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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 1. Introduction

Covering 6% of the world's surface, coastal waters are a vital part of the envi-2 ronment and provide between 22 and 43% of global ecosystem services (Costanza 3 et al., 2014). The highly dynamic coastal regions and the associated biogeochemical 4 processes play a key role in phytoplankton growth, being primary production between 5 3 to 5 times higher than in oceanic regions (Simpson and Sharples, 2012). In many 6 coastal regions, tides are an important physical forcing factor with a major impact on 7 primary production (Pingree and Griffiths, 1978; Daly and Smith, 1993; Otto et al., 8 1990). The tidal cycle is responsible for a series of periodic fluctuations at different 9 time scales. The release on internal tidal waves causes a horizontal displacement of 10 water masses and subsequent maxima in tidal current speed, at the same time that 11 the associated current shear results in internal turbulent mixing (e.g., Holloway et al., 12 2001; Rippeth and Inall, 2002; Dale et al., 2003). Thus, locally, tide-topography in-13 teraction can have a significant impact on biological production by fertilisation of 14 illuminated surface waters and the resuspension of phytoplankton cells and other 15 particles, concomitant to the consequent vertical mixing (Pingree et al., 1981; New 16 and Pingree, 1990; Hu et al., 2008; Sharples et al., 2007; Palmer et al., 2013). 17

This process is especially relevant in the Strait of Gibraltar (south of the Iberian 18 Peninsula), a shallow and narrow channel that separates the Atlantic Ocean and the 19 Mediterranean Sea (Figure 1). The Strait is characterised by (i) the semi-diurnal tidal 20 cycle with a periodicity of 12 hours and 25 minutes, which results in a horizontal dis-21 placement of water that generates an increase in the current speed and the associated 22 vertical mixing every 6 hours and 12 minutes; and (ii) the spring-neap tidal cycle with 23 a periodicity of ~ 15 days, related to the apogee-perigee cycle (29.50-day periodicity) 24 (García-Lafuente et al., 1990). The interaction of the tidal current with the Strait's 25 sharp topography generates undulatory processes (e.g., internal waves) that modify 26 the nutrient budget by recirculation from deeper to shallower layers (e.g., Macías 27 et al., 2007b; Ramírez-Romero et al., 2012; Sánchez-Garrido et al., 2015). However, 28 due to the hydrodynamics of this region being characterised by the superficial inflow 29 of Atlantic water towards the Mediterranean Sea, and by the short-residence time 30 of the mixed waters within the channel (Macías et al., 2007a; Bruno et al., 2013), 31 the biological impact of this tide-topography interaction results in a 40% increase of 32 productivity, not in the Strait itself, but in the adjacent Alborán Sea (western-most 33 basin of the Mediterranean Sea) (Sánchez-Garrido et al., 2015). Thus, although the 34 Strait is characterised by low productivity due to the surface circulation pattern, this 35 is not the case in the coastal Cape Trafalgar region located on its north-western limit 36 (Figure 1b). 37

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

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

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

⁸⁹ 2. Methodology

90 2.1. Circulation model

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



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.

