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

Alexandra Cravo$^1$, Sara Cardeira$^1$, Catarina Pereira$^1$, Mónica Rosa$^1$, Pedro Alcântara$^1$, Miguel Madureira$^1$, Filomena Rita$^1$, Joaquim Luis$^2$ and José Jacob$^1$

$^1$ CIMA, FCT, University of Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

$^2$ IDL, FCT, University of Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

corresponding author: acravo@ualg.pt

CIMA, FCT, University of Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

Telephone: +351 289 800900
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 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.

Key-words: Upwelling, Ria Formosa, coastal lagoon, tidal prism, nutrients, chlorophyll a
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 et al., 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 km², 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).

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 fertilise offshore waters and have a strong influence on the increase of biological productivity (Cravo et al., 2010; Levi, 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 characterised 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 (Salles et al. 2005; Pacheco et al., 2010). 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 Formosa, landward of BFO (PT1 and PT2, Fig. 1), at a depth of approximately 2.5 m below mean sea level (msl). These were deployed before the autumn 2011 and
spring 2012 experiments, to collect sea level and temperature data for approximately two months (since 14 October 2011 to 14 December 2011, and since 13 March 2012 to 18 May 2012), with a sampling interval of 10 minutes. These two locations are influenced by different oceanographic conditions: one (PT1), close to BFO, is exposed to direct influence of open ocean forcings, coastal tides and swell; the other (PT2), inside Ria Formosa, was 6 km upstream of the first and protected from the direct influence of the adjacent ocean (Jacob et al., 2013).

Water samples for the analysis of nutrients and chl \( \alpha \) were also collected hourly at a central point of the section, at three depths along the water column (1 m below surface, Secchi disk extinction depth and 1 m above the bottom, max. 13 m), using a Niskin bottle (5 L). This central point was selected since in other surveys at the two inlets, no horizontally significant differences \((p>0.05)\) in the water characteristics were found along three sites of the cross section (a central point of the inlet cross-section and both banks; data not published). Whenever possible, measurements of temperature, salinity, pH and dissolved oxygen were conducted in situ at the same three levels, using a multiparametric probe YSI 6820. At BAN, as it is shallower (maximum of 7 m, Table 1), the number of sampling depths depended on the water level which in turn was function of the tidal phase.

2.2. Meteorological and Oceanographic conditions

The tri-hourly wind velocity values (direction and intensity) and precipitation levels (whenever occurring) were provided by the Faro airport meteorological station (Fig.1), located on the border of the lagoon very close to BAN.

Daily and three-day Sea Surface Temperature (SST) images were acquired from the Advanced Very High Resolution Radiometer (AVHRR) at NOAA satellites. Chl \( \alpha \) images from MODIS-Aqua satellite, with a spatial resolution of 4 km were also acquired. The SST and chl \( \alpha \) data downloaded from the OceanColor site were processed with the procedures implemented in the Mirone suite (Luis, 2007).

2.3. Discharges, tidal prisms and mass transport

The discharge \( Q \) \( (\text{m}^3\text{ s}^{-1}) \) was numerically computed by using the composite trapezoidal rule for integral estimation applied to the expression (definition of volumetric flow rate)
\[ Q = \int_A \vec{v} \cdot \vec{n} \, dA \]

where \( \vec{v} \) (m s\(^{-1}\)) is the velocity field, \( dA \) (m\(^2\)) is the element of area on the surface of the inlet cross-section \( A \) (domain of integration) and \( \vec{n} \) is the flood directed unit vector normal to the surface at each element of area.

The transport of nutrients and chl \( a \), in kg s\(^{-1}\), was obtained hourly over the entire semi-diurnal tidal cycle multiplying the discharge, \( Q \), by the average concentration for the three selected depths along the water column at the central point. Finally, the tidal prisms (m\(^3\)) and the net transport of nutrients and chl \( a \) (kg) was obtained by integrating in the time domain the hourly transport values over the entire tidal cycle.

### 2.4. Laboratorial Analyses

For nutrients analyses (0.25 L) samples were filtered through 0.45 μm decontaminated membrane filters and frozen at −20 °C while water samples (1 L) for chl \( a \) concentrations were filtered using GF/F glass fibre filters, which were deep-frozen at −20 °C prior to analysis. Nutrients - nitrate (NO\(_3\))-, phosphate (PO\(_4^{3-}\)), silicate (SiO\(_4^{4-}\)) - and chl \( a \) determinations were conducted by spectrophotometric methods, as described by Grasshoff et al. (1983) and Lorenzen (1967), respectively. The detection limits were: 0.05 μM for nitrate, 0.04 μM for silicate and 0.02 μM for phosphate. The Marine Nutrient Standard Kit (OSI) was used as reference material to ensure accuracy. The accuracy of the procedure was high, with a relative error lower than 2.5 % for the nutrient concentrations. The precision was calculated and corresponded to ±1% for silicate and phosphate, and ±2% for nitrate.

