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Biogeochemical patterns in the Atlantic Inflow through the Strait of Gibraltar

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ABSTRACT

The effects of tidal forcing on the biogeochemical patterns of surface water masses flowing through the Strait of Gibraltar are studied by monitoring the Atlantic Inflow (AI) during both spring and neap tides. Three main phenomena are defined depending on the strength of the outflowing phase predicted over the Camarinal Sill: non-wave events (a very frequent phenomenon during the whole year); type I Internal wave events (a very energetic event, occurring during spring tides); and type II Internal wave events (less intense, occurring during neap tides).

During neap tides, a non-wave event comprising oligotrophic open-ocean water from the Gulf of Cádiz is the most frequent and clearly dominant flow through the Strait. In this tidal condition, the inflow of North Atlantic Central Water (NACW) provides the main nutrient input to the surface layer of the Alboran Sea, supplying almost 70% of total annual nitrate transport to the Mediterranean basin. A low percentage of active and large phytoplankton cells and low average concentrations of chlorophyll (0.3–0.4 mg m^{-3}) are found in this tidal phase. Around 50% of total annual phytoplankton biomass transport into the Mediterranean Sea through the Strait presents these oligotrophic characteristics.

In contrast, during spring tides, patches of water with high chlorophyll levels (0.7–1 mg m^{-3}) arrive intermittently, and these are recorded concurrently with the passage of internal waves coming from the Camarinal Sill (type I internal wave events). When large internal waves are arrested over the Camarinal Sill this implies strong interfacial mixing and the probable concurrent injection of coastal waters into the main channel of the Strait. These processes result in a mixed water column in the AI and can account for around 30% of total annual nitrate transport into the Mediterranean basin. Associated with type I internal wave events there is a regular inflow of large and active phytoplankton cells, transported in waters with relatively high nutrient concentrations, which constitutes a significant supply of planktonic resources to the pelagic ecosystem of the Alboran Sea (almost 30% of total annual phytoplankton biomass transport).

1. Introduction

The Strait of Gibraltar is the only connection between the Atlantic Ocean and the Mediterranean Sea, the largest semienclosed water body on Earth. The Strait represents an example of a relatively small marine area where the analysis of local phenomena is relevant in the context of global cycles. Thus, this is a key place to evaluate processes that affect the biogeochemical budget of the entire Mediterranean basin (e.g., Huertas et al., 2012). At the same time, the Mediterranean outflow is a crucial player in the North Atlantic thermohaline circulation (Ambar and Howe, 1979; Baringer and Price, 1997). The overall circulation through the Strait can be described as a two-layer inverse-estuarine exchange, with a superficial inflow of Atlantic waters and a deep outflow of Mediterranean waters (Armi and Farmer, 1985). However, this averaged scheme is strongly modified at tidal scales, where very energetic processes dominate (García-Lafuente and Vargas, 2003). Differences in tidal amplitude between the western and eastern parts of the Strait induce barotropic and baroclinic tidal currents along its main channel (Lacombe and Richez, 1982). These currents are 4 times greater in magnitude than the time-averaged flow (García-Lafuente and Vargas, 2003). The bottom topography of the Strait presents a main sill on the western side (the Camarinal Sill), which lifts the seabed from a depth of nearly 900 m to a depth of only ~300 m. The interaction between tidally-forced flows and the sharp topography of the channel of the Strait generates a very complicated hydrodynamic pattern. This interaction generates undulatory features at the Atlantic–Mediterranean Interface (AMI), such as internal bores (Boyce, 1975; Armi and Farmer, 1985), internal waves (Bruno et al., 2002) and horizontal surface divergences

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(Izquierdo et al., 2001; Macías et al., 2007). In addition, at larger scales, such as the subinertial, there is a modification of the flows forced by the atmospheric pressure fluctuations over the western Mediterranean Sea (Crepon, 1965; Candela et al., 1989; García-Lafuente et al., 2002; Vázquez et al., 2008). An increase (or decrease) in the atmospheric pressure over the Mediterranean is followed by a subsequent decrease (or increase) in the intensity of the Atlantic Inflow (AI). The opposite effect can be observed in the velocity of the Mediterranean outflow. Therefore, these atmospheric pressure oscillations can either reinforce or inhibit the generation of internal waves (Vázquez et al., 2008). Finally, Atlantic inflowing waters constitute the Atlantic Jet (AJ), a significant physical feature characterized by a typical flow speed of ca. 1 m s^{-1}, and ~30 km wide, that feeds the Western Alboran Gyre and controls the dynamics of the Alboran Sea (Renault et al., 2012).

