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Diapycnal nutrient fluxes on the northern boundary of Cape Ghir upwelling region

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ABSTRACT

In this study we estimate diffusive nutrient fluxes in the northern region of Cape Ghir upwelling system (Northwest Africa) during autumn 2010. The contribution of two co-existing vertical mixing processes (turbulence and salt fingers) is estimated through micro- and fine-structure scale observations. The boundary between coastal upwelling and open ocean waters becomes apparent when nitrate is used as a tracer. Below the mixed layer (56.15 ± 15.56 m), the water column is favorable to the occurrence of a salt finger regime. Vertical eddy diffusivity for salt (K_s) at the reference layer (57.86 ± 8.51 m, CI 95%) was 3×10^{-5} ($\pm 1.89 \times 10^{-9}$, CI 95%) $m^2\ s^{-1}$. Average diapycnal fluxes indicate that there was a deficit in phosphate supply to the surface layer (6.61×10^{-4} mmol $m^{-2}\ d^{-1}$), while these fluxes were 0.09 and 0.03 mmol $m^{-2}\ d^{-1}$ for nitrate and silicate, respectively. There is a need to conduct more studies to obtain accurate estimations of vertical eddy diffusivity and nutrient supply in complex transitional zones, like Cape Ghir. This will provide us with information about salt and nutrients exchange in onshore–offshore zones.

1. Introduction

In the open ocean, cross-isopycnal mixing via turbulence is the main route of nutrients from the deep layers to the well-lit surface waters where they fuel phytoplankton primary productivity (Hamilton et al., 1989). These diapycnal turbulent fluxes also are especially important in coastal upwelling regions as the irreversible part of the physical mixing process (Hales et al., 2005). They act as a nutrient replenishment mechanism in the coastal shelf but also as a continuous nutrient transport through the water column to the surface (Hales et al., 2005). Although the magnitude of advective transport may surpass that of vertical turbulent diffusion by up to four orders of magnitude, it should be pointed out that the latter has a permanent and irreversible character at spatial and temporal scales (Hamilton et al., 1989; Hales et al., 2005).

Despite the relevance of vertical turbulent diffusion in mixing processes, the continuous application of inadequate local micro- and fine-structure parameterization schemes in field studies has often leaded to an inconsistency in biological uptake and nutrient supply estimates (Dietze et al., 2004). Such inaccurate estimates inevitably hinder our ability to constrain biological activity rates such as 'new production' and associated carbon export to the deep ocean (Dugdale and Goering, 1967; Hamilton et al., 1989; Oschlies, 2002). Turbulent vertical mixing includes processes which take place at fine-structure scale (1–10 m) and micro-structure scale (< 1 m) (Gargett, 1976; Gregg, 1989).

Quantifying the relationship between micro- and fine-structure is essential in order to establish connections between both scales when parameterizing the effects of these turbulent processes (Schmitt et al., 1988). On the other hand, given the resolution and sensitivity of Oceanic General Circulation Models (OGCMs) with respect to vertical turbulent diffusion it is of particular importance to deepen our knowledge on mixing processes at fine-structure scale (Large et al., 1994; Zhang et al., 1998; Law et al., 2003).

The prevailing vertical diffusive mixing mechanisms at central waters (majorly the Atlantic basin, Southeast Indian Ocean, and Southwest Pacific Ocean) are as follows: (1) the vertical shear (mechanical turbulence produced by horizontal currents), (2) salt fingers (double diffusion), and (3) internal waves (Hamilton et al., 1989; MacDougall and Ruddick, 1992; Figueroa, 1995). The contribution of (3) is usually low and varies according to the inner energy of the wave (Garret–Munk *internal wave model*), and

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according to a floatability constant (Garrett and Munk, 1972, 1975; Large et al., 1994). In general terms, internal waves are considered constant or are totally disregarded. The contribution of (1) and (2) is independent given their intermittent nature both in space and time (McDougall and Ruddick, 1992). Salt fingers occur in highly stratified systems where relatively warmer and saltier water lays over cooler and less saline water. The molecular diffusion of heat is faster than that of salt, which makes the more saline layer to become more dense forming convection plumes (termed 'salt fingers'), which conserve its salinity variance. These structures move downwards efficiently mixing the water vertically (St. Laurent and Schmitt, 1999). Indeed, Hamilton et al. (1989) observed that previous measurements of vertical diffusive nitrate fluxes which only considered dissipation-diffusivity methods (Osborn, 1980; Gregg, 1989) were six times lower than diapycnal fluxes induced by salt fingers.

For this reason, in regions such as the subtropical Northeast Atlantic where central waters dominate (North Atlantic Central Water – NACW), and where the efficiency of salt finger mixing has been recognized, the use of combined parameterization models for salt vertical eddy diffusivity (K_s) is essential (Hamilton et al., 1989; McDougall and Ruddick, 1992; St. Laurent and Schmitt, 1999).

The northern boundary of Cape Ghir upwelling region is an important transition zone for cross-shelf exchange of biogenic materials and nutrients between the coast and the adjacent open ocean (Mason et al., 2012). This exchange occurs mainly through the recurrent upwelling filaments (Álvarez-Salgado et al., 2007), which are mesoscale features which may extend hundreds of kilometers offshore. The Cape Ghir coastal transition zone is also subject to strong seasonal variability mainly associated with the intensity of the coastal upwelling and the variability of the Canary Current (Barton et al., 1998; Pelegrí et al., 2005a,b).