### 2.5. Statistical Treatment

ANOVA followed by a Post-hoc Tukey pair-wise multiple comparison test was applied to determine if there were significant differences in chl \( a \) and nutrient concentrations along the three selected depths (surface, middle depth and bottom) of the water column at the central point of the inlets cross-section. The minimum level of confidence considered was 95 %.
To establish the relationships between the different environmental variables, a principal component analysis (PCA) was applied to the overall data achieved for the four sampling surveys. This analysis was performed using the software XLStat 2013.

3. Results

3.1. Environmental characterization and oceanographic settings

Winds, satellite imagery and PT recordings will be described below. It is important to remark that Iberian upwelling responds in short time scales to wind; it responds to favourable pulses of the wind within 1 to 2.5 days (Fiúza, 1982; Fiúza et al., 1982). It should be also mentioned that episodes of heavy rainfall were only recorded during autumn conditions at BAN (22 November 2011), during the ebb period, from 16:30 to 19:00.

Winds, SST satellite imagery and PT recording

The wind velocity intensity and direction for the previous two weeks and during each one of the four field campaigns are displayed in Figure 2. For these periods, the wind was predominantly from the west, favourable to the upwelling on the southern coast of Portugal. However, the variability of the wind direction and intensity has an important effect on the upwelling strength.

In the period from 15 April to 1 May 2009, that includes the first campaign (27 April 2009 at BAN), the wind was relatively weak (< 10 m s\(^{-1}\), Fig. 2A) and predominantly eastward. During the field work the wind direction was maintained, despite decaying in intensity (~5 m s\(^{-1}\)). Previously, from 22 to 24 April (Fig. 2A) there was a short period of wind relaxation. The SST satellite image for the survey day (Fig. 3) clearly shows the upwelling event. It was particularly intense near the coastline, including the study area (~8° W). There, the colder water (~15 °C) was ~3 °C lower than the water temperature offshore. Unfortunately, during this first campaign no PT recording data was available.

In the period from 10 to 24 November 2011, covering the following field campaigns (22 November at BAN and 24 November at BFO), the wind regime (Fig. 2B) was quite variable, with westerlies and easterlies interleaved and an intensity similar to that of the first campaign in April 2009 (<10 m s\(^{-1}\)). From 13 to 15 November westerlies were predominant, while in the subsequent week the direction
reversed to mostly easterlies with decay in intensity; during the surveying days westerlies were interleaved with easterlies. Consequently, upwelling conditions were not achieved during the field work, unlike in the April 2009 campaign. The 3-day composite SST satellite images (Fig. 4A-D) confirmed the upwelling in the coastal zone in front of both inlets from 5 to 10 November (Fig. 4A-B). The temperature in the coast contrasts with the temperature of the surrounding waters (~3 °C higher; Fig. 4B). Afterwards, there was a change in the wind regime and the warmer water recirculating from the Gulf of Cadiz pushed back westward the colder upwelling waters (Fig. 4C-D). In consequence, a small increase of temperature at both sampling sites during the field work (22 – 24 November) was promoted. Water temperature data recorded by the PT (Fig. 2D) also confirm the upwelling event as a response to favourable wind stress. Between 3 and 10 November there was a decrease of temperature from ~19.5 °C to ~16.5 °C, in agreement with the wind and SST satellite data (Figs. 2B and 4A-B). After that, during a shift of the wind regime, easterlies prevailed and water temperature increased again to ~19.5 °C, remaining relatively constant until the field surveys (Fig. 2D).