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

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

The model solution was evaluated against different data sources. Modelled Sea 136 Surface Temperature (SST) was compared to satellite-retrieved SST observations (re-137 processed Pathfinder V5.3; CMEMS). The model tends to overestimate slightly the 138 annual mean but otherwise, it captures well the spatial-temporal distribution, show-139 ing colder waters in coastal regions (due to upwelling) and warmer waters in open 140 ocean regions for both the Gulf of Cádiz and the Alborán Sea (see Figure A.1). We 141 also compared temperature-salinity (TS) diagrams using modelled outputs versus in 142 situ observations from the Medatlas II dataset (http://www.ifremer.fr/medar/). The 143 main water masses are well reproduced by our regional model as inferred from the TS 144 diagrams (Figure A.2). Further details can be found in the supplementary material. 145 Finally, thermistors and Acoustic Doppler Current Profiler (ADCP) data col-146 lected in the proximity of Cape Trafalgar from September 3^{rd} to October 10^{th} , 2015 147 (MEGAN Project; Bolado-Penagos et al., 2020), were compared with model outputs 148 to evaluate the tidal variability (Figure 2). The mooring was bottom-mounted at 149 $6.05 \,^{\circ}\text{W} - 36.00 \,^{\circ}\text{N}$ (red cross in Figure 1b) at a bottom depth of 200 m. At this 150 emplacement was deployed a thermistor chain of 43 thermistors disposed 3-m apart 151 from each other, from 10 to 136 m depth and programmed with a sample interval of 1 152 minute. Additionally, it was also deployed a 75-kHz Teledyne RD Instrument (RDI) 153 ADCP, with a sampling interval of 3 minutes and a 4-m bin size covering between 154 40 and 140 m of the water column. Because the model outputs represent a climato-155 logical year, to compare the observed and modelled data it was identified the closest 156 tidal moment to the observations. Model data showed a temperature overestimation 157 of 1.21 ± 0.64 °C (Figure 2a). Meanwhile, the current velocity data, usel and vvel, 158 range between very similar ranges. However, modelled uvel seems to slightly overes-159 timate the observations (Figure 2b), while vvel seems to slightly underestimate them 160

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 (°C), (b) mean zonal component of the current speed (uvel; m s⁻¹), and (c) mean meridional component of the current speed (vvel; 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 °W - 36.0 °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

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

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

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

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

The seasonal variability of the ecosystem model was evaluated with satellite chl-a204 $(mg m^{-3})$ data, a proxy for the surface phytoplankton biomass. Ocean colour im-205 ages for the study area were downloaded from the CMEMS (from 1998 to 2016). To 206 enable this comparison, the model total phytoplankton biomass (mmol $P m^{-3}$) was 207 first converted to carbon by applying the canonical Redfield ratio C:P = 106:1 (mol 208 mol^{-1}), and then converted to chl-a concentration by applying a variable C:Chl ratio 209 calculated as a function of light levels following Lefèvre et al. (2002) (see supplemen-210 tary material for more details). Figure 3 shows the comparison between the seasonal 211 climatology derived from remote sensing images and the model-derived seasonal av-212 erage of the simulated year for surface chl-a. The modelled chl-a distribution reflects 213 well the observed oligotrophic nature of the Western Alborán Gyre. Furthermore, 214 the model also captures the meridional gradient of chl-a with higher values along the 215 northern coast of the study area, as well as the decrease west-to-east of chl-a con-216 centration in the Alborán Sea, being the north-western region the richest area (e.g., 217 Sarhan et al., 2000; Macías et al., 2008). The under-estimation of chl-a concentra-218 tion by our simulations over the northern coastal area of the Gulf of Cádiz may be 219 attributed to the fact that the model does not prescribe nutrient inputs from river 220



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

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

et al. (2008) for a review). Here, wavelet analysis is used to disentangle the temporal 227 patterns of several state variables of the MITgcm + Darwin model, both in time and 228 frequency domains. In particular, we use it to identify the dominant periodicities of 229 salinity, temperature, NO₃ and phytoplankton biomass. We used the MatLab toolbox 230 developed by Cazelles and Chavez (Cazelles et al., 2008), applying the Morlet wavelet 231 that provides a good balance between time and frequency localisation (Grinsted et al., 232 2004). In a time-frequency plane, the wavelet power spectrum represents the relative 233 importance of frequencies at each time step. Values closer to the edge of the time 234 series, delimited by the cone of influence, were rejected to avoid false periodic events 235 (Torrence and Compo, 1998). For each period, the average wavelet power spectrum 236 was calculated, identifying the averaged variance contained in all wavelet coefficients 237 of the same frequency. Furthermore, a 5% significance level was determined for WPS 238 through a bootstrapping scheme using a hidden Markov model, to assess whether 239 the wavelet-based quantities were due to just random processes (Cazelles and Stone, 240 2003). 241

