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Modelling the effect of the tidal cycle on the high phytoplankton biomass area of Cape Trafalgar (SW Iberian Peninsula)

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Abstract

Physical-biological interactions in the ocean are known to be crucial for understanding ecosystem processes. This is particularly relevant in the highly dynamic coastal regions, where the biogeochemical processes associated with higher-frequency perturbations such as tidal waves play a key role in primary production. In this study, we examine the influence of the tide-topography interaction on the high productivity area of Cape Trafalgar (NW limit of the Strait of Gibraltar, Iberian Peninsula) using a high-resolution ocean circulation model coupled to an ecosystem model. The obtained results highlight the relevance of the tidal cycle explaining the high phytoplankton biomass that characterises this region through an active and periodic forcing, resulting in a pulsating upwelling system. Our model shows that the interaction of the westward zonal component of the tidal current (uvel) with the submarine ridge (i.e., Barbate High) that characterises this region, which is perpendicular to the coast, results in the pumping of deep, cold, salty, and nutrient-rich waters to the well-illuminated subsurface waters, fuelling phytoplankton growth. At the same time, the interaction of the westward tidal current with the ridge leads to the development of a cyclonic eddy, which enables the redistribution of the upwelled waters over and to the east of Barbate High. The fortnightly tidal period has been identified as the most influential because (an effective) tidal-pumping process only takes place when the westward uvel is $\sim 0.42 \text{ m s}^{-1}$, a condition attained between ~ 3 days before and after the moment of maximum tidal flow during spring tides. Simultaneously, the energy and the associated horizontal and vertical mixing of the cyclonic gyre also vary

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with the tidal cycle, being stronger during spring tides. Both tidally driven processes, i.e., the cyclical upslope advection of deep nutrient-rich water and the influence of the cyclonic gyre, are the main mechanisms that lead to the development of a persistent phytoplankton-rich tongue over Barbate High. Consequently, Cape Trafalgar acts as a source of nutrient- and phytoplankton-rich waters to the surrounding waters.

Key words: tidal mixing, physical-biological coupled model, phytoplankton, Cape Trafalgar, Strait of Gibraltar

1. Introduction

Covering 6% of the world's surface, coastal waters are a vital part of the environment and provide between 22 and 43% of global ecosystem services (Costanza et al., 2014). The highly dynamic coastal regions and the associated biogeochemical processes play a key role in phytoplankton growth, being primary production between 3 to 5 times higher than in oceanic regions (Simpson and Sharples, 2012). In many coastal regions, tides are an important physical forcing factor with a major impact on primary production (Pingree and Griffiths, 1978; Daly and Smith, 1993; Otto et al., 1990). The tidal cycle is responsible for a series of periodic fluctuations at different time scales. The release on internal tidal waves causes a horizontal displacement of water masses and subsequent maxima in tidal current speed, at the same time that the associated current shear results in internal turbulent mixing (e.g., Holloway et al., 2001; Rippeth and Inall, 2002; Dale et al., 2003). Thus, locally, tide-topography interaction can have a significant impact on biological production by fertilisation of illuminated surface waters and the resuspension of phytoplankton cells and other particles, concomitant to the consequent vertical mixing (Pingree et al., 1981; New and Pingree, 1990; Hu et al., 2008; Sharples et al., 2007; Palmer et al., 2013).

This process is especially relevant in the Strait of Gibraltar (south of the Iberian Peninsula), a shallow and narrow channel that separates the Atlantic Ocean and the Mediterranean Sea (Figure 1). The Strait is characterised by (i) the semi-diurnal tidal cycle with a periodicity of 12 hours and 25 minutes, which results in a horizontal displacement of water that generates an increase in the current speed and the associated vertical mixing every 6 hours and 12 minutes; and (ii) the spring-neap tidal cycle with a periodicity of ~ 15 days, related to the apogee-perigee cycle (29.50-day periodicity) (García-Lafuente et al., 1990). The interaction of the tidal current with the Strait's sharp topography generates undulatory processes (e.g., internal waves) that modify the nutrient budget by recirculation from deeper to shallower layers (e.g., Macías et al., 2007b; Ramírez-Romero et al., 2012; Sánchez-Garrido et al., 2015). However, due to the hydrodynamics of this region being characterised by the superficial inflow of Atlantic water towards the Mediterranean Sea, and by the short-residence time of the mixed waters within the channel (Macías et al., 2007a; Bruno et al., 2013), the biological impact of this tide-topography interaction results in a 40% increase of productivity, not in the Strait itself, but in the adjacent Alborán Sea (western-most basin of the Mediterranean Sea) (Sánchez-Garrido et al., 2015). Thus, although the Strait is characterised by low productivity due to the surface circulation pattern, this is not the case in the coastal Cape Trafalgar region located on its north-western limit (Figure 1b).

38 Cape Trafalgar has been highlighted in several studies as a hotspot of high chloro-
39 phyll concentration (e.g., Prieto et al., 1999; Echevarría et al., 2002; García et al.,
40 2002; Navarro and Ruiz, 2006), with the along-shore tide-topography interaction be-
41 ing suggested as the main responsible process (Vargas-Yáñez et al., 2002; Sala et al.,
42 2018). A distinctive feature of Cape Trafalgar is a submarine ridge, known as Bar-
43 bate High (Figure 1b), that extends offshore perpendicular to the coast. Vargas-Yáñez
44 et al. (2002), using a 2D-model, studied the capacity of the tide-topography interac-
45 tion to reproduce a situation similar to the pool off Trafalgar. Although their model
46 was very simple, it captured the vertical excursions of heat and nutrients produced by
47 the tide-topography interaction, cooling, and fertilising areas around the topographic
48 accident. Later, Sala et al. (2018) examined the chlorophyll-*a* (chl-*a*) dynamics in this
49 region using 10 years of ocean colour images (MERIS sensor, 300 m full resolution).
50 The authors found that Cape Trafalgar is characterised by a quasi-permanent high
51 chl-*a* concentration, with an average value of 1.44 mg m^{-3} throughout the whole stud-
52 ied period. A Wavelet Power Spectrum analysis showed that the temporal variability
53 of chl-*a* concentration in Trafalgar did not show any clear pattern of variability. How-
54 ever, when the covariation between the zonal component of the current speed (*uvel*)
55 and the chl-*a* concentration was analysed with a Wavelet Coherence analysis, it was
56 observed a strong covariation at the fortnightly tidal cycle. In comparison, the ad-
57 jacent platform of the Gulf of Cádiz showed an average chl-*a* concentration of 0.79
58 mg m^{-3} with a seasonal variability (Sala et al., 2018). Furthermore, Bolado-Penagos
59 et al. (2020) analysing the trajectory of several passive drifters released close to Cape
60 Trafalgar, together with performing a series of hydrodynamic simulations, identified
61 the formation of a cyclonic eddy on the eastern flank of Trafalgar. This cyclonic
62 eddy increases the residence time of the upwelled nutrient-rich waters in the region,
63 favouring the high chl-*a* concentration that characterises this biomass hotspot. Nev-
64 ertheless, although the study by Sala et al. (2018) identified a strong covariation of
65 chl-*a* concentration with the fortnightly tidal cycle, the study was unable to analyse
66 in detail the influence of the tidal cycle on chl-*a* dynamics, due to an inadequate sam-
67 pling resolution. Furthermore, satellite ocean colour imagery only shows the most
68 superficial layer, making it impossible to analyse properly the influence of the tidal
69 cycle on the phytoplankton community for the whole water column.

70 The correct description of physical processes and their coupling with phytoplank-
71 ton growth is a complex issue in regions highly influenced by tidal forcing. On the
72 one hand, as tidal currents become more intense, they will lead to a more active
73 pumping of deep saltier water to shallow areas, with a nutrient enrichment of well-
74 illuminated (i.e., euphotic) layers, and subsequent growth of primary producers with
75 a given temporal delay of the order of days. On the other hand, the intensification of
76 the tidal current leads to a more active horizontal mixing and dispersal, thus decreas-
77 ing nutrient concentration or phytoplankton accumulation. These are two opposing
78 mechanisms affecting the phytoplankton community that are driven by the same sin-
79 gle process: tidal forcing. Thus, using a modelling approach is probably the best
80 way to understand the dynamics of Cape Trafalgar, which is of great importance as a
81 source of phytoplankton biomass in the surrounding waters. This study aims at per-
82 forming accurate simulations of the study area to evaluate how the upwelling process
83 mediated by the tide-topography interaction can affect the phytoplankton biomass
84 in the area of Cape Trafalgar. Furthermore, our approach will allow us to study how

85 the seasonal variability that governs the adjacent Gulf of Cádiz may influence our
 86 region of interest. For these two purposes, we have implemented a high-resolution
 87 circulation model that computes the main tidal constituents, coupled to an ecosystem
 88 model.

89 2. Methodology

90 2.1. Circulation model

91 The physical model used in this study is the Massachusetts Institute of Technology
 92 general circulation model (MITgcm; Marshall et al., 1997a,b). The MITgcm solves
 93 the Boussinesq form of the Navier-Stokes equations for an incompressible fluid on a
 94 staggered C-grid, with level vertical coordinates, and partial cell representation of
 95 the bottom topography. A KPP (K-Profile Parametrization) scheme parametrizes
 96 the sub-grid-scale vertical diffusion by turbulence (Large et al., 1994). Temperature,
 97 salinity, and biochemical tracers are advected with a third-order direct-space-time
 98 scheme with a flux limiter to prevent negative values in the solutions (Hundsdoerfer and
 99 Trompert, 1994). This numerical scheme is stable and sufficiently diffusive without
 100 explicit horizontal diffusion. The model configuration is similar to the one applied
 101 by Sánchez-Garrido et al. (2015), which uses a curvilinear grid that is squeezed into
 102 the Strait of Gibraltar and the Alborán Sea enhancing the resolution of both areas
 103 (Figure 1a). With a horizontal high resolution of ~ 0.50 km within the Strait, small-
 104 scale topographic features and processes are well captured, such as internal hydraulic
 105 jumps with the associated mixing and propagating internal waves. In the vertical
 106 dimension, there are 46 depth levels with increasing cell size from the surface to the
 107 bottom.

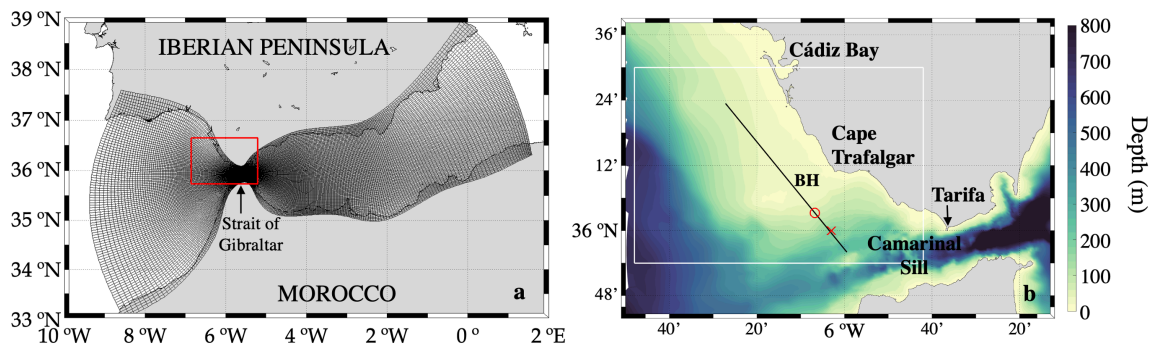


Figure 1: (a) Model domain and computational grid. The red rectangle encloses (b) a zoom of the region of interest. The spatial and temporal evolution of different variables (i.e., salinity, nitrate concentration and total phytoplankton biomass) are analysed at the Trafalgar region (enclosed by the white box), along the black line parallel to the coast, and at the point represented by the red circle. The red cross indicates the mooring position. BH: Barbate High. More details are in section 3.3.

108 Initial and boundary conditions were derived from the Iberia-Biscay-Ireland (IBI)
 109 Regional Seas reanalysis product from Copernicus Marine Environment Monitoring
 110 Service (CMEMS, <http://marine.copernicus.eu/>; Sotillo et al., 2015). Daily tempera-
 111 ture, salinity and horizontal velocity fields were computed for the model lateral
 112 forcing. At the sea surface, the model is driven by wind stress, heat fluxes, freshwa-
 113 ter flux from precipitation, and downward short-wave and long-wave radiation. All

114 these forcings were obtained from ERA-Interim and provided by the European Centre
115 for Medium-range Weather Forecasts (ECMWF, <https://www.ecmwf.int/>; Dee et al.,
116 2011). The atmospheric data has a time resolution of 6 hours and a spatial resolution
117 of 0.125 degrees. The forcing fields for open boundary and atmospheric conditions
118 correspond to the year 2010. We decided not to use a climatological year (i.e., the av-
119 erage of several selected years) because averaging smooths out daily fields and would
120 result in an underestimation of submesoscale processes (Oguz et al., 2017). Latent
121 and sensible heat fluxes are interactively calculated by the model using standard
122 bulk formulas. Finally, tidal forcing is incorporated by prescribing time-dependent
123 barotropic velocities across the open boundaries in association with the main eight
124 tidal constituents in the region: the diurnal constituents, K1, O1, P1 and Q1, with
125 periods of 23.93 h, 25.82 h, 24.07 h, and 26.87 h, respectively; and the semi-diurnal
126 constituents M2, S2, N2, and K2, with periods of 12.42 h, 12.00 h, 12.66 h, and 11.97
127 h, respectively (García-Lafuente et al., 1990). This forcing yields a spring-neap tide
128 cycle every 29.50 days, with the tidal range fluctuating from spring tide (maximum)
129 to neap tide (minimum) and back to the spring tide. Moreover, the tidal range and
130 the timing change daily, shifting by about 50 min per day (Ippen, 1966). Zero-flux
131 and non-slip conditions are applied to all solid boundaries (i.e., bathymetry) together
132 with a nonlinear bottom drag at the seafloor. The integration time step is 15 sec-
133 onds. To obtain a stable (repeated seasonal cycle) solution of the circulation model,
134 the simulation was run for 3 years. Two years of spin-up were required to stabilise
135 the numerical model and therefore they were excluded from the analysis.

136 The model solution was evaluated against different data sources. Modelled Sea
137 Surface Temperature (SST) was compared to satellite-retrieved SST observations (re-
138 processed Pathfinder V5.3; CMEMS). The model tends to overestimate slightly the
139 annual mean but otherwise, it captures well the spatial-temporal distribution, show-
140 ing colder waters in coastal regions (due to upwelling) and warmer waters in open
141 ocean regions for both the Gulf of Cádiz and the Alborán Sea (see Figure A.1). We
142 also compared temperature-salinity (TS) diagrams using modelled outputs versus *in*
143 *situ* observations from the Medatlas II dataset (<http://www.ifremer.fr/medar/>). The
144 main water masses are well reproduced by our regional model as inferred from the TS
145 diagrams (Figure A.2). Further details can be found in the supplementary material.