For the period covering 23 March – 7 May 2012, which encompasses the last campaign (7 May 2012 at BFO), the wind was more regular, weaker and similar to that of the first campaign. In the two weeks previous to the field campaign (Fig. 2C) the wind was predominantly from west, with velocities similar to the previous campaigns of April 2009 and November 2011 (<10 m s⁻¹). Apparently, despite the slight decay of intensity, no wind relaxation occurred previously or during the campaign, distinct from that recorded for the first survey in April 2009. In fact, the 3-day composite satellite SST images for the week previous to the campaign (Fig. 5A) show upwelling characteristic temperatures, particularly close to the coast, with water temperature ~15 °C, ca. 3-4 °C lower than that offshore. The following 3-day composite SST satellite images, and particularly that covering the field work (Fig. 5C), confirmed that upwelling weakened, since the difference of water temperature between the coast and offshore decreased. From 13 March to 22 May, PT data (Fig. 2E) showed that during the sampling period and days before the water temperature close to BFO was ~15 °C. Afterwards, a gradual increase to ~20 °C until 17 May was recorded, corresponding to the transition from spring to summer conditions. This suggests that previously and during field work, when westerlies were dominant (Fig. 2C), upwelling was persistent.
In summary, coastal upwelling was depicted in spring conditions (April 2009 and May 2012). During this period, westerlies were consistently dominant and water temperature colder (~15 °C) than in November 2011, when warmer water temperatures were reached (16 – 18 °C). In this last period, the increase of temperature could be attributed to shifts in wind direction and contribution of the warm coastal countercurrent recirculating from the Gulf of Cadiz. The PT data confirm that under favourable wind forcing, i.e. westerlies, upwelling occurred and extended its influence into the Ria Formosa lagoon, as recorded in the first fortnight of November 2011 and April-beginning of May 2012. It was even detected by PT2, 6 km upstream of BFO (Fig.1), where the water temperature decrease in autumn (Fig. 2D) was more marked than close to BFO in consequence of a shallower water column and heat loss to the cooler atmosphere above.

**Chlorophyll a satellite imagery**

To understand how coastal waters adjacent to the Ria Formosa extend their influence to the chl a concentration within this system during the surveyed periods, chl a satellite images for the southern coast of Portugal were analysed. A longitudinal distribution between 7.3°W and 9.0°W, averaged in latitude between 36.8°N and 36.9°N, of monthly average chl a derived from satellite data was constructed for the period from January 2009 to July 2011 (Fig. 6A). The field survey periods, indicated by the dashed rectangle, are shown in detail: April 2009 (Fig. 6B), November 2011 and May 2012 (Fig. 6C), along the arc of longitude 7.75°W - 8°W to include the area of the two inlets of Ria Formosa. The red symbols point out the field surveys location and date. These images show that for the surveyed periods the highest chl a concentrations matched the lowest SST, i.e., in April 2009 and May 2012 (Figs. 3 and 5). The images also show that chl a values in April 2009 in the coastal area adjacent to Ria Formosa were highest (1-2 mg m⁻³), conforming the increased intensity of upwelling (Fig. 3). In May 2012, the chl a concentrations attained lower values, ~1 mg m⁻³. During the autumn campaigns (November 2011), under no upwelling conditions, chl a concentrations were minimal and did not exceed 1 mg m⁻³. However, 2 weeks before, under upwelling conditions (Figs. 4A-B), chl a concentrations reached ~2.5 mg m⁻³.

**3.2 Discharge and tidal prism**
To calculate discharge values and tidal prisms, velocity measurements along the sections of both inlets was conducted in each of the four sampling surveys. As expected, velocity varied in function of the tidal phase. The maximum velocity values were reached at mid tides, during flood or ebb, while minimum values (~0 m s\(^{-1}\)) occurred at slack waters in tidal peaks. The maximum velocities were consistently recorded during mid ebb, for all the four surveys. The average velocity along the tidal cycle was about 1 m s\(^{-1}\) for the two inlets. The maximum velocity of 2.2 m s\(^{-1}\) was attained at BFO while at BAN it was 2.0 m s\(^{-1}\).

The flood and ebb tidal prisms along semi-diurnal tidal cycles for the four sampling campaigns are presented in Table 1, together with the tidal characteristics (ebb and flood periods and maximum range). The ebb and flood prisms at BAN were one order of magnitude lower than at BFO. At BAN the smallest tidal prism was recorded in the autumn 2011 campaign. For the four campaigns, the flood prism was higher than the ebb prism, which leads to a flood dominated (landward directed) residual flow in both inlets.

### 3.3 Chlorophyll a and nutrients concentrations

To determine mass exchanges of chl \(a\) and nutrients through BAN and BFO in spring and autumn conditions, concentrations were assessed along complete tidal cycles. Mean chl \(a\) concentrations (average of the three levels along the water column) recorded in April 2009, November 2011 and May 2012 surveys are presented in Figure 7A. These data clearly show seasonal differences between the campaigns. The highest chl \(a\) concentrations (>3 - 5.7 µg L\(^{-1}\)) were reached in the April 2009 campaign at BAN, followed by the May 2012 campaign (~2 µg L\(^{-1}\)) at BFO, while the lowest values (< 1 µg L\(^{-1}\)) were found in the November 2011 campaigns, at both BAN and BFO. Comparing both spring conditions, the chl \(a\) concentrations in the April 2009 campaign were higher than those in the May 2012 campaign. It is also important to remark that for both spring campaigns the highest values were found during the flood period, indicating that chl \(a\) was transported from the adjacent coastal zone to the Ria Formosa through these two inlets.