Of particular interest is the fact that wavelet analysis allows the estimation of 242 the coupling between driver and response variables, as well as the level of synchrony 243 between them (Keitt and Fischer, 2006; Ménard et al., 2007; Buttay et al., 2017). 244 The wavelet coherence analysis (WCo) was applied to analyse the synchrony between 245 the zonal component of the current velocity (uvel; driver variable) and several model 246 state variables: salinity, NO₃ concentration and phytoplankton biomass (response 247 variables). Once identified the time scale at which the two non-stationary time series 248 were locally linearly correlated, their phases, for this time scale, were extracted and 249 compared (Cazelles et al., 2008). The phase difference between signals indicates 250 whether or not they are in synchrony; and if they are not, the time lag between them. 251

252 3. Results

²⁵³ 3.1. Spatial and temporal variability

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

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

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



Figure 4: Temporal evolution of the mean zonal component of the current velocity (uvel; 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.

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



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 (uvel; 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.

During both neap and spring tides, NO_3 concentration along the vertical section 299 parallel to the coast also displays a non-symmetric distribution (see left-hand panels 300 in Figure 6). Maximum values, between ~ 1.50 and 3.00 mmol m⁻³, are found at the 301 eastern side of the submarine ridge, mainly between 6.13 and 6.06 °W, concurrent 302 with the band of high salinity values (see left-hand panels in Figure 5). Like salinity, 303 this band of NO_3 -rich water presents the highest concentration values in the deeper 304 layers and during spring tides, when the intensity of the westward tidal current is 305 stronger. However, in contrast to salinity distribution, there is not an east-to-west 306 gradual decrease of NO_3 concentration since the lowest values are registered over the 307 shallowest area of Barbate High ($< 1.00 \text{ mmol m}^{-3}$). The superficial distribution of 308 NO_3 , at both tidal moments, shows a spot of relatively high NO_3 concentration (> 309 1.50 mmol m⁻³) around the location of the band of NO₃-rich water observed in the 310 vertical section (i.e., black circle on the right-hand panels in Figure 6). As with salin-311 ity, NO₃ surface distribution is affected by the cyclonic eddy. Thus, during neap tides, 312 when the current speed in the cyclonic gyre is low resulting in a weaker horizontal dis-313 persion, NO_3 concentration around the upwelling point is higher. Meanwhile, during 314 spring tides, when the current speed in the gyre is higher, increasing the horizontal 315 dispersion, NO_3 concentration around this point is lower. However, the presence of 316 a NO₃-rich tongue is not as clearly defined as the salinity tongue over Barbate High. 317 Moreover, along the coast from the Cádiz Bay to Barbate High, following the bathy-318

metric lines, we observe a fringe with minimum NO₃ concentration values (< 1.00 mmol m⁻³; Figure 6b, d).



Figure 6: Nitrate concentration (NO₃, 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 (uvel; 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. Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

Total phytoplankton biomass distribution along the vertical section (see left-hand 321 panels in Figure 7), shows a pattern quite different from the other state variables. 322 During both neap and spring tides, maximum phytoplankton biomass values appear 323 over the shallowest area of the ridge (> 0.70 mmol N m⁻³). During neap tides, high 324 biomass values are also observed in the most superficial layers of the water column to 325 the east side of the ridge (Figure 7a). The vertical distribution of total phytoplankton 326 biomass along the band between 6.13 and 6.06 °W, shows an opposite distribution to 327 salinity and NO_3 concentration, showing low phytoplankton biomass in the recently 328 uplifted waters (Figures 6 a, c and 6 a, c). Thus, low phytoplankton biomass is 329 observed at the deeper layers where NO_3 concentration is maximum, progressively 330 increasing to superficial layers at the same time that NO_3 concentration decreases (see 331 left-hand panels in Figures 6 and 7). The surface distribution of total phytoplankton, 332 at both tidal stages, shows a tongue over Barbate High characterised by high biomass 333 $(> 0.80 \text{ mmol N m}^{-3}; \text{ see right-hand panels in Figure 7})$ displaced to the east side 334 of the ridge due to the influence of the cyclonic eddy (Figure 7 b, d). This tongue 335 is richer in phytoplankton biomass during spring tides (Figure 7d) when the input of 336 NO₃-rich water is maximum (Figure 6 c). Moreover, phytoplankton biomass through 337