146 Finally, thermistors and Acoustic Doppler Current Profiler (ADCP) data col-
147 lected in the proximity of Cape Trafalgar from September 3rd to October 10th, 2015
148 (MEGAN Project; Bolado-Penagos et al., 2020), were compared with model outputs
149 to evaluate the tidal variability (Figure 2). The mooring was bottom-mounted at
150 6.05 °W – 36.00 °N (red cross in Figure 1b) at a bottom depth of 200 m. At this
151 emplacement was deployed a thermistor chain of 43 thermistors disposed 3-m apart
152 from each other, from 10 to 136 m depth and programmed with a sample interval of 1
153 minute. Additionally, it was also deployed a 75-kHz Teledyne RD Instrument (RDI)
154 ADCP, with a sampling interval of 3 minutes and a 4-m bin size covering between
155 40 and 140 m of the water column. Because the model outputs represent a climato-
156 logical year, to compare the observed and modelled data it was identified the closest
157 tidal moment to the observations. Model data showed a temperature overestimation
158 of 1.21 ± 0.64 °C (Figure 2a). Meanwhile, the current velocity data, *uvel* and *vvel*,
159 range between very similar ranges. However, modelled *uvel* seems to slightly overes-
160 timate the observations (Figure 2b), while *vvel* seems to slightly underestimate them

161 (Figure 2c). Both tidal components, semi-diurnal and fortnightly, are well captured
 162 by the model allowing us to pursue the aim of this study.

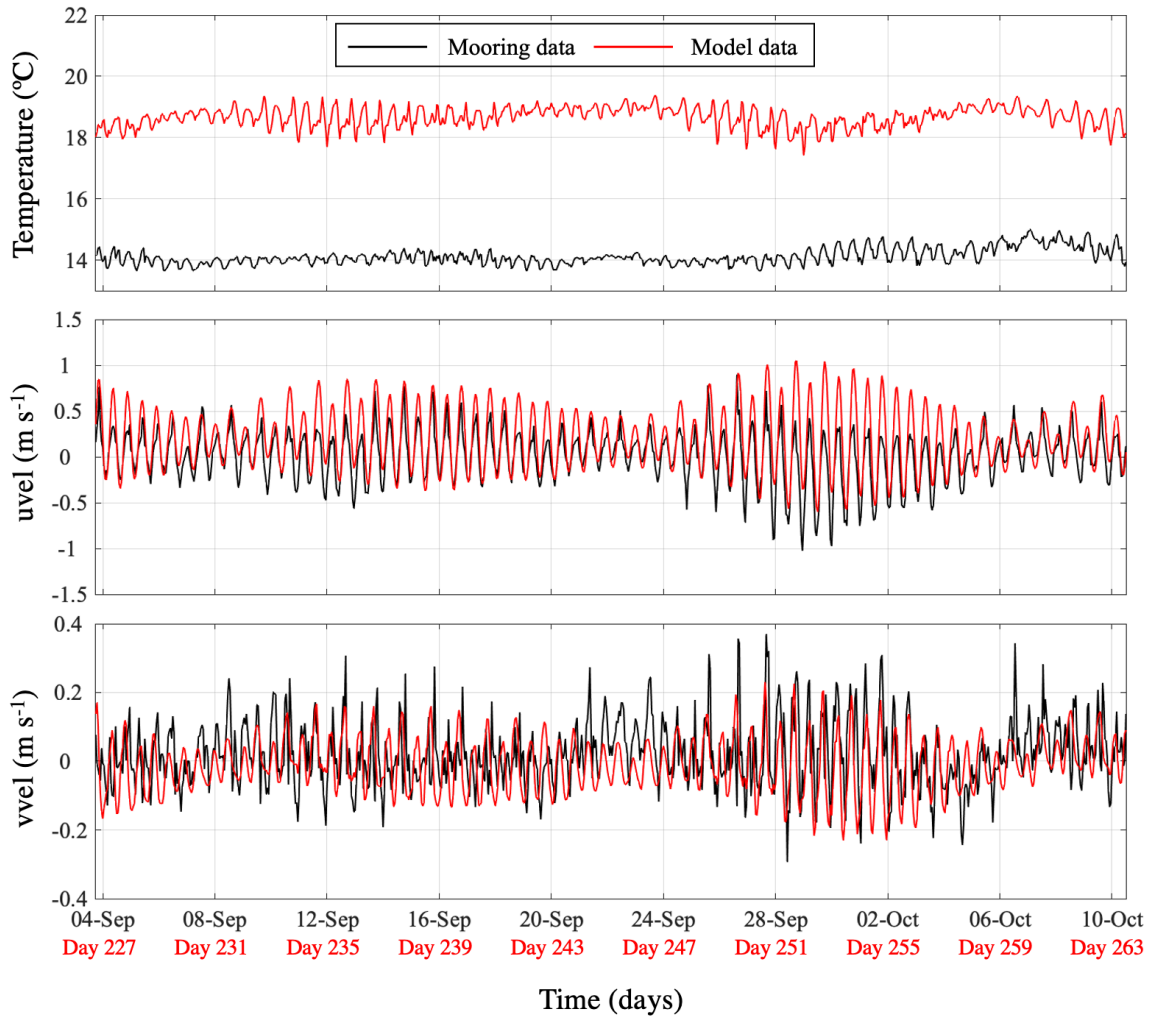


Figure 2: Temporal evolution of (a) mean temperature ($^{\circ}\text{C}$), (b) mean zonal component of the current speed (u_{vel} ; m s^{-1}), and (c) mean meridional component of the current speed (v_{vel} ; m s^{-1}) for observed (black lines) and modelled (red lines) data. All time series were computed for the whole water column at $6.05^{\circ}\text{W} - 36.0^{\circ}\text{N}$ (red cross in Figure 1b). The x-axis labels show in black the sampled days of the mooring and the corresponding days of the model in red.

163 2.2. Ecosystem model

164 We used a simplified configuration of the Darwin model (version 1) that simu-
 165 lates the planktonic ecosystem (Follows et al., 2007; Dutkiewicz et al., 2009; Vallina
 166 et al., 2014a,b), being natively coupled to the MITgcm physical ocean model de-
 167 scribed above. Four phytoplankton functional groups are defined based on nutrient
 168 requirements and uptake strategies, with a transition from gleaners to opportunists:
 169 *Prochlorococcus*, *Synechococcus*, flagellates and diatoms (see Figure 2a in Vallina
 170 et al., 2017). All groups are limited by phosphate (PO_4), nitrate (NO_3), ammonium
 171 (NH_4) and iron, while diatoms are also limited by silicate (SiO_4). The model de-
 172 fines one generic zooplankton herbivore that feeds upon all phytoplankton species
 173 (killing-the-winner behaviour), and one generic zooplankton carnivore feeding on the

174 zooplankton herbivore acting as a closure trophic level for the food web. For a detailed
175 description of the ecological model, the reader is referred to Vallina et al. (2014a,b).
176 The model parameters are given in Table B.1.

177 Initial conditions for all the ecological tracers were based on a global model out-
178 put from Vallina et al. (2014a). Phytoplankton initial conditions are the same for the
179 four functional groups, applying the same biomass distribution. The same approach
180 is used for zooplankton initial conditions. Boundary conditions were only prescribed
181 for nutrients (PO_4 , NO_3 , NH_4 , SiO_4) and phytoplankton biomass. Daily fields for the
182 prescribed boundary conditions were derived from the IBI Biogeochemical Analysis
183 and Forecast product from CMEMS (IBI-BIO). Phytoplankton boundary conditions
184 were computed from the total biomass of the IBI-BIO model, using the same bound-
185 ary condition for the four phytoplankton groups. These oceanic boundary conditions
186 are only open for the prescribed tracers, so that those state variables with prescribed
187 values at the boundary can leave the model domain through them. For those trac-
188 ers for which there are not enough data at the boundary conditions, homogeneous
189 Neumann boundary conditions (zero-flux) are applied (Sánchez-Garrido et al., 2015).
190 Finally, at the sea surface, the model is forced with daily photosynthetically active
191 radiation (obtained from ERA-Interim) and daily iron dust deposition (computed
192 from modelled monthly data from Mahowald et al., 2003).

193 Due to the high computational cost of the hydrodynamic model (integration time-
194 step of 15 seconds), the coupled biophysical model MITgcm + Darwin was run in
195 offline mode (integration time-step of 240 seconds) using as physical forcing (inputs)
196 the previously saved simulation (outputs) with the MITgcm hydrodynamic model on
197 an hourly temporal resolution of temperature, salinity, vertical mixing, and velocity
198 fields. Such a high temporal resolution (hourly) for the environmental variables was
199 necessary to capture the tidally driven processes. The coupled biophysical model was
200 run for 5 years, with 4 years of spin-up required to reach (quasi) steady-state seasonal
201 cycles that were excluded from the analysis. Despite the relative complexity of our
202 plankton model configuration and considering the aims of the study, we will only
203 focus our analyses on the total phytoplankton biomass.

204 The seasonal variability of the ecosystem model was evaluated with satellite chl-*a*
205 (mg m^{-3}) data, a proxy for the surface phytoplankton biomass. Ocean colour im-
206 ages for the study area were downloaded from the CMEMS (from 1998 to 2016). To
207 enable this comparison, the model total phytoplankton biomass (mmol P m^{-3}) was
208 first converted to carbon by applying the canonical Redfield ratio C:P = 106:1 (mol
209 mol^{-1}), and then converted to chl-*a* concentration by applying a variable C:Chl ratio
210 calculated as a function of light levels following Lefèvre et al. (2002) (see supplemen-
211 tary material for more details). Figure 3 shows the comparison between the seasonal
212 climatology derived from remote sensing images and the model-derived seasonal av-
213 erage of the simulated year for surface chl-*a*. The modelled chl-*a* distribution reflects
214 well the observed oligotrophic nature of the Western Alborán Gyre. Furthermore,
215 the model also captures the meridional gradient of chl-*a* with higher values along the
216 northern coast of the study area, as well as the decrease west-to-east of chl-*a* con-
217 centration in the Alborán Sea, being the north-western region the richest area (e.g.,
218 Sarhan et al., 2000; Macías et al., 2008). The under-estimation of chl-*a* concentra-
219 tion by our simulations over the northern coastal area of the Gulf of Cádiz may be
220 attributed to the fact that the model does not prescribe nutrient inputs from river

221 discharges (e.g., Guadalquivir River; Huertas et al., 2005; Navarro et al., 2006).

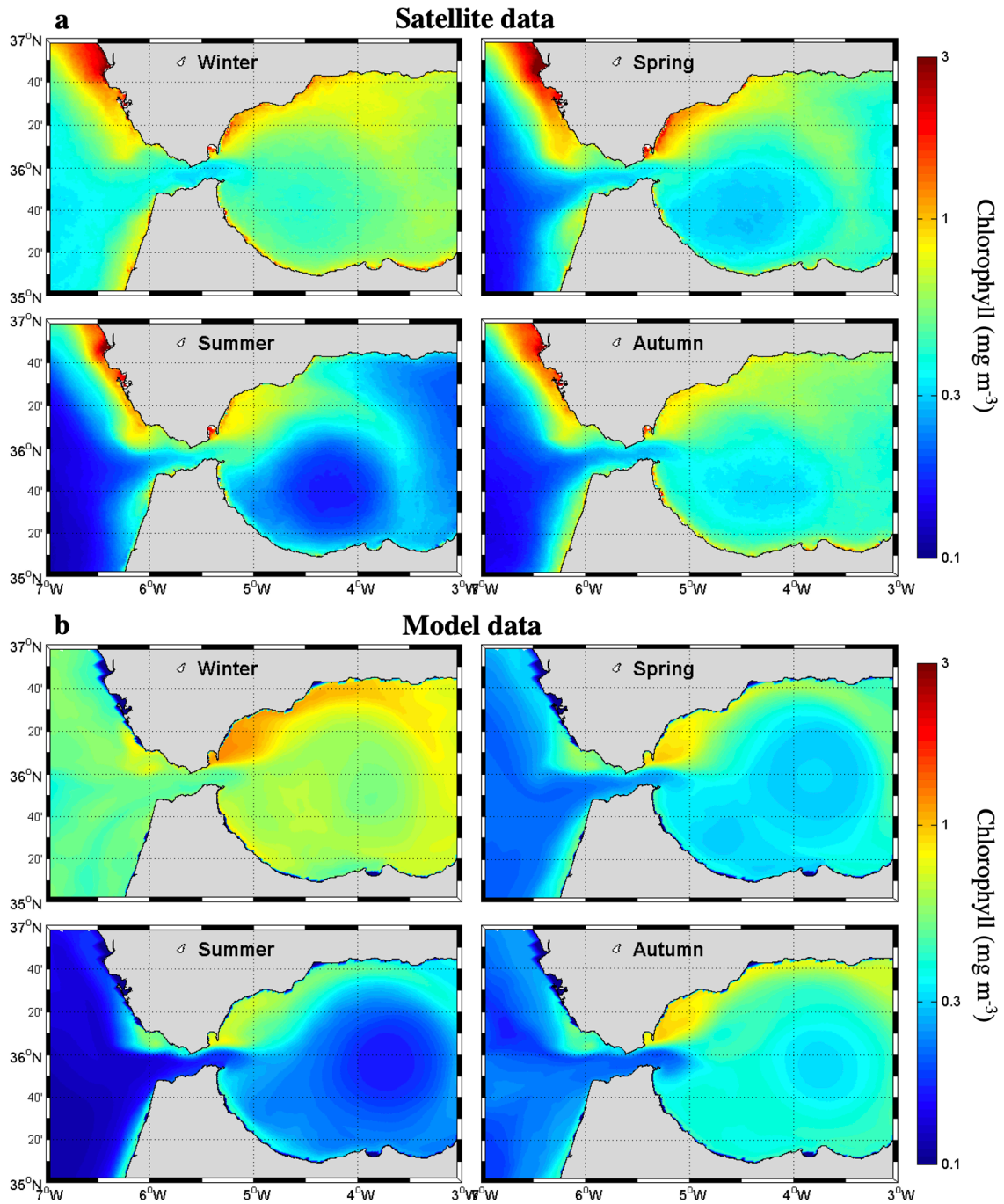


Figure 3: (a) Seasonal climatology of surface chlorophyll (mg m^{-3}) derived from remote sensing images corresponding to the period 1998 - 2016. (b) Model-derived seasonal climatology of surface chlorophyll (mg m^{-3}) for the 5th year of simulation.