The hourly variation of the mean nitrate (NO\(_3\)), phosphate (PO\(_4^{3-}\)) and silicate (SiO\(_4^{4-}\)) concentrations (average values of the three levels along the water column) along the complete semi-diurnal tidal cycles for the four surveys are represented in Figure 7B, C and D, respectively. The nutrient
concentration, nitrate and silicate in particular (Fig. 7B and D, respectively), show a similar pattern of variation. These nutrients also depict to some extent an opposite trend of variation of that of chl \(a\) (Fig. 7A). The nutrient concentrations variations in antiphase with tidal height along the tidal cycle is evident. In general, the highest values were found close to low tide, in opposition to the lowest concentrations observed around high tide. In the April 2009 campaign, the nutrient concentrations were the lowest with nitrate almost depleted (<0.25 \(\mu\)M; Fig. 7B). In this campaign, during the flood period, concentrations of phosphate (Fig. 7C) increased while silicate (Fig. 7D) decreased. In the autumn of 2011 campaign, at BAN inlet, nutrients were higher than in the April 2009 campaign. The highest concentrations of nitrate and silicate were found during the ebb. Throughout this period a heavy rainfall event (6 mm) occurred, leading to a salinity decrease from 36.3 down to 34.6. This corresponds to the maximum salinity amplitude recorded along the studied tidal cycles, since most of the values were around 36. At BFO inlet the concentrations were lower in the autumn 2011 campaign than in May 2012.

It is also important to remark that for all four campaigns the nitrogen was the limiting element with \(\text{NO}_3^- : \text{PO}_4^{3-}\) ratios < 13.

### 3.4. Principal Component Analysis (PCA)

To identify the factors that best explain the results variability for all four campaigns, a PCA was applied to nutrients, chl \(a\), temperature and salinity along with tidal height (Fig. 8). Data show that the two main axis explain 68 % of the variance, from which PC1 contributes for 42% and PC2 for 26%. This analysis reveals that the primary factor explaining the variance of results was the influence of mixing, as depicted by the inverse relationships between both nitrate and silicate with salinity (and tidal height). The mixing is promoted by tidal advection and dilution by diffusion processes since ocean water is poorer in those nutrients than water from the Ria Formosa. The highest nitrate and silicate concentrations were found at BAN inlet in November 2011, when salinity was minimum. This fact points the continental origin of these two nutrients. The secondary factor explaining variance of results is the influence of upwelling seasonality upon chl \(a\). There was a dependency of chl \(a\) on water temperature, the highest concentrations were recorded in colder waters in spring conditions (April and May), associated with upwelling events. This component also confirms that chl \(a\) and phosphate were imported from the adjacent ocean reaching the maximum values during the periods of highest tidal
height, i.e. the flood period. In the opposite sense, chl a was minimum during the autumn campaigns (November 2011), in a period of higher temperature when upwelling events did not occur.

3.5 Chlorophyll a and nutrients transport

Mass transport of chl a and nutrients were estimated for each semi-diurnal tidal cycle for both ebb and flood periods (~6 h), providing the residual transports (Table 2). Regarding water mass exchanges, the two inlets showed positive flood-ebb differences in tidal prisms (flood dominated behaviour), with the highest tidal prisms at BFO. In fact, the volumes exchanged through this inlet can reach one order of magnitude higher than those passing through BAN (Table 1).

For chl a, during all campaigns, there was a net import from the coastal ocean to the Ria Formosa, more evident in spring conditions (April 2009 and May 2012). In this season, the amounts of chl a exchanged were greatly higher at BFO than at BAN, i.e. during flood ~160 kg were imported through BFO against ~25 kg at BAN (Table 2). However, the residual transport was similar at both inlets (20.5-27.2 kg – Table 2). During the November campaigns the net transport of chl a was low, particularly at BAN (0.3 kg), almost two orders of magnitude lower than that in spring conditions (Table 2).

For nutrients, like for chl a, the amounts exchanged during flood or ebb periods were much higher at BFO than at BAN. However, those differences between both inlets were not evidently reflected in the net nutrients transport. At BAN, there was a net export of silicate in both spring and autumn seasons (~70-90 kg – Table 2). At BFO, nitrate was consistently exported, highest in the May 2012 campaign (~240 kg, Table 2), while in the same campaign silicate was maximum imported (~960 kg, Table 2). In spring conditions, for both inlets there was a net import of phosphate (9-13 kg, Table 2), as for chl a, confirming the PCA results, with maximum ebb and flood transports at BFO (~632-640 kg, respectively - Table 2). Considering the autumn campaigns, for both inlets there was a net export of nitrate (22-32 kg – Table 2) and phosphate (3-49 kg – Table 2).

