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Exchanges of nutrients and chlorophyll a through two inlets of Ria Formosa, South of Portugal, during coastal upwelling events

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ABSTRACT

The Ria Formosa is a shallow and multi-inlet coastal lagoon system in southern Portugal, with six permanent connections to the Atlantic Ocean. The western sector of Ria Formosa comprises three of the main inlets, Ancão, Faro-Olhão and Armona, which contribute ~90% of the total tidal prism of the lagoon. Of those three inlets, Ancão and Faro-Olhão supply the minimum and maximum contribution for these exchanges, respectively. Four field surveys were conducted at these two inlets during the upwelling season (from spring to autumn) to determine the influence of upwelling process upon the hydrographic characteristics in spring tidal conditions: i) spring 2009 (Ancão inlet), ii) autumn 2011 (both inlets) and iii) spring 2012 (Faro-Olhão inlet). Water samples were collected hourly (at three levels), along complete semi-diurnal tidal cycles, to determine chlorophyll *a* (chl *a*) and nutrient concentrations. At the same time, the water velocity was measured along the cross section to estimate the tidal prism, nutrients and chl *a* transports. Ancão inlet contributes a much lower volume to the total tidal prisms than Faro-Olhão inlet. The temporal data variability reveals that chl *a* and nutrient dynamics through these inlets depends not only on the tidal influence and characteristics of the boundary waters, but also on the intensity of the atmospheric and oceanic forcings acting on the adjacent coastal zone. During pulses of coastal upwelling events, more evident in spring season (mainly in April 2009 and May 2012), the two inlets imported chl *a* and phosphate. In contrast, in the absence of upwelling conditions, due to wind reversals and/or long periods of wind relaxation, both inlets exported nitrate and phosphate, fertilizing the coastal ocean. However, the Ria Formosa is a highly complex hydrodynamic system, and hydrographic temporal differences can be expected at different scales as a result of changes in: i) morphological configuration of the natural inlets, ii) interconnectivity of channels, and iii) the seasonal meteorological and oceanographic conditions.

1. Introduction

Coastal lagoons represent about 13% of the coastal areas worldwide (Barnes, 1980) and are recognized as productive natural ecosystems. They derive large amounts of nutrients either from land or from the ocean as a result of coastal upwelling (Barbosa, 2010; Cervantes-Duarte et al., 2013). These systems are highly responsive to wind forcing, and their currents are rapidly damped by bottom friction because of their large surface area to depth ratio (Smith, 2001).

Located on the southern coast of Portugal, the Ria Formosa (Fig. 1) is one of the major national lagoon systems. With an area of about 80 km^2, this shallow (average depth <2 m) multi-inlet system is permanently connected to the Atlantic Ocean through six inlets. Consequently, a high water exchange rate of 50–75% of the total volume occurs in each semi-diurnal tidal cycle (Tett et al., 2003). The lagoon is characterized by a mesotidal regime, with a tidal range of about 2.8 m in spring tides and 1.3 m in neap tides (Loureiro et al., 2006; Pacheco et al., 2011). Tidal exchanges are important in limiting the impact of nutrients supplied to this coastal lagoon by several sources, including those of anthropogenic origin (Newton and Icely, 2004). Moreover, concentrations of nutrients and other compounds in the Ria Formosa lagoon strongly depend on the chemical variability of the adjacent coastal waters, which are also affected by coastal upwelling events, among other environmental conditions (Alcântara et al., 2012). The upwelling events along the southern Portuguese coast are not uncommon, and occur mainly between May and October, under predominant westerly winds. These appear to be more intense off the western part of the southern coast, from Cape São Vicente to Cape Santa Maria (Relvas and Barton, 2002). Under strong and persistent westerly winds, upwelling events may occupy the entire southern coast of Portugal (García-Lafuente et al., 2006), propagating well beyond the Guadiana River coastal zone (Fig. 1) (Cardeira et al., 2013).

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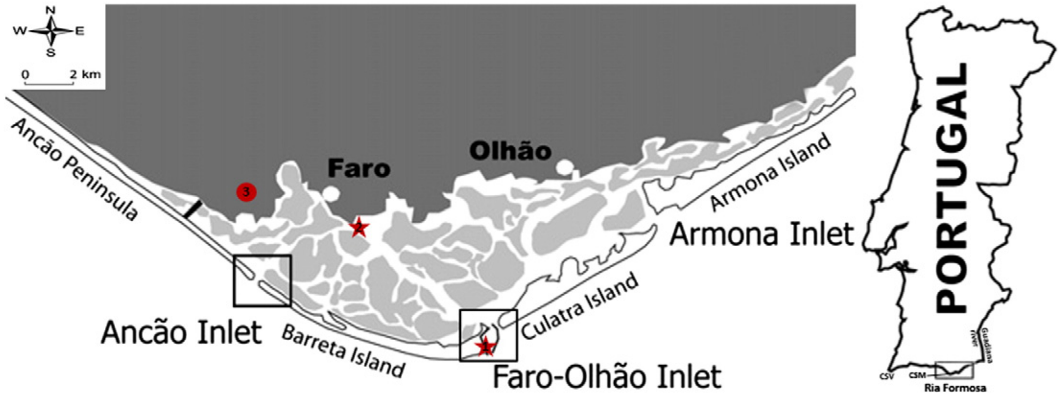

Fig. 1. Representation of the Ria Formosa lagoon western sub-embayment, which includes the three inlets Ancão (BAN), Faro-Olhão (BFO) and Armona, focusing on the location of the inlets under study, BAN and BFO, the PTs (red stars with numbers inside, 1 - PT1 close to BFO, and 2 - PT2 in Faro commercial pier, 6 km upstream BFO) and the Faro airport meteorological station (red circle with number 3 inside) (adapted from Pacheco et al., 2011).