222 2.3. Wavelet analysis

223 Wavelet analysis is a powerful tool that allows a local time-scale decomposition
224 of the signal in both time and frequency domains simultaneously (Lau and Weng,
225 1995; Torrence and Compo, 1998; Klvana et al., 2004; Cazelles et al., 2008). This
226 tool is especially relevant for the analysis of non-stationary systems (see Cazelles

227 et al. (2008) for a review). Here, wavelet analysis is used to disentangle the temporal
228 patterns of several state variables of the MITgcm + Darwin model, both in time and
229 frequency domains. In particular, we use it to identify the dominant periodicities of
230 salinity, temperature, NO_3 and phytoplankton biomass. We used the MatLab toolbox
231 developed by Cazelles and Chavez (Cazelles et al., 2008), applying the Morlet wavelet
232 that provides a good balance between time and frequency localisation (Grinsted et al.,
233 2004). In a time-frequency plane, the wavelet power spectrum represents the relative
234 importance of frequencies at each time step. Values closer to the edge of the time
235 series, delimited by the cone of influence, were rejected to avoid false periodic events
236 (Torrence and Compo, 1998). For each period, the average wavelet power spectrum
237 was calculated, identifying the averaged variance contained in all wavelet coefficients
238 of the same frequency. Furthermore, a 5% significance level was determined for WPS
239 through a bootstrapping scheme using a hidden Markov model, to assess whether
240 the wavelet-based quantities were due to just random processes (Cazelles and Stone,
241 2003).

242 Of particular interest is the fact that wavelet analysis allows the estimation of
243 the coupling between driver and response variables, as well as the level of synchrony
244 between them (Keitt and Fischer, 2006; Ménard et al., 2007; Buttay et al., 2017).
245 The wavelet coherence analysis (WCo) was applied to analyse the synchrony between
246 the zonal component of the current velocity (uvel; driver variable) and several model
247 state variables: salinity, NO_3 concentration and phytoplankton biomass (response
248 variables). Once identified the time scale at which the two non-stationary time series
249 were locally linearly correlated, their phases, for this time scale, were extracted and
250 compared (Cazelles et al., 2008). The phase difference between signals indicates
251 whether or not they are in synchrony; and if they are not, the time lag between them.

252 3. Results

253 3.1. Spatial and temporal variability

254 For the simulated year, we evaluated the dynamics of salinity, temperature, NO_3
255 concentration, and total phytoplankton biomass along a (i) vertical two-dimensional
256 section perpendicular to the submarine ridge (Barbate High) and parallel to the coast
257 (black line in Figure 1b), and (ii) at the surface waters of the Trafalgar region (see
258 the white box in Figure 1b). Due to the curvilinear grid of the model, we had to
259 perform a data interpolation to properly show the vertical section. Thus, the values
260 shown in the surface map (left-hand panels in Figures 5, 6, 7) do not always match
261 exactly those shown along the vertical section (right-hand panels in Figures 5, 6, 7),
262 but the general trend can be well appreciated.

263 The dynamics of the spatial distribution observed for the several tracers in the
264 Trafalgar region show a temporal variability closely related to the tidal cycle. There-
265 fore, in this particular subsection, we place the focus on the fortnightly tidal cycle
266 that runs approximately from day 20 at 02:00 hours to day 34 at 20:00 hours. We can
267 observe that the strongest tide-topography interaction in Barbate High takes place
268 when the tidal current flows westward. This interaction is closely related to the in-
269 tensity of the tidal current, being stronger at higher uvel values. Therefore, for the
270 sake of simplicity, only the time of maximum tidal current towards the Gulf of Cádiz
271 during neap and spring tides will be described (i.e., NT1 and ST1; Figure 4). The

272 time of maximum tidal current towards the Alborán Sea during neap and spring tides
 273 (NT2 and ST2, respectively) are shown in Figures D.1 to D.3. We will use salinity
 274 as a good upwelling indicator for this region.

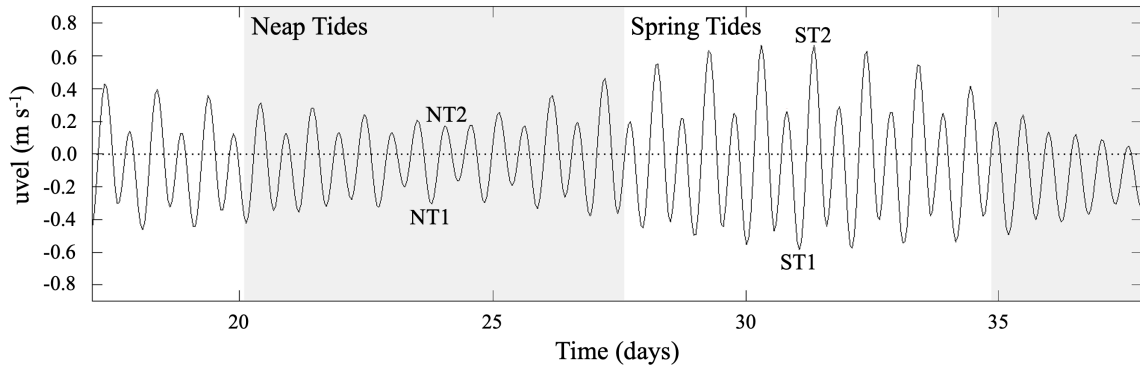


Figure 4: Temporal evolution of the mean zonal component of the current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N (red circle in Figure 1b), between days 17 and 38 of the simulated year. The black dashed line represents the zero reference, which delimits positive (negative) values that indicate flow driven eastward (westward), towards the Alborán Sea (Gulf of Cádiz). Points NT1 and NT2 indicate the examined neap tidal moments. Points ST1 and ST2 indicate the examined spring tidal moments. Grey background identifies neap tidal periods.

275 Figure 5 shows the vertical (left-hand panels) and the surface (right-hand panels)
 276 distribution of salinity in the Cape Trafalgar region. Both during neap and spring
 277 tides, along the vertical section parallel to the coast, we can observe a non-symmetric
 278 distribution of salinity determined by the presence of the submarine ridge (i.e., Bar-
 279 bate High), which has a steeper slope on its east side ($\sim 44\%$) than on its west side
 280 ($\sim 15\%$). However, during the neap tide period, this west-to-east asymmetry is less
 281 pronounced (Figure 5a). On the east side of the ridge, between 6.13 and 6.06°W ,
 282 we observe the highest salinity values (left-hand panels in Figure 5). This band of
 283 high salinity waters shows higher values at deeper layers than at the surface. During
 284 the spring tide, when the u_{vel} towards the Gulf of Cádiz is maximum (-0.58 m s^{-1}),
 285 the upwelling of saltier waters is most intense and reaches the most superficial layers
 286 of the water column ($\sim 36.50 - 36.80$; Figure 5c). Meanwhile, during the neap tide
 287 (-0.31 m s^{-1}), the upwelled water is less saline (coming from a shallower depth) and
 288 does not reach the most superficial layers ($\sim 36.40 - 36.50$; Figure 5a). The surface
 289 distribution of salinity displays a tongue characterised by moderately high values rela-
 290 tive to the surrounding waters, over and to the east of Barbate High (right-hand
 291 panels in Figure 5). The origin of this tongue is the region characterised by the band
 292 of high salinity waters observed in the vertical section (around the black circle) and
 293 its distribution is affected by the cyclonic eddy that develops due to the interaction
 294 of the westward tidal current with the eastern edge of Barbate High (see the black
 295 arrows in the right-hand panels in Figure 5). This eddy is more energetic (stronger
 296 horizontal mixing) during spring tides, leading to a less salty tongue (~ 36.45 ; Figure
 297 5d) than during neap tides when it leads to a saltier tongue (weak horizontal mixing)
 298 (~ 36.40 ; Figure 5b).

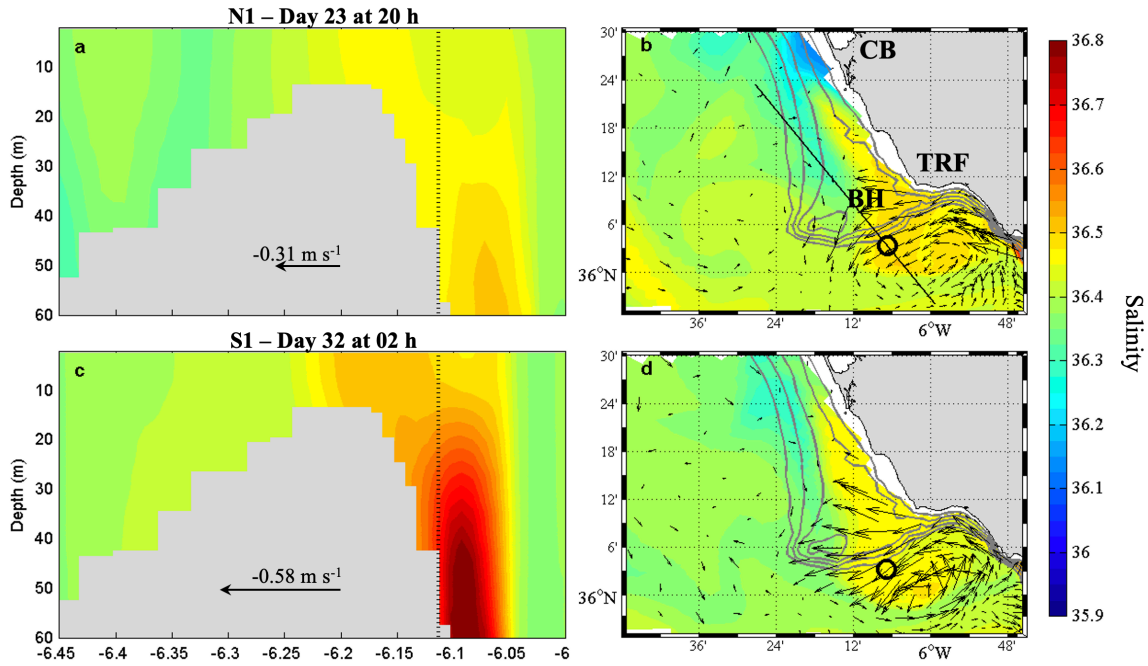


Figure 5: Salinity distribution in the Cape Trafalgar region during the maximum westward flow of the neap tide period (NT1: a, b) and the spring tide period (ST1: c, d) (see Figure 3). Left-hand panels show the vertical distribution along a section perpendicular to the submarine ridge (black line in panel b). Vertical dashed lines correspond to the position of open circles in the right-hand panels. Black arrows (a, c) represent the magnitude and direction of the mean zonal component of current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N at each time-step. Right-hand panels show the surface distribution. Black surface vectors represent the surface current (m s^{-1}). Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

299 During both neap and spring tides, NO_3 concentration along the vertical section
300 parallel to the coast also displays a non-symmetric distribution (see left-hand panels
301 in Figure 6). Maximum values, between ~ 1.50 and 3.00 mmol m^{-3} , are found at the
302 eastern side of the submarine ridge, mainly between 6.13 and 6.06°W , concurrent
303 with the band of high salinity values (see left-hand panels in Figure 5). Like salinity,
304 this band of NO_3 -rich water presents the highest concentration values in the deeper
305 layers and during spring tides, when the intensity of the westward tidal current is
306 stronger. However, in contrast to salinity distribution, there is not an east-to-west
307 gradual decrease of NO_3 concentration since the lowest values are registered over the
308 shallowest area of Barbate High ($< 1.00 \text{ mmol m}^{-3}$). The superficial distribution of
309 NO_3 , at both tidal moments, shows a spot of relatively high NO_3 concentration ($>$
310 1.50 mmol m^{-3}) around the location of the band of NO_3 -rich water observed in the
311 vertical section (i.e., black circle on the right-hand panels in Figure 6). As with salin-
312 ity, NO_3 surface distribution is affected by the cyclonic eddy. Thus, during neap tides,
313 when the current speed in the cyclonic gyre is low resulting in a weaker horizontal dis-
314 persion, NO_3 concentration around the upwelling point is higher. Meanwhile, during
315 spring tides, when the current speed in the gyre is higher, increasing the horizontal
316 dispersion, NO_3 concentration around this point is lower. However, the presence of
317 a NO_3 -rich tongue is not as clearly defined as the salinity tongue over Barbate High.
318 Moreover, along the coast from the Cádiz Bay to Barbate High, following the bathy-

319 metric lines, we observe a fringe with minimum NO_3 concentration values (< 1.00
 320 mmol m^{-3} ; Figure 6b, d).

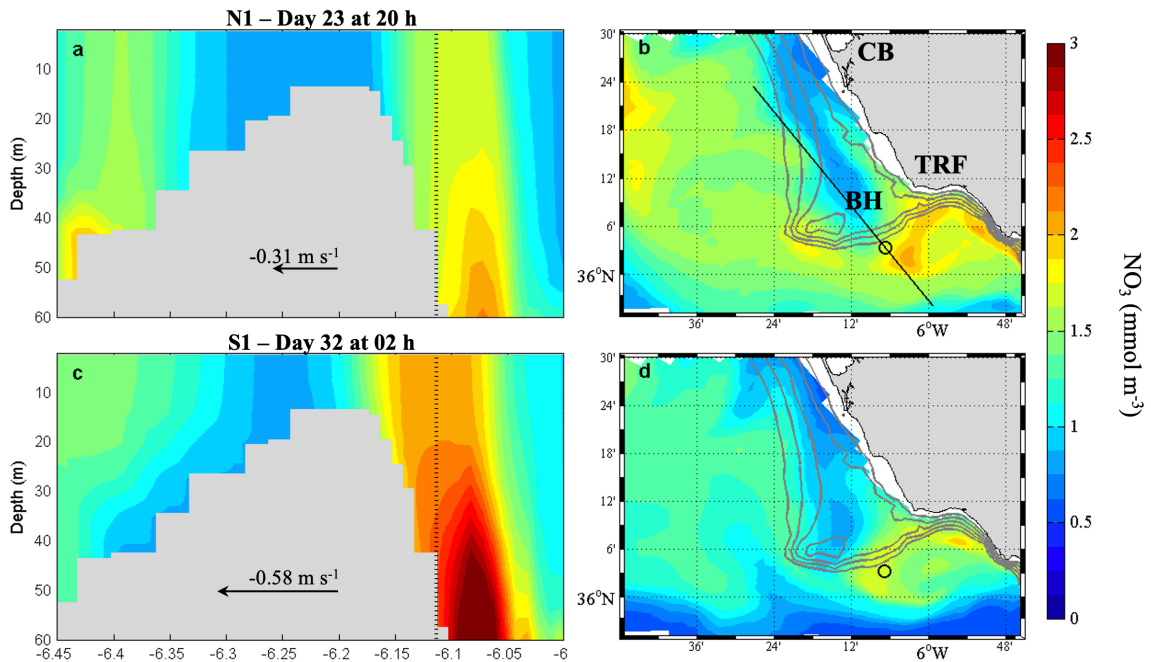


Figure 6: Nitrate concentration (NO_3 , mmol m^{-3}) distribution in the Cape Trafalgar region during the maximum westward flow of the neap tide period (NT1: a, b) and the spring tide period (ST1: c, d) (see Figure 3). Left-hand panels show the vertical distribution along a section perpendicular to the submarine ridge (black line in panel b). Vertical dashed lines correspond to the position of open circles in right-hand panels. Black arrows (a, c) represent the magnitude and direction of the mean zonal component of current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N at each time-step. Right-hand panels show the surface distribution. Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

