 1991). NACW have their source in the North Atlantic subducting zone, defined as where the Ekman pumping velocity is negative, and reach subsurface waters at lower latitudes through the thermocline circulation (Sarmiento et al., 1982; Kawase and Sarmiento, 1985). Only water masses formed in the subducting zone during late winter and early spring may escape the surface layers and get injected in the permanent thermocline; during the rest of the year, waters subducted remain in the mixed-layer as the escape velocities caused by Ekman pumping are less than the seasonal advance of the mixed-layer thermocline. The vertical extension of the NACW in lower latitudes will be determined by the densest winter-outcrop isopycnal within the subducting zone, near $\sigma_\theta = 27.3$ (Kawase and Sarmiento, 1985; Reid, 1994). SACW, on the other hand, are originated in the subantarctic zone of the southern ocean, and travel through the South Atlantic thermocline into the equatorial and tropical regions (Frantantoni et al., 2000; Zhang et al., 2003; Sarmiento et al., 2004; Williams et al., 2006). Intermediate waters (Antarctic Intermediate Waters in the 600–1000 m range and Mediterranean Waters down to nearly 1500 m) and deep waters complete the water column, but their study falls beyond the scope of this paper.

The time-dependent response in the region is characterized by the passage of different waves (Hagen, 2001, 2005). Along the coast these should be northward propagating waves, fast as the Kelvin wave and slow as topographically trapped Rossby waves (Hagen, 2001). At a certain latitude we may find westward propagating Rossby waves (Price and Maagard, 1986; Müller and Siedler, 1992; Siedler and Finke, 1993; Hagen, 2001, 2005). In this paper we will be concerned with the steady-state response, for a thorough review of these free traveling waves the reader is referred to Hagen (2001).

The North Atlantic subtropical gyre is a large-scale anticyclone, with its margins raising towards the surface. The southeastern margin is the Cape Verde front while the eastern one is the eastern boundary current system, its easternmost branch taking place in the coastal transition zone. The steady-state connection between the offshore and coastal upwelling fronts is controlled by three main factors: the location of the Cape Verde frontal zone, the intensity and latitudinal extension of coastal upwelling, and the size and location of the Guinea Dome open-ocean upwelling area.

The Cape Verde frontal zone corresponds to the southern limit of the North Atlantic thermocline recirculation (Kawase and Sarmiento, 1985; Stramma and Siedler, 1988; Zenk et al., 1991; Arhan et al., 1994). It stretches southwest from Cape Blanc to the Cape Verde Islands, and effectively separates relatively new (salty, warm, nutrient-poor, and oxygen-rich) NACW from the older (fresh, cold, nutrient-rich, and oxygen-poor) SACW. The position of the front is linked to the westward veering of the Canary Current as it becomes the North Equatorial Current, and displays relatively small meridional excursions, north in summer and south in winter (Stramma and Siedler, 1988). Hagen (2001) has proposed that the frontal position is fixed by the vanishing of the sea-surface wind-stress curl.

As a result of the surface trade winds, coastal upwelling is present between the Strait of Gibraltar and Cape Blanc all year long, being most intense south of the Canary Islands (Wooster et al., 1976; Speth and Detlefsen, 1982; Nykjaer and Van Camp, 1994). During summer upwelling intensifies north of the Canary Islands and reaches the Iberian Peninsula, and during winter it reaches south past Cape Verde, e.g. Fig. 14 in Pelegrí et al. (2006). Pelegrí et al. (2005) have discussed the double role played by the coastal upwelling zone, both linking the surface and subsurface waters through the vertical upwelling cell and providing a meridional connection through the coastal upwelling jet. One important consideration is that this upwelling boundary current must accommodate an interior flow of some 2–3 Sv north of the Canary Islands, so it must have an inertia that goes well beyond the response to synoptic atmospheric variability. This is why we may speak of the Canary Upwelling Current as the permanent eastern boundary current of the North Atlantic subtropical gyre (Pelegrí et al., 2005, 2006).

South of the Cape Verde frontal zone we find a cyclonic circulation region, composed by the eastward North Equatorial Counter Current (NECC) and the westward North Equatorial Current (NEC). This current system flows around the Guinea Dome, an open-ocean upwelling region forced by the surface cyclonic winds (Siedler et al., 1992; Yamagata and Iizuka, 1995; Elmoussaoui et al., 2005). The dome and associated circulation move offshore, towards the central Atlantic, during summer. At this time it appears natural to expect that the cyclonic pattern will close through a northward current off Africa, between Capes Verde and Blanc. During winter Ekman pumping intensifies and moves east (Nykjaer and Van Camp, 1994), effectively merging with the coastal upwelling zone and possibly breaking the cyclonic coastal connection between NECC and NEC. The SACW in this region are transported north along the slope, typically centered at depths of 300 m, via the poleward undercurrent (Hughes and Barton, 1974). This current may reach the Canary Islands and even the Iberian Peninsula (for a review see Hagen, 2001), displaying substantial seasonal variability (Machín et al., 2006).

When considering the main controls on the steady-state dynamics, it is important to keep in mind that the mean field also experiences remotely forced interannual and interdecadal variations. Arfi (1985) used local data at 20°N to suggest that upwelling intensified from the 1960s to the 1970s. Roy (1991) also presented results supporting that the 1970s was a period of relative intense upwelling, which decreased in the 1980s. More recently satellite-derived sea