The aim of this study was to estimate the magnitude of diapycnal fluxes of different nutrients in the northern boundary of the Cape Ghir region. The observations were carried out in the frame of the PROMECA project (Mixing Processes in the Canary Basin), during autumn 2010, when the trade wind regime is weak and the coastal upwelling is less intense (Barton et al., 1998). In addition, here we examine the relationship of K_s at micro- and fine-structure scale. Finally, we estimate the relative contribution of the mixing processes involved (mechanical turbulence and salt fingers) and the diapycnal nutrient fluxes at fine-structure.

2. Data and methods

The data used in this study was collected during the PROMECA cruise onboard the R/V *García del Cid* from 18 to 29 October 2010. Fourteen hydrographic stations in the region north of Cape Ghir (Fig. 1). The horizontal resolution between stations was from ~5 to 60 km. Temperature and salinity measurements were obtained at 1 db intervals using a SBE 911 plus CTD probe mounted on a rosette sampler equipped with 12 Niskin bottles (12 L). Seawater samples for nutrient analysis were collected in 15 mL polyethylene tubes (VWR) at 50, 75, 100, 150, 200, 250, 350, 500, 800, 1200, 1500 and 2000 m depth. The samples were stored frozen at −20 °C until analysis ashore. Nutrient concentration analyses were performed using an AA3 Bran+Luebbe autoanalyzer with detection limits of 0.01, 0.001, 0.02 and 0.016 μM for nitrate, nitrite, phosphate and silicate, respectively. In this study, we will refer to 'nitrate' as nitrate plus nitrite.

Fine-structure scale measurements were obtained using the vessel-mounted Ocean Surveyor ADCP (SADCP) at 75 kHz (8 m cell size). Current velocity data was processed with the CODAS software (Common Ocean Data Access System; Firing et al., 1995). Measurements of turbulent kinetic energy dissipation rate (ε) and thermal variance (χ) were performed using a vertical free-falling micro-structure profiler (TurboMAP) at integrate intervals of 2 m down to ~470 m depth. The TurboMAP was equipped with shear probe ($\Delta u/\Delta z$), temperature ($\Delta t/\Delta z$) and CTD probes. Free-falling speed was ~0.6–0.7 m s^{-1} at a rate of 512 Hz. The data was processed using TMTools (version 3.04A) (TMTools, 2008).

2.1. Micro- and fine-structures processing

Our study was focused on the depth comprised between below the mixed layer depth (MLD) and ~600 m. For this reason, a reference layer was established as the depth where the vertical transport of nutrients to the surface waters did not involve the mixed layer. This ensures the correct delimitation of the boundary layer oceanic mixing regime near the surface in order to apply the appropriate mixing schemes (Large et al., 1994). Finally, the reference layer at each station was established as the level of maximum Brunt–Väisäla frequency plus 10 m, which was in good agreement with the estimated MLD using the algorithm by Kara et al. (2000). SADCP and nutrient profiles were lineally interpolated at the same

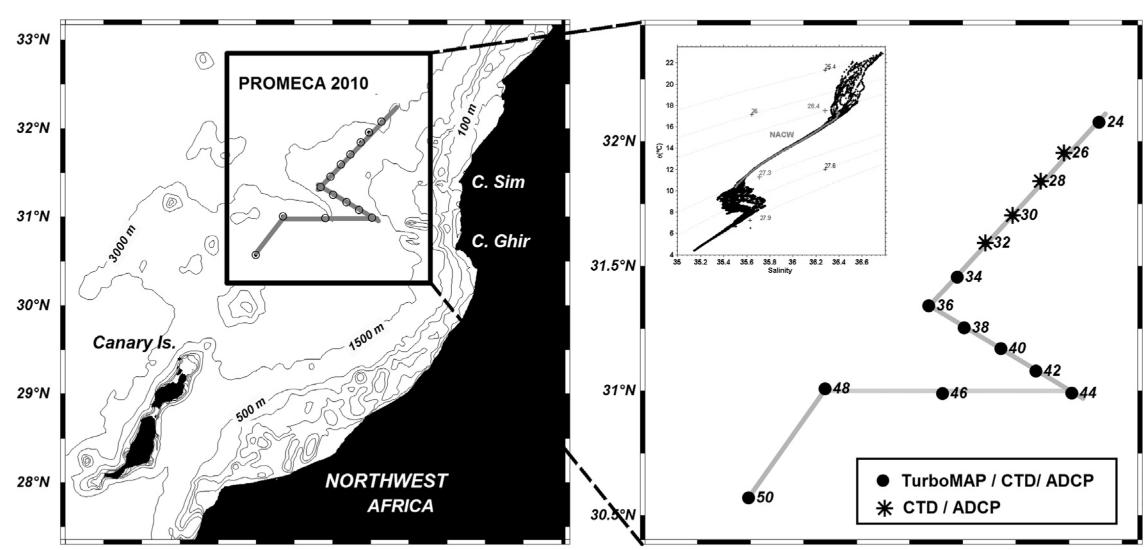

Fig. 1. Localization and oceanographic instrumentation used for sampling at hydrographic stations during the PROMECA-2010 cruise. A temperature–salinity (T–S) plot is embedded in the upper left corner zoom, including data from the 14 stations sampled. The water mass under study (North Atlantic Central Water, NACW, ~600 m) is shown in gray.