321 Total phytoplankton biomass distribution along the vertical section (see left-hand
 322 panels in Figure 7), shows a pattern quite different from the other state variables.
 323 During both neap and spring tides, maximum phytoplankton biomass values appear
 324 over the shallowest area of the ridge ($> 0.70 \text{ mmol N m}^{-3}$). During neap tides, high
 325 biomass values are also observed in the most superficial layers of the water column to
 326 the east side of the ridge (Figure 7a). The vertical distribution of total phytoplankton
 327 biomass along the band between 6.13 and 6.06°W , shows an opposite distribution to
 328 salinity and NO_3 concentration, showing low phytoplankton biomass in the recently
 329 uplifted waters (Figures 6 a, c and 6 a, c). Thus, low phytoplankton biomass is
 330 observed at the deeper layers where NO_3 concentration is maximum, progressively
 331 increasing to superficial layers at the same time that NO_3 concentration decreases (see
 332 left-hand panels in Figures 6 and 7). The surface distribution of total phytoplankton,
 333 at both tidal stages, shows a tongue over Barbate High characterised by high biomass
 334 ($> 0.80 \text{ mmol N m}^{-3}$; see right-hand panels in Figure 7) displaced to the east side
 335 of the ridge due to the influence of the cyclonic eddy (Figure 7 b, d). This tongue
 336 is richer in phytoplankton biomass during spring tides (Figure 7d) when the input of
 337 NO_3 -rich water is maximum (Figure 6 c). Moreover, phytoplankton biomass through

338 this tongue seems slightly higher close to the coastline extending from Cádiz Bay
 339 to Cape Trafalgar. Also, in the rest of the domain (mainly over the continental
 340 slope), phytoplankton biomass is higher during spring tides than during neap tides.
 341 This pattern is the opposite of the one observed for the NO_3 distribution, whose
 342 concentration over the continental shelf is slightly higher during neap tides than
 343 during spring tides (Figure 6 b, d).

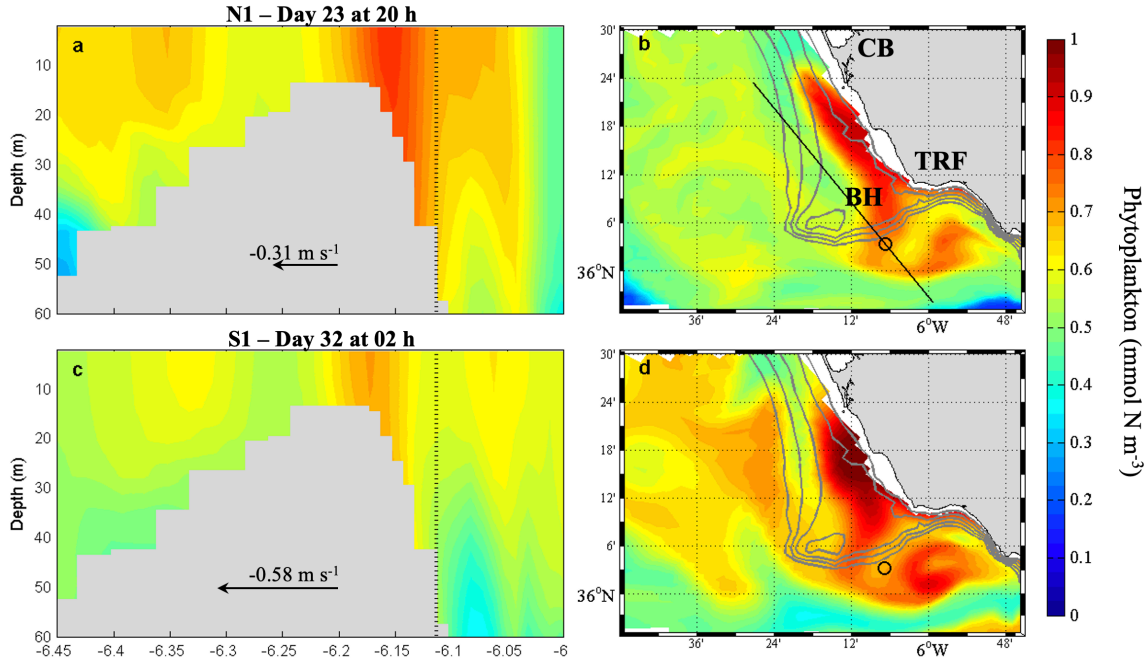


Figure 7: Total phytoplankton biomass (mmol N m^{-3}) distribution at Cape Trafalgar region during the maximum westward flow of the neap tide period (NT1: a, b) and the spring tide period (ST1: c, d) (see Figure 3). Left-hand panels show the vertical distribution along a section perpendicular to the submarine ridge (black line in panel b). Vertical dashed lines correspond to the position of open circles in right-hand panels. Black arrows (a, c) represent the magnitude and direction of the mean zonal component of current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N at each time-step. Right-hand panels show the surface distribution. Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

344 The sequential analysis of the vertical and superficial distribution of these three
 345 variables shows how the band of saltier, NO_3 -rich and with low phytoplankton biomass
 346 water, as well as the cyclonic gyre and the tongue over Barbate High (and the sur-
 347 rounding waters), oscillate continuously from east-to-west due to the cyclical change
 348 of direction of the zonal component of the tidal current. Thus, the ‘water masses’ in
 349 the Trafalgar region are displaced to the east when u_{vel} flows towards the Alborán
 350 Sea (positive values), and to the west when u_{vel} flows towards the Gulf of Cádiz
 351 (negative values). Furthermore, these east-to-west-to-east oscillations are more or
 352 less noticeable depending on the intensity of u_{vel} . To better observe this oscillating
 353 movement that is a consequence of the tidal cycle, and all its associated processes,
 354 the reader is referred to the supplementary video that shows the computer simulation
 355 of these variables for the first 3 months of the simulation (<http://t.ly/bVQQ>).

356 *3.2. Hovmöller diagram*

357 In the previous subsection, we described how an entry of saltier, nutrient-rich and
358 low phytoplankton biomass water is observed between ~ 6.13 and 6.06 °W, with a
359 time-dependent variability closely related to the tidal cycle. To examine this process
360 in more detail, in Figure 8 we show the Hovmöller diagrams (depth-variability as
361 a function of time) of several state variables and R_i together with the temporal
362 dynamics of uvel to outline the tidal cycle. We do so for a particular location at 6.11
363 °W - 36.06 °N (see the red circle in Figure 1b) and for the whole simulated year.

364 The time-dependent distribution of salinity shows a fortnightly periodicity. Higher
365 values of salinity are observed during spring tides (Figure 8b). During the most
366 intense spring tide periods (every ~ 30 -days) the water is slightly saltier than during
367 the less intense periods, although in both cases the upwelled water always reaches the
368 most superficial layers of the water column. Whereas during the neap tide periods
369 (i.e., weak turbulent mixing) the lowest values of salinity are observed. It should
370 be noted that for the entire period, the salinity of the water column continuously
371 oscillates between relatively high and relatively low values, in good agreement with
372 the tidal current oscillations both in direction and intensity. From July to November,
373 the upwelling events seem to be less intense than during the rest of the year, with
374 shallower (intermediate) and less salty upwelled water than that observed in other
375 spring tide periods, probably North Atlantic Central Water (NACW), reaching the
376 most superficial layers. Furthermore, from October to December we observe the
377 lowest salinity values for the whole year of simulation.

378 The temperature at the selected location point also shows a pattern of variability
379 associated with the fortnightly tidal cycle, although it is less appreciable than for
380 salinity (Figure 8c). During spring tide periods, we observe the lowest water-column
381 temperatures and highest salinity values (Figure 8b), the temperature is colder during
382 the most intense spring tides. Conversely, during neap tides, the observed temper-
383 ature is ~ 2 °C warmer. As with salinity, the water temperature oscillates between
384 relatively high and relatively low values depending on the tidal cycle. During the
385 winter months (January to April), as expected, the coldest temperatures of the year
386 are observed. While from July to November, in the first 30 m of the water column
387 are observed the highest temperatures (~ 22 - 24 °C) of the whole year.

388 The seasonal variability of stratification and tides modulate the intensity of di-
389 apycnal mixing over the water column, as suggested by the Richardson number,
390 $R_i = N^2/U_z^2$ reaches the greatest values from June to October associated to a strong
391 summer thermocline that warrants flow stability ($R_i \gg 1/4$). During the rest of the
392 year, the flow is also rather stable ($R_i > 1/4$), but with some small-scale potentially
393 unstable patches of the fluid where vertical mixing is enhanced ($R_i < 1/4$). At fort-
394 nightly tidal scale, R_i shows smaller values (enhanced mixing) during spring tides.
395 The fortnightly signal is especially noticeable during the summer months.

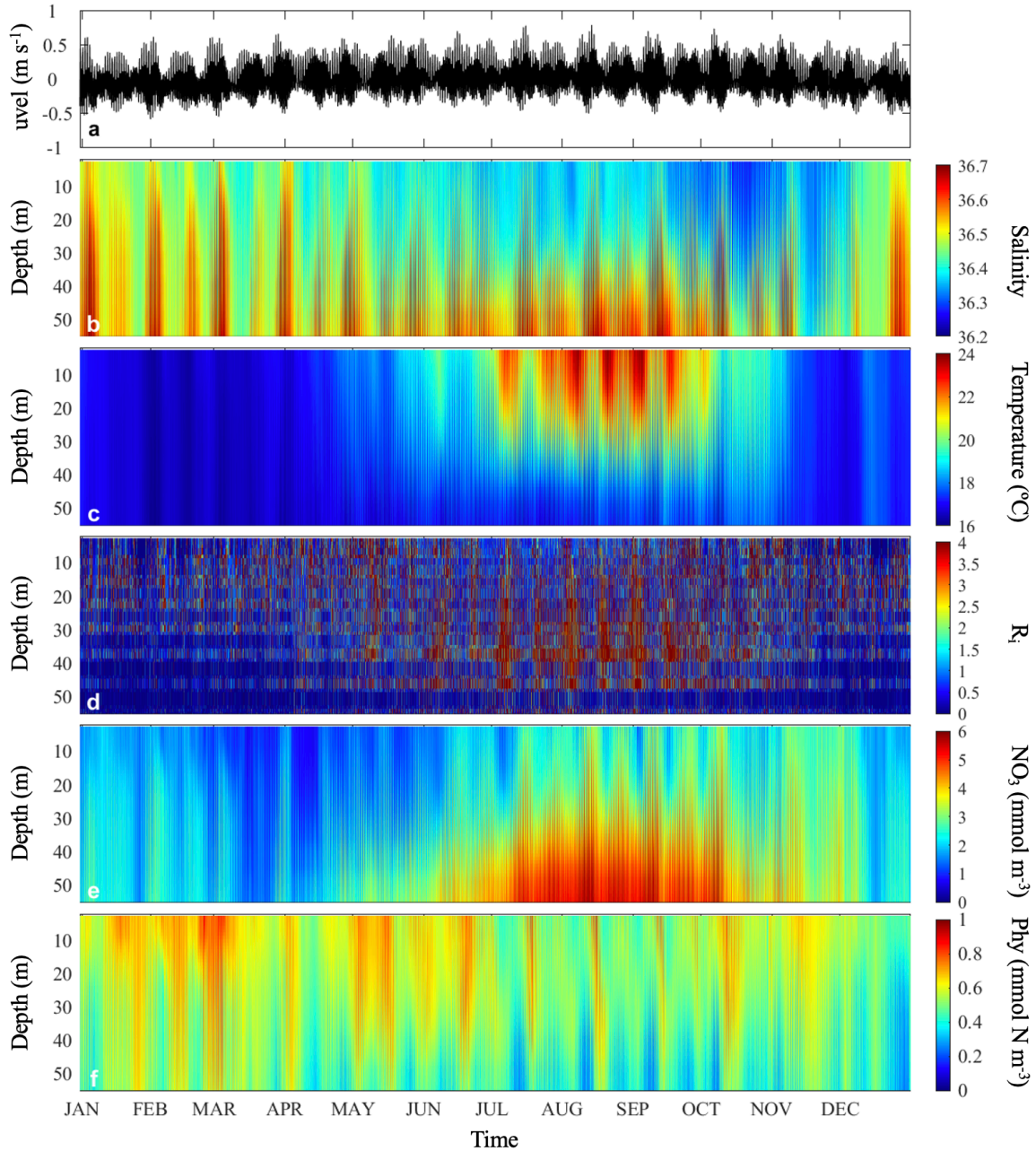


Figure 8: (a) Temporal evolution of the mean zonal component of current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N (red circle in Figure 1b), along the whole-year simulation. Hovmöller diagrams, computed at the same point (red circle in Figure 1b), illustrating spatial (i.e., depth) and temporal variability of (b) salinity, (c) temperature ($^\circ\text{C}$), (d) the Richardson number (R_i , adimensional), (e) nitrate concentration (NO_3 , mmol m^{-3}) and (f) total phytoplankton biomass (Phy, mmol N m^{-3}).

396 NO_3 concentration also displays a fortnightly periodicity (Figure 8e). Only during
 397 the most intense spring tides, NO_3 -rich water seems to reach the surface layers. During
 398 neap tides, NO_3 concentration throughout the water column is relatively low ($<$
 399 1.00 mmol m^{-3}). As with salinity and temperature, the NO_3 concentration of the
 400 whole water column continuously alternates between relatively high and relatively
 401 low values, in agreement with the tidal current oscillations (direction and intensity).

402 Throughout the whole year, the lower NO_3 concentration values are observed from
403 March to May (Figure 8e). While the maximum NO_3 concentrations are observed
404 from July to October, coinciding with the period of highest stratification of the water
405 column (Figure 8d). As a result, the nutrient-rich upwelled water is unable to reach
406 the most superficial layers of the water column. The upwelling of less salty and
407 nutrient-rich waters (compared with other upwelling events) supports the fact that
408 during fall there is an upwelling of NACW in this region.