4. Discussion

Hydrodynamic conditions in coastal lagoons are influenced by the coastal-ocean tidal forcing. In the present study only spring tide conditions were surveyed to assess the maximum influence of water
exchanges throughout the inlets. However, the response of a coastal lagoon to tidal forcing will depend on factors such as morphology, friction and changes in cross-sectional area throughout the system (Aubrey and Speer, 1985). Dias et al. (2009), using a modelling approach, demonstrated that water exchanges in the Ria Formosa depend on the position and morphological configuration of the inlets. Both inlets considered in this study showed flood tidal prisms larger than ebb tidal prisms in spring tide conditions (Table 1). While this conforms to a feature of BFO (Pacheco et al., 2010) the same is not valid for BAN, described as a dominant ebb tidal prism inlet (Pacheco et al., 2010; Salles, 2001; Williams et al., 2003). The small differences and variability of tidal prisms between this study (Table 1) and those measured by others authors (Pacheco et al., 2010, Salles, 2001), could result either from differences in the tidal range or in the period of semi-diurnal tidal cycles considered. The decrease of about 50% in tidal prisms at BAN from the campaigns of 2009 to 2011 (Table 1) could be attributed to morphological and bathymetric changes and to the evolution of BAN. This is a natural inlet, in opposition to BFO, an artificially stabilized inlet. BAN is a cyclic eastward migrating inlet which moved ~900 m since its artificial relocation in 1997 until 2009 (~75 m/year). Moreover, it migrated ~1 km since 2009, due to extreme SW storm events occurred in the winters of 2009-2010 and 2010-2011. BAN has lost hydraulic efficiency that may be ascribed to the increase of resistance to flow due to sand accretion at the Ancão channel and flood tidal delta (Cravo et al., 2013a) and to the increased length of the channel caused by the recent inlet migration. Presently this inlet contributes for < 6% to the total tidal prisms for the three main inlets in the Ria Formosa western sector (Jacob et al., 2013). Comparing the tidal characteristics of BAN (Table 1) with the values of Salles (2001) and Pacheco et al. (2010), the main difference is the increase of the ebb period from values of 5.8-5.9 hours in 2009 and before, to a value of 6.1 hour on the 2011 campaign possibly due to the increased resistance to flow mentioned above, whose effect is greater on the ebb currents. However, the greatest water volume imported by BFO suggests a residual circulation towards the other two inlets of the western sector of the lagoon (Pacheco et al., 2010).

It is difficult to compare the chemical characteristics and mass balances of the Ria Formosa with those of other European coastal lagoons. On the northwestern coast of Portugal there is the Ria de Aveiro and on the northwestern coast of Spain, the Galician Rias. Both systems are mesotidal and affected by upwelling events under pulses of favourable north winds. However, these represent estuarine systems rather than coastal lagoons, due to rivers discharge influence. These systems show a
marked salinity gradient, with an evident increase of nutrients concentration during the ebb period (lower salinity), and subsequently, a decrease during the flood (higher salinity) by dilution with seawater impoverished in nutrients. However, for both systems on the Atlantic coast, affected by similar oceanographic processes, the magnitude of nutrients and chl $\alpha$ concentrations are similar. In the Mediterranean basin there are microtidal coastal lagoons, but a direct comparison with the Ria Formosa is unreliable due to restricted tidal effects observed there.

In the Ria Formosa, the water chemical properties depend upon land runoff, anthropogenic pressure (e.g. Brito et al., 2012; Cabaço et al., 2008; Newton et al., 2003; Newton and Mudge, 2005; Loureiro et al., 2006) and mixing with the adjacent coastal waters (Newton and Icely, 2004). Within this mesotidal system, the variability of water chemical features is deeply dependent on tidal influence, i.e. tidal range, tidal phase and distance from the inlets. The effect of tidal mixture was the primary factor explaining the variability of results at both inlets, as clearly depicted from the PC1 of the PCA (Fig. 8). Under wind-driven coastal upwelling, it was still observed a fingerprint of its influence in this ecosystem. In fact, PC2 shows that during these periods of decreased temperature, there was an import of chl $\alpha$ and phosphate from the adjacent coast. This decrease in water temperature was extended at least ~6 km upstream from BFO, as recorded by the PT2 (Fig. 2D).

