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Net ecosystem metabolism of a coastal embayment fertilised by upwelling and continental runoff

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ABSTRACT

O_2, N, P and Si net ecosystem metabolism of the Ría de Ares–Betanzos (NW Iberian upwelling system) was estimated during two 3-wk periods of contrasting summer downwelling and autumn upwelling conditions by means of a transient 2-D kinematic box model. The subtidal circulation was positive in both situations, although it was depressed during downwelling and enhanced during upwelling. Concurrently, the ría was fertilised mainly by shelf bottom waters, which introduced from 69% (under downwelling) to almost 100% (under upwelling) of the limiting N nutrients. The ría was an efficient nutrient trap: about 70% of the N nutrients that entered the embayment were retained under downwelling conditions (average flushing time, 9 days) and about 50% under upwelling conditions (average flushing time 3 days). Although the trapping efficiency was lower, the net ecosystem production (NEP) was much higher under upwelling (from 1.0 ± 0.3 to 1.5 ± 0.4 g C m^{-2} d^{-1}), than under downwelling favourable winds (from 0.2 ± 0.1 to 0.3 ± 0.1 g C m^{-2}). The stoichiometry of NEP suggests that P and N compounds recycled faster than C compounds, specially in the inner segment of the ría. The net degree of silification was twice in the inner than in the outer segment of the ría.

1. Introduction

Disproportionately large organic and inorganic nutrient inputs from land, atmosphere and adjacent ocean waters in relation to its small size makes the coastal ocean one of the most productive and biogeochemically active zones of the biosphere (Gattuso et al., 1998; Gazeau et al. 2004). Despite it represents $<10\%$ of the surface and $<1\%$ of the volume of the global ocean, the coastal ocean is responsible for 18–33% of the primary production, 27–50% of the export production (Walsh, 1991; Wollast, 1993, 1998), 83% of the benthic mineralization and 87% of the organic matter burial of the global ocean (Middleburg et al., 1993; Dunne et al., 2007). All these processes are intensified in eastern boundary upwelling systems (EBUS) as a result of enhanced nutrient inputs from the adjacent ocean (Walsh, 1991; Wollast, 1998). Moreover, the coastal ocean provides more than 90% of the global fish catches (Pauly and Christensen, 1995; Lindeboom, 2002), one fifth of which are extracted from EBUS (Fréon et al., 2009).

The Galician coast is at the northern limit of the Iberian–Canary current EBUS, where upwelling favourable north-easterly winds blow predominantly during the spring and summer. On the contrary, downwelling favourable south-westerly winds prevail the rest of the year (Wooster et al., 1976; Arístegui et al., 2009). This seasonal cycle is frequently disrupted by upwelling events during the downwelling season and vice versa (Prego et al., 2007; Álvarez et al., 2009). The Galician coast is occupied by a series of coastal indentations of variable size and orientation freely connected with the adjacent shelf, collectively known as rías. The estuarine-like subtidal circulation of the rías, positive under upwelling and negative under downwelling conditions (Piedracoba et al., 2005), allowed the application of transient 2-D box models to compute the exchange of water with the continental shelf (e.g. Rosón et al., 1997; Pardo et al., 2001; Gilcoto et al., 2001). Box models have also been used to assess the net ecosystem metabolism (NEM), i.e. the balance of autotrophic production minus the respiration of autotrophs and all heterotrophs in these water bodies (Smith and Hollibaugh, 1997), based on dissolved oxygen and nutrient budgets (e.g. Pérez et al., 2000; Gilcoto et al., 2001; Dale and Prego, 2005). NEM estimates have been obtained only for the large rías (>2.5 km^3) of the western coast (Fig. 1), named Rías Baixas, where the hydrodynamics and biogeochemistry is essentially dictated by coastal winds.

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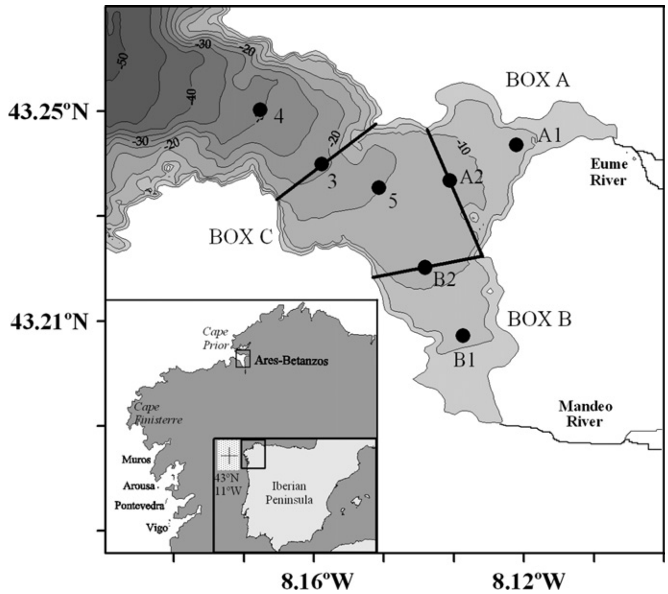

Fig. 1. Map of the Ría de Ares–Betanzos (NW Iberian Peninsula), showing the bathymetry of the embayment and the position of the sampling stations A1, A2, B1, B2, 3, 4 and 5. The DCM12 ADCP was moored at stn 3. The ría was divided in three 2-layered boxes for the calculation of water flows and nutrients salts fluxes and budgets by applying a 2-D box model. The solid lines are the open boundaries of boxes A (Ares), B (Betanzos) and C (confluence zone).