409 Figure 8f shows the dynamics of total phytoplankton biomass, with higher values
410 at surface layers that tend to decrease with depth. Nevertheless, the phytoplankton
411 biomass is quite high at all depths because the vertical domain analysed here is rela-
412 tively shallow (50 m) and therefore well illuminated. As previously observed (Figures
413 5 and 6), phytoplankton biomass distribution behaves oppositely to NO_3 concen-
414 tration. Thus, during the neap tide periods, when NO_3 concentration throughout
415 the water column is relatively low, phytoplankton biomass shows high values with a
416 pretty homogeneous distribution. For phytoplankton biomass is slightly more diffi-
417 cult to appreciate a fortnightly periodicity than for salinity, temperature or even NO_3
418 concentration. Although, as with the other variables, a continuous fluctuation be-
419 tween high and low phytoplankton biomass is still observed. Phytoplankton biomass
420 is lowest from July to October when stratification is highest (Figure 8d), preventing
421 them to access to the nutrient-rich upwelled water (Figure 8e).

422 3.3. Wavelet power spectrum

423 We performed a wavelet power spectrum analysis of the time series shown in the
424 Hovmöller diagram to extract information about the temporal variability of salinity,
425 temperature, NO_3 concentration and total phytoplankton biomass. The WPS was
426 computed using the hourly average values for each variable using their averaged values
427 for the water column.

428 The WPS for the salinity signal (time series) displays two strong peaks at ~ 15 -
429 day and ~ 30 -day periodic components (Figure 9a). The time-averaged WPS shows
430 that these two periodicities in the signal are statistically significant, contributing on
431 average $\sim 21\%$ and $\sim 31\%$ of the total variance, respectively (Figure 9b). However,
432 the ~ 15 -day WPS peak is statistically significant only during winter months, and the
433 ~ 30 -day peak from January to mid-May and from October to December (Figure 9a).
434 During the whole year, a second pair of peaks are observed at the ~ 12 -hour and \sim
435 1-day periods (Figure 9a). For the ~ 12 -hour period, high values of WPS are observed
436 during the most intense spring tides (i.e., approximately every 30 days), and weaker
437 values during less intense spring tides. These discontinuous peaks of periodicities or
438 frequencies in the WPS, disregarding the one observed (approximately) between days
439 15 and 23, are statistically significant. The peak in the ~ 1 -day periodicity shown
440 by the WPS is almost coincident in time with the 12-hour period, although it is not
441 always statistically significant. However, when looking at the time-averaged WPS,
442 these two peaks (at ~ 12 -hour and ~ 1 -day) are small and therefore do not contribute
443 significantly to the variance of the signal (Figure 9b).

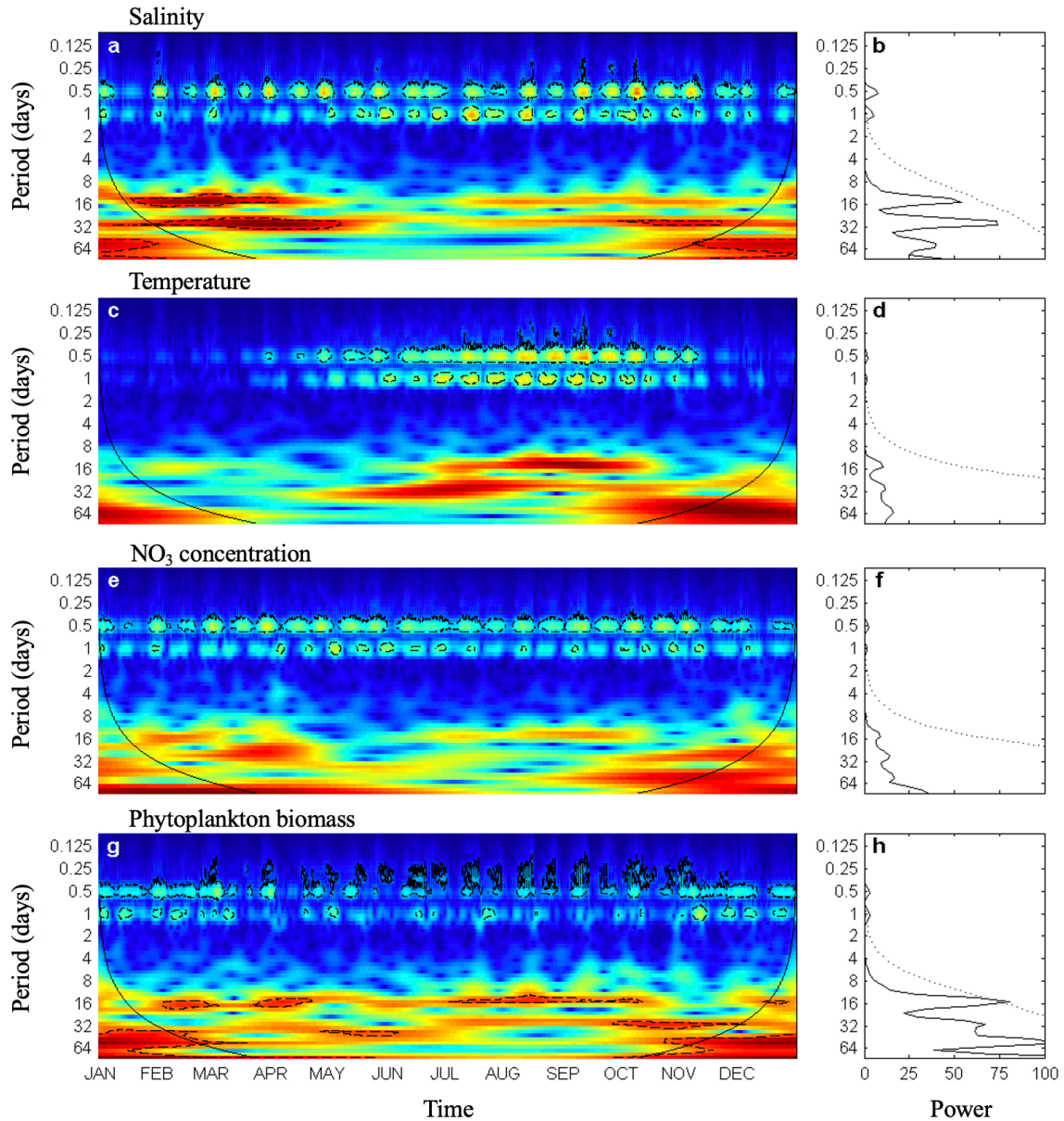


Figure 9: Wavelet analysis computed for the 1-year simulation. Left-hand panels: Wavelet power spectrum for (a) salinity, (c) temperature ($^{\circ}\text{C}$), (e) nitrate concentration (NO_3 , mmol m^{-3}) and (g) total phytoplankton biomass (mmol N m^{-3}). The colour code varies from dark blue (low values) to dark red (high values). Black lines indicate the cone of influence. Right-hand panels: Average wavelet power spectrum for (b) salinity, (d) temperature, (f) NO_3 concentration and (h) total phytoplankton biomass. Dotted lines, at all panels, show the $\alpha = 5\%$ significance level computed based on 1000 Markov bootstrapped series.

444 The WPS for temperature shows two relatively strong peaks at the ~ 15 -day and
 445 ~ 30 -day periodic components during the summer months, between June and October
 446 (Figure 9c). Both peaks, locally, are not statistically significant (i.e., time and peri-
 447 od coordinates), although the time-averaged value of the WPS does highlight these
 448 periodicities as being statistically significant (Figure 9d). In particular, the ~ 15 -day
 449 periodicity of the temperature signal, although smaller compared to the one obtained
 450 for salinity, explains $\sim 26\%$ of the total variance. From May to November, weaker but
 451 statistically significant peaks are observed for the 12-hour and 1-day periods (Figure

452 9c). Like salinity, the 12-hour periodicity peaks of temperature are slightly stronger
453 during the events of most intense spring tides and weaker during less intense spring
454 tides. The 1-day periodicity peak, which is weaker than the 12-hour peak, becomes
455 relevant only during events of the most intense spring tides. Both time-averaged WPS
456 peaks, 12-hour and 1-day, show low values not statistically significant.

457 The WPS for NO_3 concentration shows some strong but time-discontinuous peaks
458 at the ~ 15 -day and ~ 30 -day periodic components of the signal, but locally they
459 are not statistically significant (Figure 9e). However, the time-averaged WPS peaks
460 for these signal periods are statistically significant. The observed peak at ~ 15 -day
461 explains $\sim 12\%$ of the total variance (Figure 9f). A weak time-discontinuous peak
462 that is statistically significant can be observed at the ~ 12 -hour signal period (Figure
463 9e). This ~ 12 -hour peak shows slightly stronger values during the more intense
464 spring tides and weaker during the less intense spring tides. At the ~ 1 -day periodic
465 component, several peaks in the time domain are observed but only half of them are
466 statistically significant. According to the time-averaged WPS, neither the ~ 12 -hour
467 nor the ~ 15 -days periodic components are statistically significant (Figure 9f).

468 The WPS for total phytoplankton biomass shows a strong peak at ~ 15 -day
469 periodic component, but its statistical significance is discontinuous in the time domain
470 (from February to March, from mid-March to May, and from July to October; see
471 Figure 9g). On average, this periodicity explains $\sim 21\%$ of the total variance (Figure
472 9h). There are other strong peaks in the WPS between the ~ 30 -day and 60-day signal
473 periods. As with previous state variables, weaker peaks are observed at ~ 12 -hour and
474 ~ 1 -day periodicities, both discontinuous in time (Figure 9g). At the beginning and
475 the end of the year, the 12-hour peak seems more uniform over time, without showing
476 a discontinuous pattern as clear as for the other variables. The ~ 1 -day periodicity
477 peak is slightly stronger and statistically significant at both the beginning and end of
478 the simulated year. Between April and November, few of these peaks in the WPS at
479 the ~ 12 -hour or ~ 1 -day signal periods are statistically significant. Furthermore, at
480 the time-averaged WPS, both peaks were very weak and not statistically significant
481 (Figure 9h). It should be noted that at several moments in the year, we can observe
482 a peak in the WPS for the ~ 6 -hour signal period which is statistically significant,
483 coinciding with the semi-diurnal tidal cycle.

484 3.4. Wavelet coherence analysis

485 Finally, we performed a wavelet coherence analysis to study the covariance be-
486 tween uvel as the driving variable and salinity, temperature, NO_3 concentration, and
487 phytoplankton biomass as the response variables. The consistency of the coherence
488 between the driver and the different response variables can be identified from the
489 average wavelet cross-spectrum (see left-hand panels in Figure 10). The most con-
490 sistent signal period for each pair of variables (i.e., the periodicity with the highest
491 cross-spectrum power value) was identified, and subsequently, the corresponding os-
492 cillations were extracted for the whole period to compare their amplitudes and phases
493 (see right-hand panels in Figure 10).

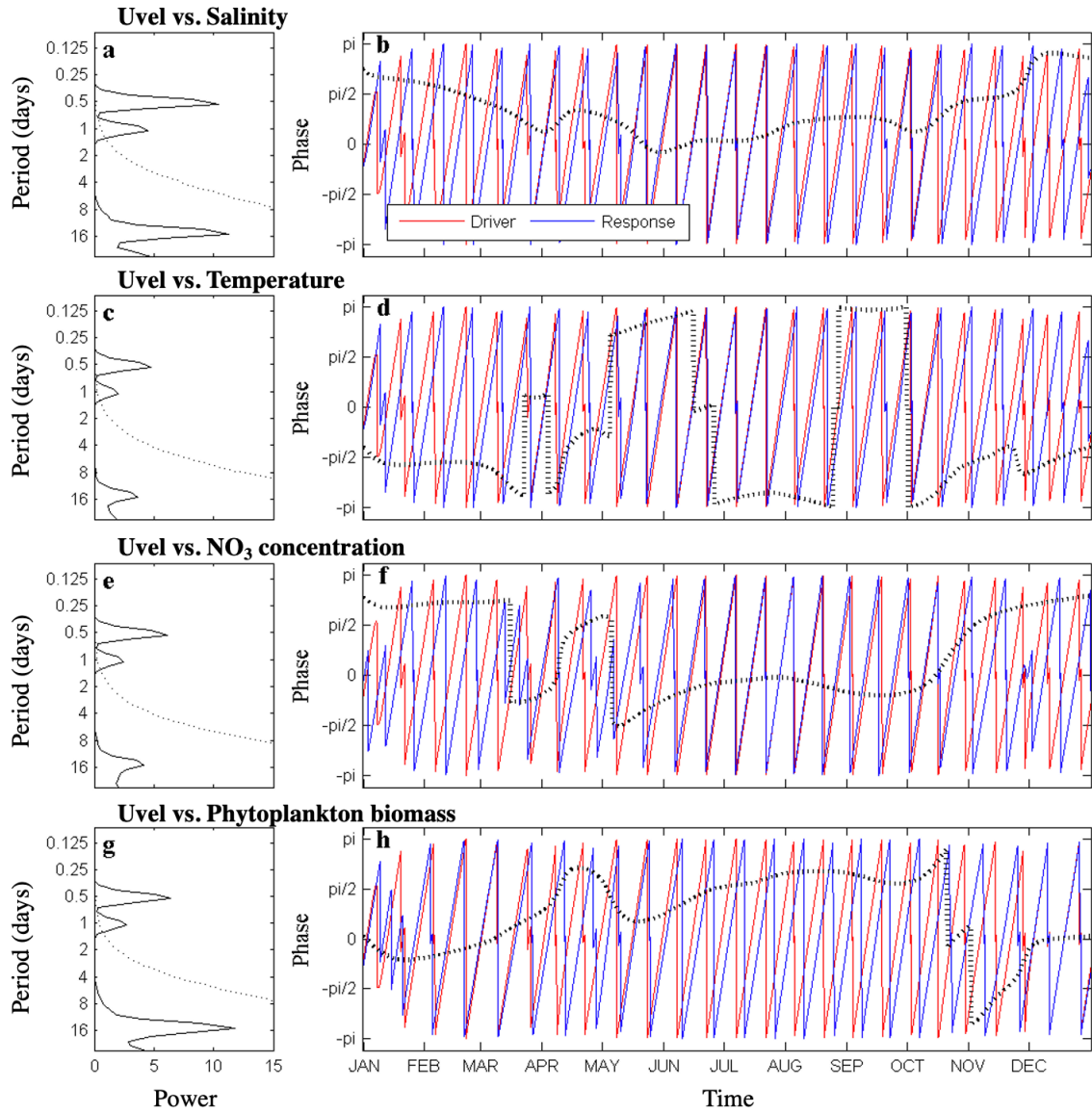


Figure 10: Wavelet coherence analysis computed for the zonal component of current velocity (uvel; m s^{-1}) versus (a, b) salinity, (c, d) temperature ($^{\circ}\text{C}$), (e, f) nitrate concentration (NO_3 , mmol m^{-3}), and (g, h) total phytoplankton biomass (mmol N m^{-3}) for the 1-year simulation. Left-hand panels (a, c, e, g) show the average wavelet cross-spectrum. Dotted lines show the $\alpha = 5\%$ significance levels computed based on 1000 Markov bootstrapped series. Right-hand panels show the phases of both time series computed for the peak of highest coherence: uvel (red line) versus (b) salinity, (d) temperature, (f) NO_3 , and (h) total phytoplankton biomass (blue lines). Dashed lines represent the phase difference between both signals.