However, upwelling is not a spatially uniform or temporally continuous process; rather, it displays periods of more favourable conditions (Cervantes-Duarte et al., 2013). This study confirms that coastal upwelling events in the southwest tip of the Iberia are not spatially limited to Cape São Vicente region. Not infrequently, under favourable westerlies, upwelling pulses occur along the southern coast of Portugal as a direct response to wind stress (Cardeira et al., 2013; Cravo et al., 2013b; Criado-Aldeanueva et al., 2006a, 2006b; García-Lafuente et al., 2006). Temporally, the described campaigns were conducted in spring and autumn, when phytoplankton density is usually highest. Additionally, these seasons overlap the period of more intense upwelling on the southern Portuguese coast (March to October; Relvas et al., 2002). As shown in the present study, upwelling season was extended to November and the key factor to promote upwelling was the forcing by westerlies. Iberian upwelling has a quick response to wind stress, in a time scale of a couple of days (Fiúza, 1982; Fiúza et al., 1982). Hence, like reported in the Northern Galician Rias, upwelling can arise out of season (in winter; Alvarez et al., 2003, 2009) if favourable winds occur.
The wind forcing has also profound effects on the chemical and biological processes occurring in the water. The upwelled water induces a response of phytoplankton along a conveyor (Dugdale et al., 1990). At the beginning of this process, the water advected upward causes rapid changes in nutrient availability and light intensity that does not provide time for physiological adaptations of phytoplankton (Bode et al., 1997). Meanwhile, chlorophyll concentrations are low and nutrients levels high (Wilkerson et al., 2006). There is a delay in the photosynthesis process; the greatest development of the bloom (expressed by high chlorophyll levels) occurs after the end of the upwelling event by wind relaxation, following an optimal period of water-column stability. Afterwards, high phytoplankton uptake rates occur and nutrients are almost depleted within a period of approximately 3 to 7 days (Dugdale et al., 1990; Wilkerson et al., 2006).

In the present study chl α concentrations varied not only along the day and along the semi-diurnal tidal cycle but also seasonally; these were highest during the spring surveys. The maximum chl α values in both spring campaigns agree with the seasonal peak of phytoplankton development in the Gulf of Cadiz. The analysis of a long times series (1997-2010), identified higher values from March to May, despite the high interannual variability (Navarro et al., 2012). Differences in wind field conditions between the two spring surveys led to upwelling events at different stages. Phytoplankton growth was particularly intense in the April 2009 campaign, reaching maximum concentrations of ~6 µg L⁻¹. These levels can be considered high and typical of bloom periods, since average values close to the Ria Formosa inlets are generally <2 µg L⁻¹ (Barbosa, 2010). Concurrently, nutrients concentrations were low, particularly for nitrate that was almost depleted (<0.25 µM; Fig. 7B). Decrease in nutrients almost to exhaustion has been ascribed for other upwelling systems, such as the Galician Rias (Bode et al., 1997; Fraga et al., 1999; Seeyave et al., 2013). These low nutrient concentrations reflect an efficient phytoplankton consumption after upwelling pulses, interrupted by wind relaxation periods (Fig. 2A). During the May 2012 campaign, with no record of a wind relaxation period, the optimal conditions for an intense phytoplankton development were not promoted. Indeed, a spring bloom already had occurred in March-April 2012, stronger by the end of March (Fig. 6C). It is also important to remark that during the last field campaign the spring to summer transition already started (Fig. 2E). During the autumn campaigns, despite preceded by at least two upwelling events, chl α concentrations were low (<0.5 µg L⁻¹; Fig. 7A). Wind direction reversal did not promote water stabilization for further
phytoplankton development, and sometimes led to downwelling (Wilkerson et al., 2006). By the time of the campaign colder waters were pushed back by a westward progression of an inner warm countercurrent, recirculating from the Gulf of Cadiz (Fig. 4). This warm current is usually impoverished in nutrients and considered typically oligotrophic (Navarro et al., 2006). In addition, the transition to winter conditions could have also contributed to the phytoplankton decrease by that time of the year.

The values of nutrients concentrations varied among the four campaigns but, globally, can be considered in the range of the values recorded recently at a site close to BAN (Loureiro et al., 2006; Pereira et al., 2007). Nitrogen was consistently the limiting element, which is typical of coastal waters (Howarth and Marino, 2006) and already reported for this ecosystem (Loureiro et al., 2005; Newton and Mudge, 2005). This limitation was stronger during the campaign of April 2009 (N:P ratio <4), when upwelling and phytoplankton development (expressed by the maximum chl α) were more intense. Large phytoplankton such as diatoms are dominant during upwelling events (Fawcett and Ward, 2011; Silva et al., 2009; Wilkerson et al., 2006) and have an early rapid response to newly upwelled nitrate. This phytoplankton group is typical in similar coastal upwelling areas, like the NW Iberia and California coasts (Estrada and Blasco, 1985; Chavez et al., 1991, respectively). Unfortunately, the identification of phytoplankton was not carried out to confirm it. Low N:P ratios may also suggest an incomplete organic nitrogen oxidation compared to phosphorus oxidation, as observed in coastal waters during upwelling events (Alvarez-Salgado et al., 1997).