this tongue seems slightly higher close to the coastline extending from Cádiz Bay to Cape Trafalgar. Also, in the rest of the domain (mainly over the continental slope), phytoplankton biomass is higher during spring tides than during neap tides. This pattern is the opposite of the one observed for the NO₃ distribution, whose concentration over the continental shelf is slightly higher during neap tides than 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 (uvel; 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. Grey solid lines represent the bathymetry (10, 20, 30, 40 and 50 m depth). BH: Barbate High. CB: Cádiz Bay. TRF: Cape Trafalgar.

The sequential analysis of the vertical and superficial distribution of these three 344 variables shows how the band of saltier, NO₃-rich and with low phytoplankton biomass 345 water, as well as the cyclonic gyre and the tongue over Barbate High (and the sur-346 rounding waters), oscillate continuously from east-to-west due to the cyclical change 347 of direction of the zonal component of the tidal current. Thus, the 'water masses' in 348 the Trafalgar region are displaced to the east when uvel flows towards the Alborán 349 Sea (positive values), and to the west when uvel flows towards the Gulf of Cádiz 350 (negative values). Furthermore, these east-to-west-to-east oscillations are more or 351 less noticeable depending on the intensity of uvel. To better observe this oscillating 352 movement that is a consequence of the tidal cycle, and all its associated processes. 353 the reader is referred to the supplementary video that shows the computer simulation 354 of these variables for the first 3 months of the simulation (http://t.ly/bVQQ). 355

356 3.2. Hovmöller diagram

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

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

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

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



Figure 8: (a) Temporal evolution of the mean zonal component of current velocity (uvel; 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 (°C), (d) the Richardson number (R_i , adimensional), (e) nitrate concentration (NO₃, mmol m⁻³) and (f) total phytoplankton biomass (Phy, mmol N m⁻³).

³⁹⁶ NO₃ concentration also displays a fortnightly periodicity (Figure 8e). Only during ³⁹⁷ the most intense spring tides, NO₃-rich water seems to reach the surface layers. During ³⁹⁸ neap tides, NO₃ concentration throughout the water column is relatively low (<³⁹⁹ 1.00 mmol m⁻³). As with salinity and temperature, the NO₃ 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). Throughout the whole year, the lower NO₃ concentration values are observed from March to May (Figure 8e). While the maximum NO₃ concentrations are observed from July to October, coinciding with the period of highest stratification of the water column (Figure 8d). As a result, the nutrient-rich upwelled water is unable to reach the most superficial layers of the water column. The upwelling of less salty and nutrient-rich waters (compared with other upwelling events) supports the fact that during fall there is an upwelling of NACW in this region.

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

422 3.3. Wavelet power spectrum

We performed a wavelet power spectrum analysis of the time series shown in the Hovmöller diagram to extract information about the temporal variability of salinity, temperature, NO₃ concentration and total phytoplankton biomass. The WPS was computed using the hourly average values for each variable using their averaged values for the water column.

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



Figure 9: Wavelet analysis computed for the 1-year simulation. Left-hand panels: Wavelet power spectrum for (a) salinity, (c) temperature (°C), (e) nitrate concentration (NO₃, 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) NO₃ concentration and (h) total phytoplankton biomass. Dotted lines, at all panels, show the $\alpha = 5\%$ significance level computed based on 1000 Markov bootstrapped series.