494 The strongest phase coherence between the uvel and salinity signals is found at
 495 the ~ 15 -day period, with a cross-spectrum power value that explains $\sim 37\%$ of the
 496 total variance (Figure 10a). For the entire simulation, there is an average delay of 1.05
 497 days between the phase of the two variables, with the driver variable (uvel) peaking
 498 before the response variable (salinity) (Figure 10b). The maximum delay between
 499 uvel and salinity signals is observed at the beginning and the end of the year, with
 500 a delay of 2.36 and 2.84 days, respectively, between driver and response. While the
 501 minimum delay is observed from June to August.

502 Between uvel and temperature, the strongest peak in the WCo analysis is ob-
503 served at the ~ 12 -hour period (Figure 10c), although the area under this peak is
504 not statistically significant. Therefore, as we did with salinity, we focus our analysis
505 on the ~ 15 -day signal period. This peak has a power value that explains the \sim
506 32% of the total variance. During most of the simulated year, the response variable
507 (temperature) appears before the driver variable (uvel), with an average delay of 1.97
508 days (Figure 10d). However, between May and July and between September and
509 October, the driver variable appears before the response variable, with a delay of up
510 to 3.14 days.

511 The coherence between uvel and NO_3 concentration also shows the strongest and
512 statistically significant peak at the ~ 15 -day period (Figure 10e). The ~ 15 -day
513 cross-spectrum power value explains $\sim 23\%$ of the total variance. Again, driver and
514 response variables show a lack of synchrony (Figure 10f), with the response variable
515 appearing before or after the driver. At the beginning and the end of the year, the
516 driver (uvel) appears before the response (NO_3 concentration), with a mean delay of
517 2.27 days. From May to October, the response variable appears before the driver,
518 with a mean delay of ~ 0.50 days.

519 Likewise, total phytoplankton biomass displays the strongest coherence with uvel
520 at the ~ 15 -day signal period, with a cross-spectrum power value that explains \sim
521 48% of the total variance (Figure 10g). The delay between both variables follows a
522 pattern almost opposite to uvel and NO_3 concentration (Figure 10f). The response
523 variable appears before the driver at the beginning and the end of the simulated year,
524 with a mean delay of 0.71 days. While from April to October, the driver variable
525 appears before the response variable, with a mean delay of 1.38 days (see Figure 10h).

526 To verify that these results are not a consequence of our approach, both the
527 WPS and the WCo analyses were repeated using two different time series: (i) a time
528 series that only considers the temporal dynamics of salinity, NO_3 concentration and
529 phytoplankton biomass at 20 m depth at $6.11^\circ\text{W} - 36.06^\circ\text{N}$ (red circle in Figure
530 1b); and (ii) a time series obtained from the average values, of each variable, for the
531 whole water column and considering the entire upwelling band region, i.e., between
532 6.13 and 6.06°W . In both cases, the obtained results were similar to those described
533 here (data not shown).

534 4. Discussion

535 In the Cape Trafalgar region, the tide-topography interaction of the westward
536 tidal current (towards the Gulf of Cádiz) with the eastern steep edge of the submarine
537 ridge, results in a tidal pumping process that brings up deep, saltier, colder, nutrient-
538 rich and phytoplankton-poor water onto Barbate High. This process is similar to
539 the interaction previously described at Georges Bank, a shallow submarine feature
540 located on the Gulf of Maine (e.g., Chen and Beardsley, 1998; Franks and Chen,
541 2001; Hu et al., 2008; Ji et al., 2008). Particularly during spring tides, denser water
542 is advected upslope to subsurface layers leading to a spatial asymmetry between
543 the eastern and the western side of the ridge (see left-hand panels in Figures 5-7)
544 (Vargas-Yáñez et al., 2002). Concurrently, the interaction of the tidal current with
545 the eastern edge of Barbate High leads to the formation of a cyclonic eddy (Bolado-
546 Penagos et al., 2020), which spreads the upwelled waters over and to the west of the

547 ridge. This interaction results in the development of a water tongue with particular
548 properties that are slightly different from the surrounding waters (right-hand panels,
549 Figures 5-7). The upwelling of deep, salty and nutrient-rich water is more effective
550 during spring tides, but due to the greater horizontal mixing mediated by the cyclonic
551 gyre the water properties of are diluted, while during neap tides the lower horizontal
552 mixing leads to a saltier and enriched water tongue.

553 The high phytoplankton biomass observed over Barbate High (right-hand panels
554 in Figure 7), is favoured by the continuous and cyclical input of nutrients (e.g., Chen
555 and Beardsley, 1998; Hu et al., 2008; Ji et al., 2008; Blauw et al., 2012, 2018). Ac-
556 tually, a previous study with a similar model configuration (Sánchez-Garrido et al.,
557 2015) shows how a simulation with tidal forcing results in a chl concentration over
558 Barbate High ~ 3 times higher than in a simulation without tides. At the selected
559 location point for in-depth analysis of the upwelling dynamics, we observe that NO_3
560 concentration and phytoplankton biomass display an anti-phase behaviour (Figure
561 8d, e). The ‘water masses’ observed in this region (i.e., Trafalgar’s tongue, upwelled
562 water) are continuously moving back and forth due to the fluctuations of the tidal
563 current intensity and direction (see Supplementary video – <http://t.ly/bVQQ>). The
564 pumping of NO_3 -rich waters takes place when the tide flows towards the Gulf of Cádiz
565 while Trafalgar’s tongue moves westward. Hence, at the analysed upwelling point
566 there is an uplifting of nutrient-rich water with relatively low phytoplankton biomass
567 and a low influence of the phytoplankton-rich Trafalgar’s tongue. Nevertheless, when
568 the tide flows towards the Alborán Sea, there is no pumping of nutrient-rich water
569 and the phytoplankton-rich Trafalgar’s tongue is advected eastwards on the analysed
570 upwelling point, and re-distributed along the whole water column. This coincides
571 with a maximum in phytoplankton biomass. This fact can be appreciated in Figure
572 11a, where mean NO_3 concentration and phytoplankton biomass computed for the
573 whole water column at the upwelling point (red circle in Figure 1b) over two tidal
574 cycles behaves oppositely.

575 The tide-topography interaction occurs during both neap and spring tides (Figures
576 5 and 6). However, during neap tides the water advection is weak, so the pumped
577 waters (slightly more saline and moderately rich in NO_3 than the surrounding waters)
578 do not reach the most superficial waters (Figure 8c). The intensity of the tidal
579 pumping of saltier, colder and NO_3 -rich waters depends on the tidal current speed,
580 being stronger and reaching the most superficial layers when the westward current
581 speed (towards the Gulf of Cádiz) is higher (Figures 5, 6, 8 b-d). In Figure 8 b-d, it
582 can be observed that the tidal pumping of saltier, colder and NO_3 -rich waters takes
583 place several days before uvel achieves its maximum speed during spring periods;
584 when the tidal current speed is strong enough to cause a significant upwelling of deep
585 waters. Figure 11b shows the temporal dynamics of the average uvel (m s^{-1}) and
586 salinity, computed for the whole water column at $6.11^\circ\text{W} - 36.06^\circ\text{N}$ (red circle in
587 Figure 1b) over two tidal cycles. It should be noted that the semi-diurnal tidal cycle
588 in Trafalgar, with two high tides and two low tides per day, shows a diurnal inequality
589 with one high-low tidal cycle more intense than the other. It also should be noted
590 that during a semi-diurnal tidal cycle, due to the expected time delay between the
591 maximum westward current flow (negative uvel) and the horizontal displacement of
592 the water mass (high tide), the maximum upwelling of salty waters is observed 2 - 3
593 hours after the maximum flow. Thus, each peak of maximum salinity is caused by

594 the previous peak of maximum westward tidal current (towards the Gulf of Cádiz).
 595 Moreover, due to the diurnal inequality, the oscillations of salinity peaks are also
 596 asymmetric.

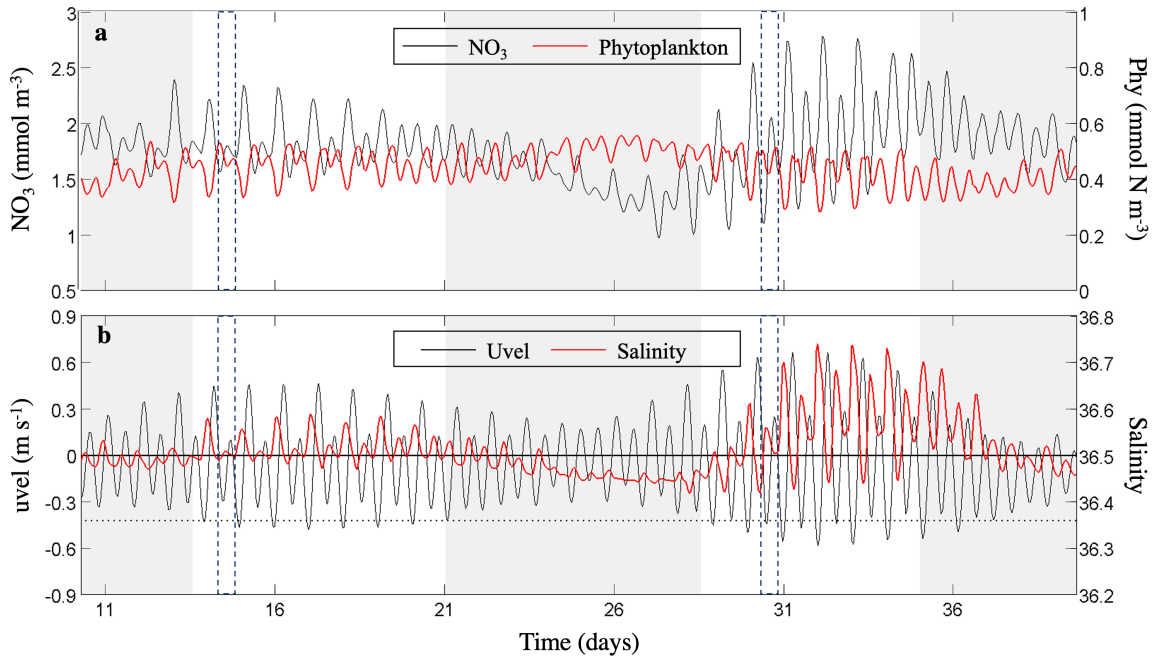


Figure 11: (a) Temporal evolution of mean nitrate concentration (NO_3 , mmol m^{-3} ; black line) versus mean phytoplankton biomass (Phy, mmol N m^{-3} ; red line). (b) Temporal evolution of the mean zonal component of the tidal current (uvel, m s^{-1} ; black line) versus mean salinity (red line). The black horizontal line represents the zero uvel reference (delimiting positive (negative) values that indicate flow driven eastward (westward), towards the Alborán Sea (Gulf of Cádiz)) and the mean salinity (36.47) value computed for the whole year. The black dashed line represents uvel equal to -0.42 m s^{-1} . Black dashed rectangles point out the first tidal-pumping event during both spring tide periods. The grey background identifies the neap tide periods. All time series were computed for the whole water column at $6.11^\circ \text{W} - 36.06^\circ \text{N}$ (red circle in Figure 1b).

597 Considering Figure 11b, it seems that the upwelling of saltier waters does not
 598 take place when the westward tidal current speed is lower than 0.42 m s^{-1} (negative
 599 uvel values, black dashed line). Black dashed rectangles mark the first effective tidal-
 600 pumping event during both spring tide periods. During the less intense spring tide,
 601 the first tidal-pumping event of deep and saltier water towards the more superficial
 602 layers occurs around day 13 at 02:30 hours, raising the average salinity to 36.58.
 603 Three hours before (around day 12 at 23:36 hours), the westward uvel is $\sim 0.42 \text{ m s}^{-1}$.
 604 In the previous days, characterised by lower uvel values, the upwelling of deep
 605 and saltier water does not take place. Similarly, during the most intense spring tide
 606 event, the first tidal-pumping episode takes place around day 29 at 03:48 hours, as
 607 a result of $\text{uvel} > 0.42 \text{ m s}^{-1}$ (around day 29 at 01:54 hours). This behaviour is
 608 observed throughout the whole year (data not shown). However, this dynamic is
 609 influenced by the summer stratification of the water column (Figure 8d) linked with
 610 the seasonal variability of solar irradiance (and thus heat flux). In summer, although
 611 during spring tides the upwelling of salty and nutrient-rich waters continues to take
 612 place (Figure 8b-e), the heat-flux induced stratification reduces the vertical mixing
 613 preventing the upwelled waters from reaching the most superficial layers (Figure 8d).

614 Hence, the phytoplankton located in the most superficial layers will not have access
615 to the uplifted nutrients, decreasing the phytoplankton community nutrient uptake
616 rate and biomass (Figure 8f). This seasonal variability was previously observed in the
617 study region using 10-years of ocean colour observations using the MEdium Resolution
618 Imaging Spectrometer (~ 300 m resolution Sala et al., 2018).

619 For all the analysed variables, salinity, temperature, NO_3 concentration and total
620 phytoplankton biomass, the time-averaged WPS shows a peak at the fortnightly tidal
621 cycle, explaining $\sim 21\%$, $\sim 26\%$, $\sim 12\%$ and $\sim 21\%$ of the total variance respectively
622 (right-hand panels in Figure 9). Although the time-averaged WPS peak observed at
623 the ~ 15 -day signal period for temperature is smaller than for salinity, it explains a
624 higher percentage of the total variance (Figure 9d). However, the local WPS analysis
625 shows statistically significant results for salinity at certain time periods of the simu-
626 lated year but not for temperature (Figure 9 a and c), confirming that temperature is
627 not a good proxy to identify tidally driven upwelling events in this region. Salinity and
628 temperature are intrinsic properties of the upwelled water, and no biological activity
629 can alter them. However, upwelled nutrients may be assimilated by phytoplankton,
630 weakening the fortnightly periodicity component of NO_3 concentration, which would
631 explain the absence of statistically significant peaks in the WPS analysis (Figure 9e).
632 Furthermore, the lack of a statistically significant fortnightly periodicity component
633 may also be related to the lack of continuity in the upwelling events, which are less
634 intense during neap periods (Figure 8). In fact, the WPS analysis with daily aver-
635 aged time series results in stronger fortnightly signals, statistically significant over
636 longer periods (data not shown). Supporting these findings, the WCo analysis be-
637 tween state variables (drivers against responses) identifies the strongest statistically
638 significant covariation patterns at the fortnightly tidal period (see left-hand panels
639 in Figure 10). However, only in very few certain moments of the temporal domain,
640 the driver variable (uvel) is in synchrony with the response variables (i.e., salinity,
641 temperature, NO_3 concentration and total phytoplankton biomass). For most of the
642 year, the time delay between driver and response variables varies back and forth. Al-
643 though the tidal-topography interaction is the main responsible for the temporal and
644 spatial variability in the Trafalgar region, it is not until the westward uvel reaches a
645 threshold value of ~ 0.42 m s $^{-1}$ that deep water is pumped to the most superficial
646 layers. Moreover, the tidal cycle is also responsible for the horizontal displacement
647 of water masses that modifies the properties of the water column. Finally, the sea-
648 sonal variability, the Gulf of Cádiz circulation pattern, and the wind regime will also
649 introduce changes (Vargas-Yáñez et al., 2002; Sala et al., 2018). Therefore, this asyn-
650 chrony between driver and response variables is conceptually expected but difficult to
651 anticipate before performing the simulations, due to non-linearities in the dynamics.