Very few studies have estimated the mass transport through the inlets of Ria Formosa, by measuring concurrently the current velocity along the cross section and the chemical parameters of the waters. The present study shows that the two inlets, representative of maximum and minimum contributions for the tidal prisms of the Ria Formosa western sector, have a different behaviour depending on the variability of atmospheric and oceanic processes. These conditions substantially affect and change the mass transport patterns induced by tidal forcing, as observed in other lagoonal systems (Smith, 2001). Under the influence of upwelling events, the Ria Formosa behaved as a sink, net importing chl α and phosphate from the adjacent coastal area (Table 2), well reflected in the PCA (Fig. 8). For this ecosystem, an import of these compounds was already pointed out in spring tides (Falcão and Vale, 2003). There is noticeable difference of ebb and flood tidal prisms at each one of the two inlets (Table 1), but, interestingly, the net amounts of chl α and phosphate imported are similar among
them (Table 2). Conversely, when coastal upwelling was not evident, this coastal lagoon acted as a source of nutrients, exporting relevant amounts of nitrate and phosphate through both inlets over a tidal cycle, even when importing water (Table 2). Silicate was consistently supplied to the ocean through BAN, whereas imported through BFO. It is also important to mention that BAN, although contributing for the lowest exchange of water volumes (Table 1), exhibited the maximum transport of nitrate and silicate during spring tidal conditions. This fact confirms that the westernmost region of Ria Formosa supply these two nutrients to the coastal zone (Alcântara et al., 2012; Falcão and Vale, 2003; Loureiro et al., 2006). Silicate export has been associated with diffusion through sediment-water column exchanges (Falcão and Vale, 2003; Vieillard et al., 2011). Nitrate export has been linked to runoff inputs derived from urban centres and agricultural areas, particularly during wet periods (Newton and Mudge, 2005). This may explain the maximum concentrations of nitrate at BAN after an event of heavy rainfall in the latest sampling hours of the November 2011 campaign (Fig. 7B). The export of nutrients from the Ria Formosa attributes its role of fertilising the adjoining ocean, contributing for the increase of biological productivity of the coastal zone (Falcão and Vale, 2003; Newton and Mudge, 2005).

5. Conclusions

The variability of hydrographical properties at BAN and BFO inlets along the four field surveys depended on tide dynamics, providing mixture and dilution with the adjacent ocean waters. However, both meteorological and oceanographic conditions are very important, and at a different time scale can be superimposed over tidal influence.

On the southern Portugal coastal waters, upwelling takes place under favourable westerlies, and its fingerprint into the Ria Formosa can be extended at least ~6 km upstream BFO. Under these conditions, or after pulses of upwelling interleaved by short periods of wind relaxation (< 1 week), phytoplankton development was augmented in spring conditions, maximum in April 2009. In consequence, there was an evident consume of nutrients. However, high variability could be expected at different time scales, i.e. short-term, seasonal or even inter-annual scales.

In the absence of direct upwelling influence, by wind reversals or decay in intensity (November 2011), these two inlets of Ria Formosa acted as source of nutrients exporting nitrate and phosphate,
fertilising the adjacent coastal waters and increasing the biological productivity of the nearby ocean. Under the influence of upwelling events (April 2009 and May 2012), Ria Formosa changed its typical behaviour and acted as a sink, importing chlorophyll $a$ and phosphate. This contributes for a further increase of biological productivity inside the lagoon.

The two inlets showed flood tidal prisms larger than ebb tidal prims during the spring tidal conditions surveyed, and regardless the highest contributions for the exchanges through BFO, the net amounts of chl $a$ and phosphate imported through both inlets during upwelling events were similar.

Besides the oceanographic processes on the adjacent coastal ocean, these exchanges are also dependent on the hydrodynamic, morphological and bathymetric conditions that control the water discharges through the main inlets of the Ria Formosa. The temporal changes occurred in the BAN inlet due to its natural evolution is a good example to illustrate this statement.

Acknowledgements

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References


the Northern Galician Rias: Frequency and oceanographic implications. Estuarine, Coastal and Shelf Science 82, 573-582.


Cardeira, S., Rita, F., Relvas, P., Cravo, A., 2013. Chlorophyll a and chemical signatures during an upwelling event off the South Portuguese coast (SW Iberia). Continental Shelf Research 52, 133-149.