Upwelled waters in coastal regions are noticeably efficient contributors to the offshore export of matter, including nutrients and chlorophyll *a* (a proxy of phytoplankton biomass). These compounds represent an effective mechanism to fertilize offshore waters and have a strong influence on the increase of biological productivity (Cravo et al., 2010; Leví, 2008). The offshore export of material induced by upwelling on the southern Portuguese coast has been documented (e.g. Cardeira et al., 2013; Cravo et al., 2010, 2013b). However, the connectivity of the coastal upwelling and associated offshore transports with the processes inside the Ria Formosa lagoon is rather unknown. Although the lagoon is relatively well characterized in terms of hydrodynamics and water quality, few studies report nutrients and chlorophyll *a* (chl *a*) dynamics inside the lagoon, with the exception of those of Alcântara et al. (2012) and Cravo et al. (2012, 2013a). Given the ecological and socio-economic significance of the Ria Formosa (Newton et al., 2003), the assessment of these dynamics is extremely important. To do that, it is imperative to understand water circulation, tidal influence and water exchanges with the ocean, issues already approached by several authors (Dias et al., 2009; Jacob et al., 2012; Pacheco et al., 2010; Salles, 2001; Salles et al., 2005; Soares et al., 2001; Williams et al., 2003). This study intends to further understand the nutrients and chlorophyll *a* (chl *a*) dynamics in the Ria Formosa by characterizing the mass exchanges between the western sector of Ria Formosa lagoon and the ocean, during coastal upwelling events.

Hydrodynamically, the lagoon may be divided into three sub-embayments (Salles et al., 2005). The western sector alone includes the three inlets: Ancão, Faro-Olhão and Armona (Fig. 1). According to Pacheco et al. (2010), these account for ~90% of the total water volume exchanged with the ocean along a semi-diurnal tide cycle. Water circulation inside the lagoon is mostly driven by tidal forcing, and tidal exchanges occur predominantly through Faro-Olhão and Armona inlets (Pacheco et al., 2010; Salles et al. 2005). Additionally, the three inlets of the western sub-embayment show a clear circulation pattern at spring tides, in which the excess flood prism at Faro-Olhão inlet ebbs through Ancão and Armona inlets (Pacheco et al., 2010). From those three, Ancão has the minimum contribution to water exchange and Faro-Olhão represents the opposite extreme (Pacheco et al., 2010). Therefore, to understand mass exchanges between the western sector of Ria Formosa lagoon and the ocean, this study focused on these two inlets (Fig. 1). Faro-Olhão is the most important inlet in the system. It was artificially stabilized and always has a flood-dominated residual flow, trapping c. 60–65% of the total tidal prism during both spring and neap tides (Jacob et al., 2013). Ancão inlet, the westernmost inlet of the Ria Formosa, was artificially relocated 3.5 km west of its previous position in June 1997 (Vila-Concejo et al., 2004). This intervention was conducted to improve water circulation between the lagoon and the adjacent ocean. Ancão has been reported in literature as a small ebb-dominated inlet with wave-dominated characteristics and cyclic eastward migration behaviour (Salles, 2001; Williams et al. 2003). During the last few years it has lost hydraulic efficiency by migration and accretion, and now accounts for <6% of the total western sector tidal prism (Jacob et al., 2013).

The main goal of this study was to evaluate the influence of coastal upwelling and its contribution to mass transport within the western sector of the Ria Formosa lagoon. The study considered the two contrasting inlets – Ancão and Faro-Olhão (Fig. 1) – and quantified the mass exchanges of water, nutrients and chl *a* between the lagoon and the ocean. Complete spring semi-diurnal tidal cycles were surveyed in spring and autumn, when tidal exchanges are maximal. The study focused on those seasons because at that time phytoplankton development is highest and the upwelling period is most intense.

2. Material and methods

2.1. Field sites and campaigns

The oceanographic campaigns were carried out within the upwelling season, in spring and autumn conditions. In spring 2009 (27 April) only Ancão inlet (BAN, Fig. 1) was selected, in autumn 2011 (22 and 24 November) both BAN and Faro-Olhão inlet (BFO, Fig. 1) were chosen while in spring 2012 only BFO (7 May) was sampled. Table 1 contains the characteristic dimensions of the cross-sections of the inlets under study, during the experimental surveys.

To quantify the mass exchanges of water, nutrients and chl *a* along complete spring semi-diurnal tidal cycles (12.5 h), the flow velocity was measured hourly along the cross-section of each inlet using a Sontek/YSI 1.5-MHz Current Surveyor Acoustic Doppler Profiler (ADP) with bottom tracking, side mounted on a boat. Bottom-tracking allows the ADP to measure both its velocity (speed and direction) over the Earth and the water depth beneath the system. These data are used to remove vessel motion from measured water velocity and determine the "true" water speed and direction (Sontek, 2005). Cell size and blanking distance were set to 0.4 m, ADP transducer draft to 0.25 m and number of cells to appropriately account for the maximum depth of each profile. The ADP was operated in continuous mode with a 5 s average interval. The software Current Surveyor v4.6 was used to record hydrodynamic data, measure the cross-section shape and dimensions, and analyse the hourly transect surveys. The signal-to-noise ratio (SNR) was set to 3 dB to remove invalid data below the ambient noise level.

To aid in the environmental characterization, two pressure transducers (PT, Level TROLL) were placed in two different sites of Ria