In this work, the transient 2-D box model successfully tested in the Rías Baixas will be applied for the first time to the Ría de Ares–Betanzos (Fig. 1), in the northern coast, to obtain subtidal circulation patterns and net ecosystem production rates (NEP) under contrasting summer downwelling and autumn upwelling conditions. The Ría de Ares–Betanzos is less than one third the size of the Rías Baixas, the ratio between the annual average river discharge and the volume of the embayment is more than twice than in the Rías Baixas, and the orientation of its mouth is also different. Therefore, a differential response to continental runoff and coastal winds is expected when compared with the Rías Baixas. Previous woks on the hydrography of the Ría de Ares–Betanzos have succinctly dealt with nutrient distributions (Prego et al., 1999), and phytoplankton diversity and productivity (Blanco, 1985; Mariño et al., 1985; Bode and Varela, 1998). But despite it supports 147 mussel rafts that produce about 10,000 metric tons of *Mytilus galloprovincialis* per year (Labarta et al., 2004) there is a lack of studies dealing with the dynamics of nutrient fertilisation and net metabolism in this embayment.

2. Material and methods

2.1. Study site

The Ría de Ares–Betanzos is the largest of the six embayments located between Cape Fisterra and Cape Prior, in the NW coast of the Iberian Peninsula (Fig. 1), with a surface area of 72 km^2, a volume of 0.75 km^3 and a length of 19 km. It consists of two branches: Ares, the estuary of river Eume, and Betanzos, the estuary of river Mandeo, with long-term average flows of 16.5 and 14.1 $m^3\,s^{-1}$, respectively (Prego et al., 1999; Sánchez-Mata et al., 1999). The two branches converge into a confluence zone that is freely connected to the adjacent shelf through a moth that is 40 m deep and 4 km wide. From the hydrographic point of view, the ría is like a partially stratified estuary where fresh and marine waters mix gradually (Sánchez-Mata et al., 1999).

2.2. Sampling strategy and measured variables

An intensive hydrographic sampling was executed in the Ría de Ares–Betanzos during two contrasting periods in 2007: 9–23 July and 10–29 October. Five fixed stations were sampled: two in Ares (A1 and A2), two in Betanzos (B1 and B2) and three in the confluence zone, stn 3 that was sampled in both periods, stn 4 that was sampled only in July and stn 5 that was sampled only in October (Fig. 1). Continuous vertical profiles of salinity, temperature, dissolved oxygen, fluorescence of chlorophyll and photosynthesis available radiation (PAR) where recorded at each station with a Seabird 19 CTD probe equipped with a Wet Lab Eco AFL/FL fluorometer, a SBE 43 oxygen sensor and a Biospherical Licor PAR sensor. Aliquots for the analysis of salinity, dissolved oxygen and nutrient salts (ammonium, nitrite, nitrate, phosphate and silicate) were collected at two depths (surface and bottom) at stns A1 and B1, three depths at stns A2 and B2, four depths at stns 3 and 5 and five depths at stn 4, using 5 L General Oceanic Niskin bottles. Dissolved oxygen was collected in Winkler flasks and fixed immediately. Nutrient samples were collected in 50 mL polyethylene bottles and frozen at $-20\,^{\circ}C$. This program was repeated every 3–5 days during the two sampling periods.

The practical salinity was determined from conductivity measurements with an Autosal 8400A using the equation of UNESCO (1983). The analytical precision of the salinity determination is ± 0.005. The density excess with respect to 1000 kg m^3, σ_t, was calculated according to UNESCO (1985) with the equation σ_t=[$\rho(S, t, P)$-1000], where ρ is the density of seawater as a function of practical salinity (S), in situ temperature (t) and pressure (P=0).

Dissolved oxygen was analysed by the Winkler method with potentiometric end-point detection using a Metrohm Titrino 72' analyser. The analytical precision is ± 0.5 μmol kg^{-1}. The apparent oxygen utilisation (AOU), i.e. the difference between the estimated dissolved oxygen concentration at saturation and the actual oxygen concentration, was calculated according to UNESCO (1986).

Inorganic nutrients were determined using standard segmented flow analysis (SFA) procedures with an Alpkem analyser. The precisions of the methods are ± 0.02 μmol kg^{-1} for nitrite, ± 0.1 μmol kg^{-1} for nitrate, ± 0.05 μmol kg^{-1} for ammonium, ± 0.02 μmol kg^{-1} for phosphate and ± 0.05 μmol kg^{-1} for silicate.

2.3. ADCP current measurements and meteorological variables

An Aanderaa DCM12 Doppler current meter was moored at stn 3, in 20 m depth (Fig. 1). The DCM12 was installed in a gymbal system at the top of a pyramidal structure. The first mooring successfully covered the period from 3 to 26 July and the second one from 15 October to 20 November 2007.

The DCM12 is an acoustic Doppler current profiler (ADCP) that measures the current velocity at five depths using the Doppler effect with a transmitted signal of 606.7 kHz. From the surface to 4 m above itself, the DCM12 divides the water column in five partially overlapped layers and measures the depth integrated velocity of each one. With the selected configuration, all layers were 4.5 m in size, and their respective centre depths were approximately at 2.7, 5.3, 8, 10.7 and 13.3 m from the surface. The recording interval of the DCM12 was set to 10 min. An $A24^2A25$ filter with a cut-off period of 30 h was passed to the time series of currents to remove the variability at tidal or higher frequencies (Godin, 1972).

Shelf (Vx, Vy) and local (Wx, Wy) winds, precipitation rates (P), humidity (h) and air temperature (T_A) were collected during the