652 The WCo analysis between uvel (as driver variable) against NO_3 concentration
653 and phytoplankton biomass (as response variables) shows an opposite pattern (disre-
654 garding May) (Figure 10 f, h). When NO_3 oscillations appear later than the driver,
655 the phytoplankton biomass oscillations appear earlier than the driver, and vice versa.
656 In any case, the maximum of phytoplankton biomass must be a response to the pre-
657 vious NO_3 tidal pumping. This is explicit in the primary production equations of the
658 ecosystem model used to perform these simulations. In the Cape Trafalgar region,
659 there seems to be always a phytoplankton community ready to assimilate nutrients
660 when there is a new input. After a neap tide period with a minimum nutrient input

661 (Figures 6c, 8c), during which the previously pumped nutrients have been consumed
662 or dispersed, a new nutrient input during spring tides (when westward uvel > 0.42 m
663 s^{-1}) can be efficiently assimilated by the pre-existing phytoplankton community. In
664 fact, some modelling exercises have shown how patterns of periodic inputs of nutri-
665 ents into the surface (especially tidal pulses) lead to the apparition of larger values
666 of phytoplankton biomass than scenarios associated with a continuous supply; fur-
667 thermore, it can favour some taxonomic groups as diatoms and larger zooplankton
668 (Macías et al., 2010).

669 Although the fortnightly period is shown to be the most influential scale of the
670 tidal variability in our study area, as previously found by Sala et al. (2018), it should
671 be highlighted that the WPS and WCo analyses show a peak at the ~ 12 -hour
672 period which confirms the influence of the semi-diurnal tidal cycle on the simulated
673 state variables (see Figure 9 and left-hand panels in Figure 10). However, the time-
674 averaged WPS and WCo analyses for the entire year show that this periodicity is
675 not statistically significant, probably due to the discontinuity of the tidal-pumping
676 events, which do not take place when uvel was < 0.42 m s^{-1} .

677 Previous studies have highlighted that the tidal pumping of nutrient-rich waters
678 could be enhanced by other mechanisms not addressed in our study, such as river
679 discharges (Huertas et al., 2005; Navarro et al., 2006) and wind-driven upwellings
680 (Vargas-Yáñez et al., 2002; Sala et al., 2018). Our model configuration does not
681 include nutrient inputs from river discharges (e.g., Guadalquivir River). This fact
682 facilitates the aim of this study by removing its possible influence on the time series
683 analysis. However, the lack of nutrient river discharges results in an underestimation
684 of primary production of the northern coastal areas in the Gulf of Cádiz, which can be
685 observed in Figure 3. The superficial circulation pattern of the Gulf would advect the
686 productive water that flow from the rivers towards the Trafalgar region, increasing its
687 primary production. Therefore, it would be interesting for future works to compare
688 our results with a model that prescribes nutrient inputs from rivers to evaluate and
689 quantify their relative importance. Regarding the wind forcing, since it was explicitly
690 resolved in our model, we have extracted the zonal component of the wind at 10 m
691 (u10) for the analyzed area. The comparison between both u10 and salinity time series
692 does not show a clear pattern of variability (Figure E1), and the lack of correlation
693 was supported by a WCo analysis (data not shown). Nevertheless, its influence may
694 introduce ‘noise’ in our analysis but, as the seasonal variability, without undermining
695 the tidal impact in the region. However, Bolado-Penagos et al. (2020) observed that
696 easterly winds increase the retention capacity of Cape Trafalgar. Moreover, due to
697 the presence of the ridge that characterizes this region a stacking of waters may take
698 place leading to a deepening of the interface. Therefore, it would be interesting to
699 carry out a more detailed analysis with a different model setup.

700 Finally, it is worth mentioning that several authors have described a secondary
701 impact of the tidal cycle in the Strait of Gibraltar that would increase the primary
702 production in the Alborán Sea. Due to the velocity divergences developed in the
703 surface layer when undulatory features are generated over the Camarinal Sill, a lat-
704 eral advection of patches with high chl-*a* concentration was observed from coastal
705 areas to the centre of the Strait (Macias et al., 2006; Vázquez et al., 2009; Ramírez-
706 Romero et al., 2012; Bruno et al., 2013). Thus, Cape Trafalgar is considered to act

707 as a source of nutrient- and biomass-rich waters that periodically will flow to the
708 Alborán Sea. Moreover, a recent study (Bolado-Penagos et al., 2020) has described a
709 transport process of phytoplankton along the coastal margin between Cape Trafalgar
710 and the Alborán Sea. These transport events would imply a loss of nutrient and
711 phytoplankton-rich waters towards Alborán that could be introducing some degree
712 of ‘noise’ in our wavelet analysis (WPS and WCo).

713 5. Conclusions

714 The results obtained in this study confirm the importance of the tidal cycle for
715 the productivity of the Cape Trafalgar region through an active and periodic forcing
716 resulting in a pulsating upwelling pattern. The interaction of the westward tidal
717 current with the eastern edge of the ridge perpendicular to the coast that characterises
718 this region results in the upwelling of deep, saltier and nutrient-rich waters that favour
719 the development of a tongue with high phytoplankton biomass over Barbate High.

720 The fortnightly period is confirmed as the most influential scale of the tidal cycle
721 when the tidal-pumping process takes place during spring tides characterised by a
722 westward tidal current $> 0.42 \text{ m s}^{-1}$, between ~ 3 days before and after the moment
723 of maximum westward flow. This tidal interaction implies cyclical fertilisation of the
724 illuminated surface waters in the region, favouring the growth of the phytoplankton
725 community. After an (effective) tidal-pumping event during spring tides, periods of
726 minimum NO_3 concentration lead to phytoplankton nutrient-limitation at the surface
727 and low primary production. However, these periods do not last long (~ 4 days).

728 The seasonal variability of solar radiation affects the Cape Trafalgar region only
729 during summer. From July to September, the stratification of the water column
730 increases the vertical thermal gradient in the water column, which decreases the
731 vertical uplifting of nutrient-rich water into the first 30 m of the water column. For
732 this reason, the upwelled nutrients driven by the tidal-topography interaction remain
733 unconsumed below the euphotic layer, doubling their concentration by accumulation.
734 Meanwhile, the phytoplankton biomass decreases due to a lower input of nutrients to
735 the most superficial layers.

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research stays were supported by PhD secondment grants from the FPI fellowship program.

Author contributions

Iria Sala: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review and editing. **Sergio M. Vallina:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Supervision, Writing – review and editing. **Marina Lévy:** Supervision, Writing – review and editing. **Marina Bolado-Penagos:** Validation, Writing – review and editing. **Carlos M. García:** Conceptualization, Funding acquisition, Project administration, Writing – review and editing. **Fidel Echevarría:** Conceptualization, Funding acquisition, Project administration, Writing – review and editing. **José C. Sánchez-Garrido:** Methodology, Formal analysis, Data curation, Supervision, Writing – review and editing.

Conflicts of interest

The authors declare no conflict of interest.

Appendix A. Validation of the circulation model

Sea Surface Temperature (SST). SST data for the study area and the period 2001 - 2010 were downloaded from the Copernicus Marine Environmental Monitoring Service (CMEMS; <http://marine.copernicus.eu/>). This product is based on the reprocessed Pathfinder V5.3 (PFV53) Advanced Very-High-Resolution Radiometer (AVHRR) data combined with a bias-corrected version of the CMEMS-NRT-L4 data, using an Optimal Interpolation algorithm to provide a full-time series of consistent daily gap-free maps with a resolution of ~ 4.63 km.

Figure A.1 shows the comparison between the measured and modelled annual climatological values of SST. The climatological SST distribution is similar in both satellite data and the model, with colder coastal waters and warmer open ocean regions at both the Gulf of Cádiz and the Alborán Sea. Furthermore, it should be highlighted the presence of colder waters in the coastal region of Trafalgar, our area of interest. However, the model overestimates the annual mean satellite SST by ~ 2 °C.

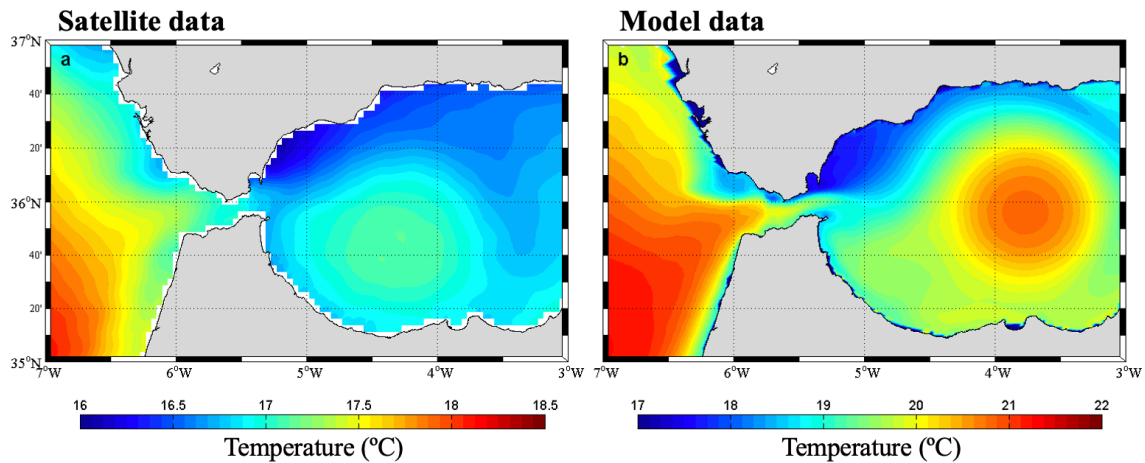


Figure A.1: (a) Sea surface temperature (SST, °C) climatology derived from remote sensing images corresponding to the period 2001 - 2010. (b) Model-derived climatology of SST for the 3rd-year simulation. Please note the different ranges of the scale between both subplots.

Temperature-salinity diagrams. Temperature and salinity data for the study area were extracted from the Medar/Medatlas II project, whose objective is to make available a comprehensive data product of temperature, salinity and biochemical data in the Mediterranean and the Black Sea, through wide cooperation of the Mediterranean countries (<http://www.ifremer.fr/medar/>). Temperature and salinity data were collected from 1911 to 1987. Temperature-salinity diagrams were computed for the centre of both sub-basins, the Gulf of Cádiz and the Alborán Sea, from observed and modelled data (Figure A.2). The main water masses present in both sub-basins were quite well reproduced by our regional model (grey points).

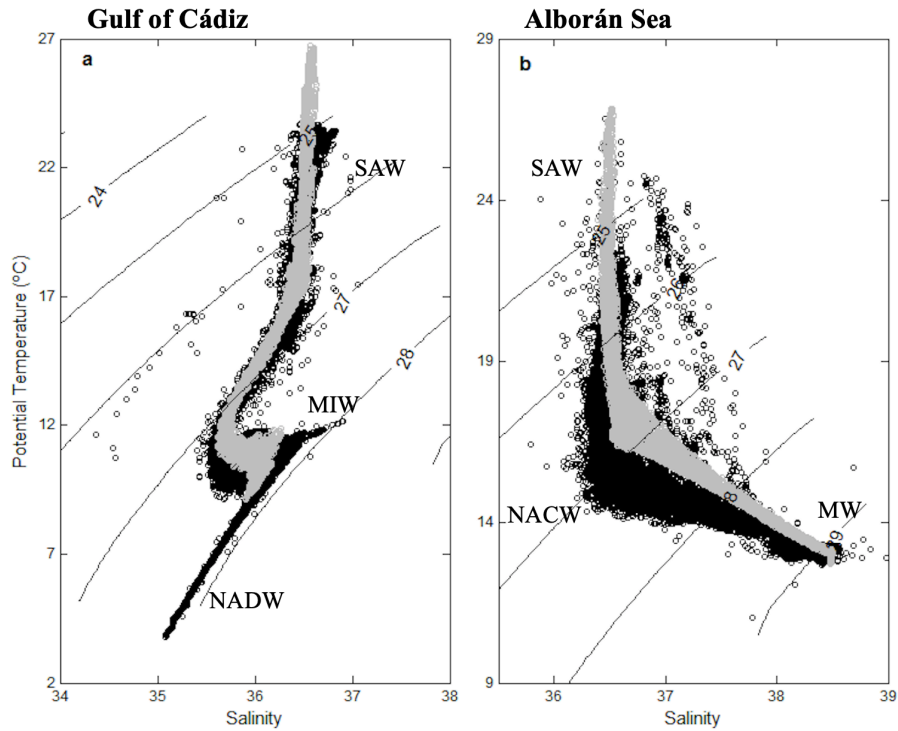


Figure A.2: Temperature-salinity diagrams comparing the Medatlas II database (black points) with the model outputs (grey points), representing the water mass characteristics of the (a) Gulf of Cádiz region, and the (b) Alborán Sea region. MIW: Mediterranean Intermediate Water. MW: Mediterranean Water. NACW: North Atlantic Central Water. NADW: North Atlantic Deep Water. SAW: Superficial Atlantic Water.

Appendix B. Ecosystem model: Ecological parameters

Table B.1: List of ecological model parameters. The values are shown in units of nitrogen. The corresponding values for phosphorus, silica and iron can be derived using a Redfield N:Si:P:Fe ratio of 16:16:1:0.001 (mol mol⁻¹). Dia.: Diatoms. DIM: dissolved inorganic matter. Din.: Dinoflagellates. DOM: dissolved organic matter. Mes.: Mesozooplankton. Mic.: Microzooplankton. n.d.: no dimensions. Phy.: Phytoplankton. POM: particulate organic matter. Pro.: *Prochlorococcus*. Syn.: *Synechococcus*. Zoo.: Zooplankton.