The intense hydrodynamic regime of the Strait has been described as the main forcing agent for the distribution and dynamics of biogeochemical variables in this area. If hydrodynamic processes are excluded, and only in situ biological processes are taken into account, the biogeochemical patterns observed cannot be explained (e.g., Echevarría et al., 2002; Macías et al., 2008). There are at least three main water masses involved in the circulation through the Strait (Gascard and Richez, 1985): the Surface Atlantic Water (SAW) (salinity ~36.4); North Atlantic Central Water (NACW) (salinity ~36–36.25); and Mediterranean Outflowing Water (MOW) (salinity ~38.5). The position of the Atlantic–Mediterranean Interface (AMI) and the distribution of the NACW are dependent on the fortnightly tidal amplitude variation (Gascard and Richez, 1985; Gómez et al., 2001; Macías et al., 2006). According to previous work (Macías et al., 2008) three biologically important contact zones must be taken into account: SAW–NACW, SAW–MOW and NACW–MOW. At these water interfaces different chlorophyll maxima have been described, with different biogeochemical characteristics and of hypothetically-different origin (Macías et al., 2008; Bartual et al., 2011). Especially relevant in the area is the observation of patches with chlorophyll concentrations higher than the background within the AJ (Vázquez et al., 2009). These possible intrusions of chlorophyll-rich patches coming from coastal water have been referred to as “coastal advection” to the central channel, “injection” or “suction” phenomena (Macías et al., 2008). It has been proposed that these intrusions are associated with the periodical tidally-induced creation of velocity divergences in the surface layer, and with the presence of internal waves arrested over the Camarinal Sill, especially during spring tides (Vázquez et al., 2009). Furthermore, these processes could account for the regular supply of planktonic material to the surface of the NW Alboran Sea and could have a considerable influence on the biogeochemical patterns in this basin, particularly when the coastal upwelling in the Estepona region (east of the Strait) is relaxed. Nevertheless, to date, neither these supplies of nutrients and planktonic material, nor the differentiated supply associated with internal wave phenomena, have been fully assessed at tidal scales.

Two main mechanisms have been described as important for the nutrient supply to the surface layer of the Alboran Sea: (1) during neap tides, the dominant input is the inflow of nutrient-enriched NACW toward the Mediterranean (Gómez et al. 2001); (2) during spring tides, provoked by the internal waves, interfacial mixing processes occur at the Camarinal Sill (Wesson and Gregg, 1994). This phenomenon could change the properties of the AJ while it flows toward the Mediterranean, thus modifying the biogeochemical budget of the Mediterranean Sea through the recirculation of nutrients from deep waters (Macías et al., 2007). Nevertheless, the differentiated contribution of each nutrient input has not been estimated before, as most of the previous studies that assess nutrient fluxes did not resolve at the tidal scale (e.g., Gómez, 2000; Huertas et al., 2012).

The present work is a comprehensive high-resolution description of the water-mass distributions and biogeochemical signatures of the AI within the Strait of Gibraltar. We focus on the tidal scale, highlighting the differences between the spring- and neap-tide periods. In particular, in this work we aim to study the effects of different internal-wave events on the biogeochemical patterns of the AI. In addition, we have analyzed the relationship between tidal conditions and the structure and characteristics of chlorophyll patches. Finally, we discuss the relative importance of the main inputs of nutrients to the Alboran Sea, and reflect on the relative importance of three factors – interfacial mixing, coastal injection and NACW inflow – to the biogeochemical budget of the Alboran basin.

2. Materials and methods

2.1. Data analysis

Data were collected during two different cruises carried out in September 2008 in the Strait of Gibraltar on board the research vessel B/O “Sarmiento de Gamboa”. During each cruise, one fixed station (“A” in the Tarifa Narrows, Fig. 1) was sampled during a period of approximately 24 h. The data were acquired under different tidal conditions, during spring tides (Fig. 2a and b) and neap tides (Fig. 2b and c).

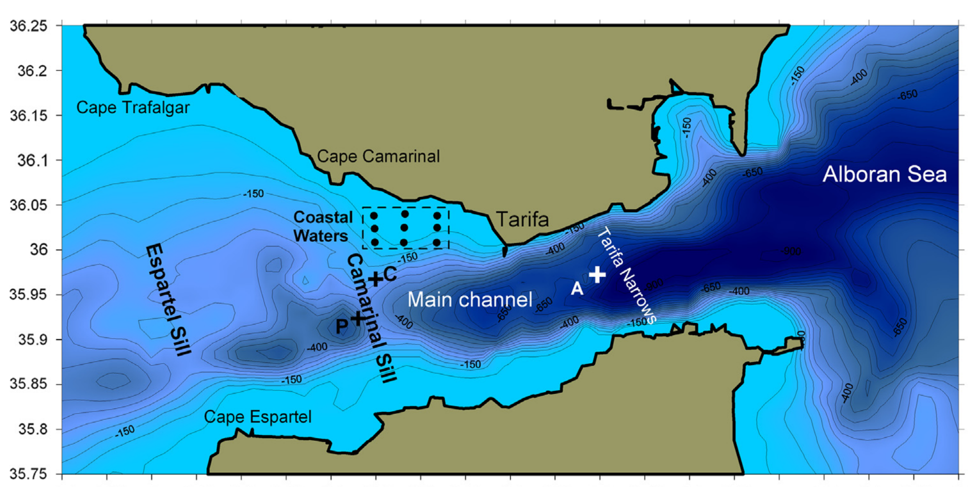

Fig. 1. Map showing the location and main geographic points of the study area. “C” marks the location of the current meter over the Camarinal Sill at a depth of 100 m. “P” marks the location of the currents predicted. “Coastal waters” marks the reference area used in Table 1.