Figure 1
Figure 3
Figure 4
Figure 5
Figure 6
Figure 7
Figure 8
Figure 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).

Figure 2. (A – C) Wind intensity (m s\(^{-1}\)) and direction recorded in Faro airport meteorological station in the 15-day period prior to and including the field campaigns: A) 15 April to 1 May 2009, B) 10 to 24 November 2011, C) 24 April to 9 May 2012. (D – E) Water temperature recorded in two PT’s deployed close to the Faro-Olhão inlet (PT1) and at Faro commercial pier, 6 km upstream from the Faro-Olhão inlet (PT2), in the period: D) 14 October to 15 December 2011, E) 13 March to 22 May 2012.

NOTE: The axes for the stick vectors are rotated - 90° from North so that up corresponds to westerlies.


Figure 6. A) Hovmuller diagram of 8-day (4 km) averaged MODIS-Aqua chlorophyll a from January 2009 to July 2012, covering the four field surveys along a section (7.3°W to 9°W) off the Portuguese southern coast, averaged between 36.8°N and 36.9°N, generated by the NASA Giovanni website. Chlorophyll a concentrations (mg m⁻³) were also averaged along the 7.75°W to 8°W section to include the two studied inlets area in the period B) January to July 2009 (first campaign, only BAN) and C) July 2011 to July 2012 (remaining three campaigns, BAN and BFO). The red symbols represent the inlets in the field surveys date. Source: OceanColor, NASA.

FIGURE 7. CONCENTRATIONS VARIABILITY OF A) CHLOROPHYLL A (CHL A, µG L⁻¹), B) NITRATE (NO₃⁻, µM), C) PHOSPHATE (PO₄³⁻, µM) AND D) SILICATE (SiO₄⁴⁻, µM), AND SEA SURFACE ELEVATION (SSE, M) ALONG COMPLETE SEASONAL TIDAL CYCLES AT BOTH BAN AND BFO INLETS DURING THE FIELD SURVEYS: 27 APRIL 2009 (BAN), 22 (BAN) AND 24 (BFO) NOVEMBER 2011 AND 7 MAY 2012 (BFO).

Figure 8. Principal component analysis (PCA) applied to the data (nutrients, chl a, temperature, salinity and tidal height) from the four field campaigns (09: April 2009; 11: November 2011; 12:
May 2012) at the two inlets, BAN and BFO. T: temperature, S: salinity, NO3: nitrate, PO4: phosphate, SiO4: silicate, chla: chlorophyll a.
Table 1. Dimensions of the cross-sections, tidal characteristics and prisms at the Ancão and Faro-Olhão inlets on the dates of the field experiments

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<tr>
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<th>Ancão Inlet</th>
<th>Faro-Olhão Inlet</th>
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<tr>
<td>Average width</td>
<td>80 m</td>
<td>600 m</td>
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<td>Maximum depth</td>
<td>7 m</td>
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<tr>
<td><strong>Campaign Date</strong></td>
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<td></td>
<td><strong>Spring</strong></td>
<td><strong>Autumn</strong></td>
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<td></td>
<td>27(^{th}) Apr 2009</td>
<td>22(^{nd}) Nov 2011</td>
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<tr>
<td>Ebb period (h)</td>
<td>5.8</td>
<td>6.1</td>
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<td>Flood period (h)</td>
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<tr>
<td>Maximum range (m)</td>
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<tr>
<td>Ebb Prism (m(^3))</td>
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<td>-2.95x10^6</td>
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<td>Flood Prism (m(^3))</td>
<td>7.76x10^6</td>
<td>3.5x10^6</td>
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Tabela 2. Net, Ebb and Flood transport (in kg) of chlorophyll \(\alpha\) (Chl \(\alpha\)), nitrate (NO\(_3\)), phosphate (PO\(_4\)^3\)) and silicate (SiO\(_4\)^4\)) at the Ancão and Faro-Olhão inlets and dates of the field experiments

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<tr>
<td>Chl (\alpha)</td>
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<td>PO(_4)^3)</td>
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<td>SiO(_4)^4)</td>
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<td><strong>Net Transport</strong></td>
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Highlights

- Influence of upwelling in Ria Formosa was assessed at Faro-Olhão and Ancão inlets
- Under upwelling, Ria Formosa imported chlorophyll a and phosphate from the ocean
- In the absence of upwelling Ria Formosa exported nitrate and phosphate to the ocean
- The highest mass transports occurred through the Faro-Olhão inlet
- Mass exchange variability depends strongly on coastal oceanographic processes