Parameter		Symbol	Value	Units
Phy. Pro.	Max. specific growth rate	μ_{max}^{pro}	0.50	d ⁻¹
Phy. Syn.	Max. specific growth rate	μ_{max}^{syn}	1.00	d ⁻¹
Phy. Fla.	Max. specific growth rate	μ_{max}^{fla}	2.00	d ⁻¹
Phy. Dia.	Max. specific growth rate	μ_{max}^{dia}	4.00	d ⁻¹
Phy. Pro.	Half-sat. for DIM uptake	ks^{pro}	0.10	μM
Phy. Syn.	Half-sat. for DIM uptake	ks^{syn}	0.30	μM
Phy. Fla.	Half-sat. for DIM uptake	ks^{fla}	0.60	μM
Phy. Dia.	Half-sat. for DIM uptake	ks^{dia}	1.20	μM
Phy.	Assim. efficiency	β_{phy}	0.80	n.d.
Phy.	Mortality specific rate	m_{phy}	0.05	d ⁻¹
Phy.	Mortality fraction to POM	ω_{phy}	0.50	n.d.
Phy.	Non-assim. fraction to POM	ψ_{phy}	0.50	n.d.
Zoo. Mic.	Max. specific ingestion rate	g_{max}^{mic}	4.00	d ⁻¹
Zoo. Mes.	Max. specific ingestion rate	g_{max}^{mes}	2.00	d ⁻¹
Zoo. Mic.	Half-sat. for ingestion	kg^{mic}	0.50	μM
Zoo. Mes.	Half-sat. for ingestion	kg^{mes}	0.30	μM
Zoo. Mic.	Preference for Small Phy.	ρ_{11}	1.00	n.d.
Zoo. Mes.	Preference for Small Phy.	ρ_{12}	1.00	n.d.
Zoo. Mic.	Preference for Large Phy.	ρ_{21}	1.00	n.d.
Zoo. Mes.	Preference for Large Phy.	ρ_{22}	1.00	n.d.
Zoo.	Assim. efficiency	β_{zoo}	0.40	n.d.
Zoo.	Mortality specific rate	m_{zoo}	0.05	d ⁻¹
Zoo.	Mortality fraction to POM	ω_{zoo}	0.50	n.d.
Zoo.	Non-assim. fraction to POM	ψ_{zoo}	0.50	n.d.
POM	Sinking rate	$ \bar{w} $	0.50	m d ⁻¹
POM	Degradation rate to DOM	m^{POM}	0.10	d ⁻¹
DOM	Degradation rate to DOM	m^{DOM}	0.10	d ⁻¹

AppendixC. Validation of the ecological model

Following Lefèvre et al. (2002), modelled chlorophyll was computed applying a variable C:Chl ratio calculated as a function of light levels following:

$$R_t = R_{max} - (R_{max} - R_{min}) \cdot \left(\frac{I_{max} - I_t}{I_{max} - I_{min}} \right), \quad (\text{C.1})$$

R represents the C:Chl ratio. R_{max} and R_{min} vary depending on phytoplankton size ($R_{max}^{sma} = 200.00 \text{ mg C mg Chl}^{-1}$; $R_{min}^{sma} = 166.67 \text{ mg C mg Chl}^{-1}$; $R_{max}^{lar} = 111.11 \text{ mg C mg Chl}^{-1}$; $R_{min}^{lar} = 90.91 \text{ mg C mg Chl}^{-1}$).

I is the photosynthetically active radiation (PAR; $\mu\text{Ein m}^{-2} \text{ s}^{-1}$) at the sea surface, derived from ERA-Interim and provided by the European Center for Medium-range Weather Forecast (ECMWF; <https://www.ecmwf.int/>; Dee et al., 2011). I_{max} , I_{min} and I_t , which represents the daily PAR, are obtained for each point of the model grid and at noon.

AppendixD. Eastward time-steps during neap and spring tides

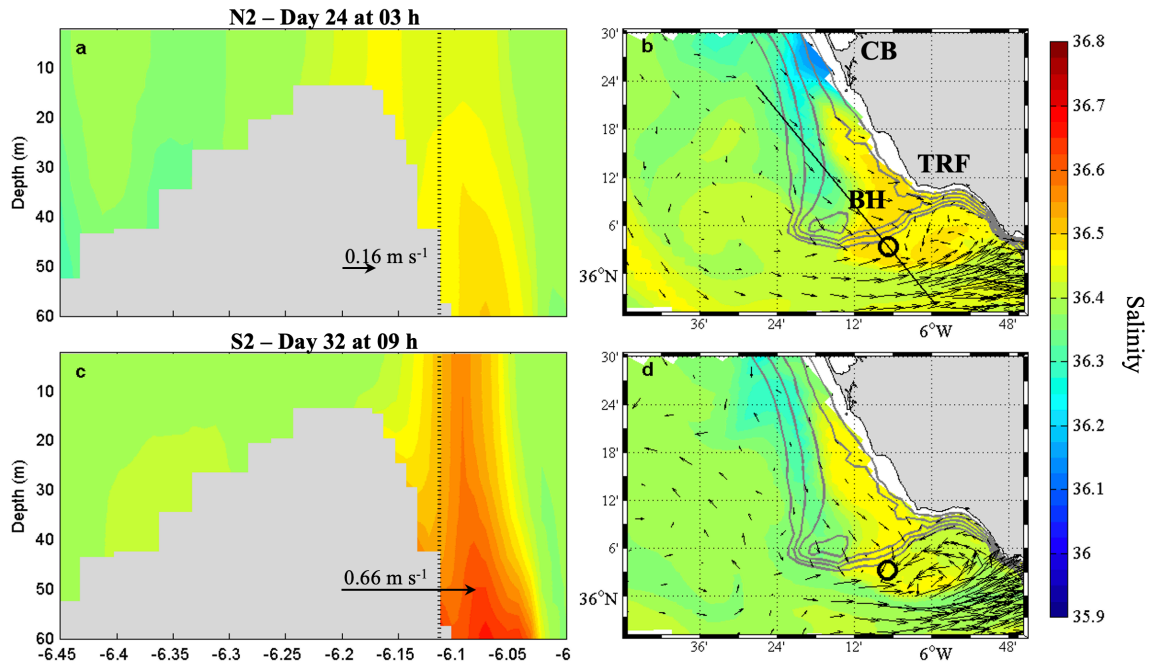


Figure D.1: Salinity distribution at the Cape Trafalgar region during the maximum eastward flow of the neap tide period (NT2: a, b) and the spring tide period (ST2: c, d) (see Figure 3). Left-hand panels show the vertical distribution along a section perpendicular to the submarine ridge (black line in panel b). Vertical dashed lines correspond to the position of open black circles in right-hand panels. Black arrows (a, c) represent the magnitude and direction of the mean zonal component of current velocity (u_{vel} ; $m s^{-1}$), computed for the whole water column at $6.11^{\circ}W$ and $36.06^{\circ}N$ at each time-step. Right-hand panels show the surface distribution. Black surface vectors represent the surface current ($m s^{-1}$). Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

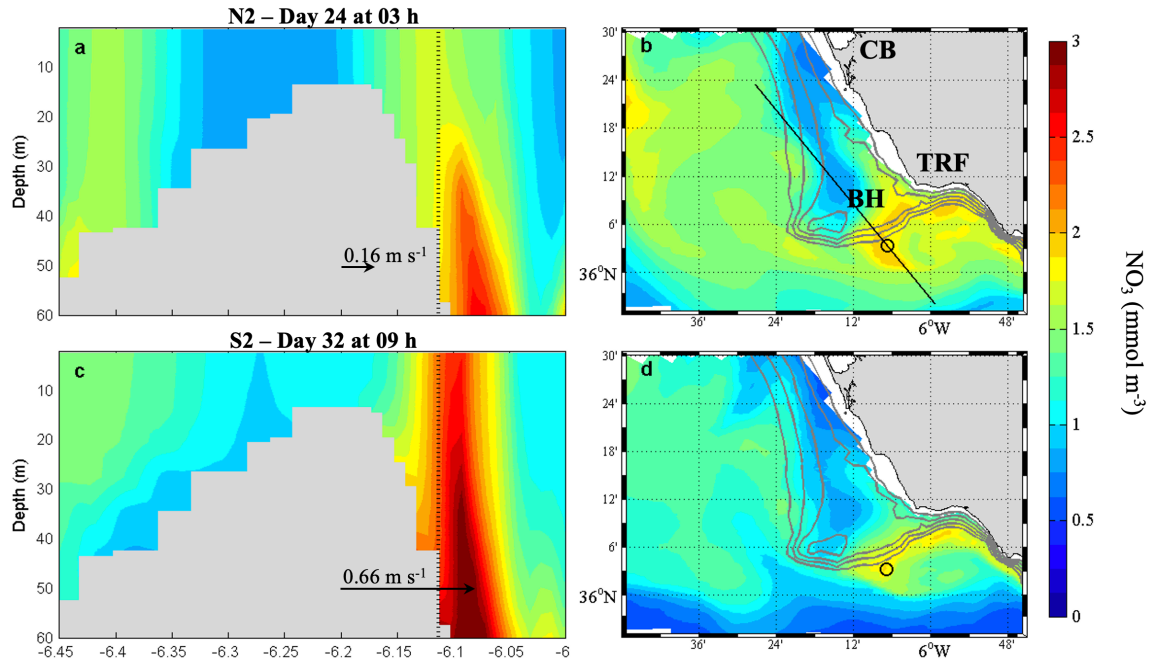


Figure D.2: Nitrate concentration (NO_3 , mmol m^{-3}) distribution at the Cape Trafalgar region during the maximum eastward flow of the neap tide period (NT2: a, b) and the spring tide period (ST2: c, d) (see Figure 3). Left-hand panels show the vertical distribution along a section perpendicular to the submarine ridge (black line in panel b). Vertical dashed lines correspond to the position of open black circles in right-hand panels. Black arrows (a, c) represent the magnitude and direction of the mean zonal component of current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N at each time-step. Right-hand panels show the surface distribution. Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

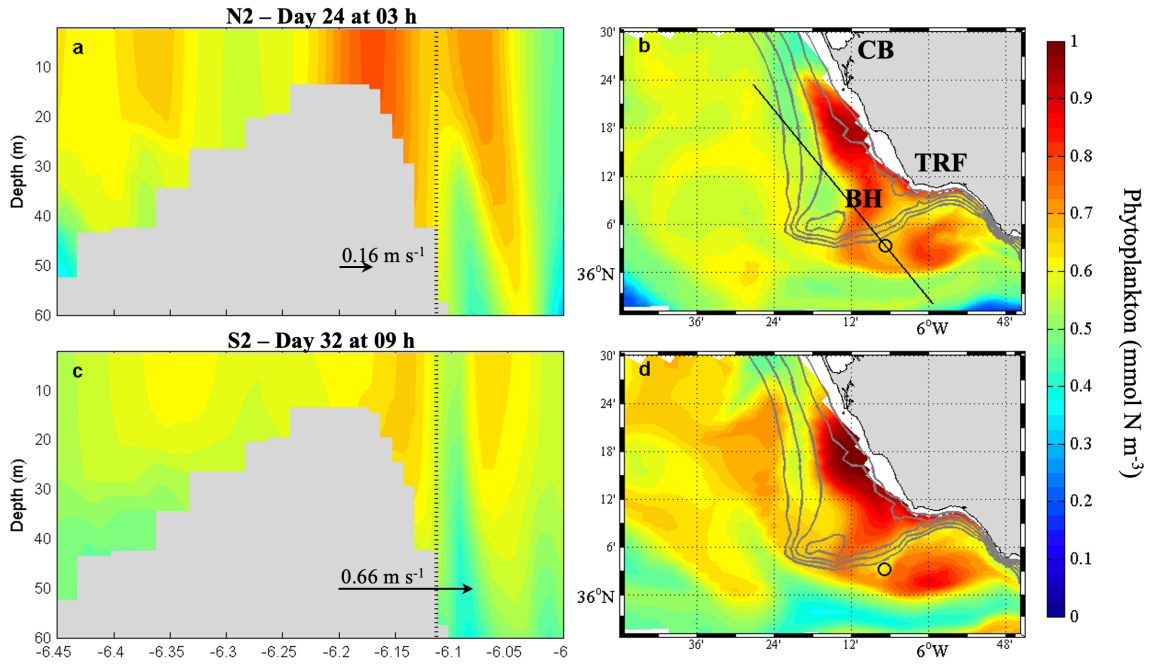


Figure D.3: Total phytoplankton biomass (mmol N m^{-3}) distribution at the Cape Trafalgar region during the maximum eastward flow of the neap tide period (NT2: a, b) and the spring tide period (ST2: c, d) (see Figure 3). Left-hand panels show the vertical distribution along a section perpendicular to the submarine ridge (black line in panel b). Vertical dashed lines correspond to the position of open black circles in right-hand panels. Black arrows (a, c) represent the magnitude and direction of the mean zonal component of current velocity (u_{vel} ; m s^{-1}), computed for the whole water column at 6.11°W and 36.06°N at each time-step. Right-hand panels show the surface distribution. Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

Appendix E. Analysis of the zonal component of the wind at 10 m

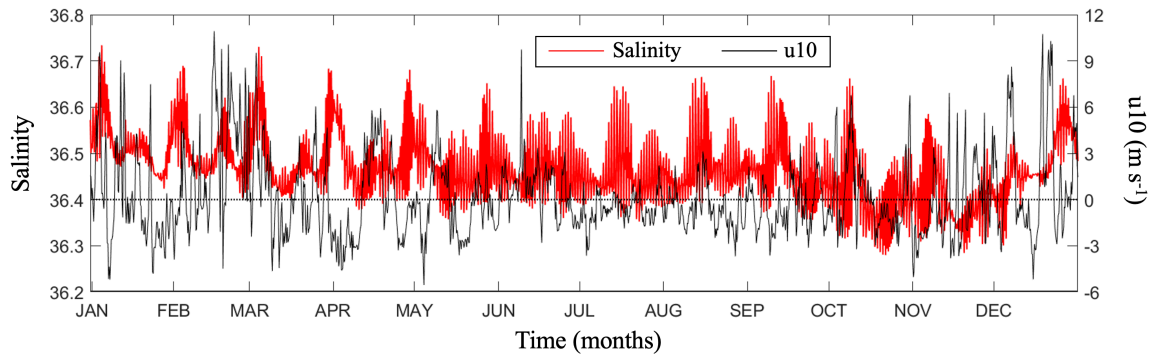


Figure E.1: Temporal evolution of salinity versus the zonal component of the wind at 10 m (u_{10} , m s^{-1}) every 6 h at 6.11°W and 36.06°N (red circle in Figure 1b). The black horizontal line represents the zero u_{10} reference delimiting positive (negative) values that indicate westerly (easterly) winds.

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