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

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

The WPS for NO₃ concentration shows some strong but time-discontinuous peaks 457 at the \sim 15-day and \sim 30-day periodic components of the signal, but locally they 458 are not statistically significant (Figure 9e). However, the time-averaged WPS peaks 459 for these signal periods are statistically significant. The observed peak at \sim 15-day 460 explains $\sim 12\%$ of the total variance (Figure 9f). A weak time-discontinuous peak 461 that is statistically significant can be observed at the \sim 12-hour signal period (Figure 462 9e). This \sim 12-hour peak shows slightly stronger values during the more intense 463 spring tides and weaker during the less intense spring tides. At the \sim 1-day periodic 464 component, several peaks in the time domain are observed but only half of them are 465 statistically significant. According to the time-averaged WPS, neither the \sim 12-hour 466 nor the \sim 15-days periodic components are statistically significant (Figure 9f). 467

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

484 3.4. Wavelet coherence analysis

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



Figure 10: Wavelet coherence analysis computed for the zonal component of current velocity (uvel; $m s^{-1}$) versus (a, b) salinity, (c, d) temperature (°C), (e, f) nitrate concentration (NO₃, 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) NO₃, and (h) total phytoplankton biomass (blue lines). Dashed lines represent the phase difference between both signals.

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

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

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

Likewise, total phytoplankton biomass displays the strongest coherence with uvel at the \sim 15-day signal period, with a cross-spectrum power value that explains \sim 48% of the total variance (Figure 10g). The delay between both variables follows a pattern almost opposite to uvel and NO₃ concentration (Figure 10f). The response variable appears before the driver at the beginning and the end of the simulated year, with a mean delay of 0.71 days. While from April to October, the driver variable appears before the response variable, with a mean delay of 1.38 days (see Figure 10h).

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

534 4. Discussion

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

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

The high phytoplankton biomass observed over Barbate High (right-hand panels 553 in Figure 7), is favoured by the continuous and cyclical input of nutrients (e.g., Chen 554 and Beardsley, 1998; Hu et al., 2008; Ji et al., 2008; Blauw et al., 2012, 2018). Ac-555 tually, a previous study with a similar model configuration (Sánchez-Garrido et al., 556 2015) shows how a simulation with tidal forcing results in a chl concentration over 557 Barbate High ~ 3 times higher than in a simulation without tides. At the selected 558 location point for in-depth analysis of the upwelling dynamics, we observe that NO_3 559 concentration and phytoplankton biomass display an anti-phase behaviour (Figure 560 8d, e). The 'water masses' observed in this region (i.e., Trafalgar's tongue, upwelled 561 water) are continuously moving back and forth due to the fluctuations of the tidal 562 current intensity and direction (see Supplementary video – http://t.ly/bVQQ). The 563 pumping of NO₃-rich waters takes place when the tide flows towards the Gulf of Cádiz 564 while Trafalgar's tongue moves westward. Hence, at the analysed upwelling point 565 there is an uplifting of nutrient-rich water with relatively low phytoplankton biomass 566 and a low influence of the phytoplankton-rich Trafalgar's tongue. Nevertheless, when 567 the tide flows towards the Alborán Sea, there is no pumping of nutrient-rich water 568 and the phytoplankton-rich Trafalgar's tongue is advected eastwards on the analysed 569 upwelling point, and re-distributed along the whole water column. This coincides 570 with a maximum in phytoplankton biomass. This fact can be appreciated in Figure 571 11a, where mean NO_3 concentration and phytoplankton biomass computed for the 572 whole water column at the upwelling point (red circle in Figure 1b) over two tidal 573 cycles behaves oppositely. 574

The tide-topography interaction occurs during both neap and spring tides (Figures 575 5 and 6). However, during neap tides the water advection is weak, so the pumped 576 waters (slightly more saline and moderately rich in NO₃ than the surrounding waters) 577 do not reach the most superficial waters (Figure 8c). The intensity of the tidal 578 pumping of saltier, colder and NO_3 -rich waters depends on the tidal current speed, 579 being stronger and reaching the most superficial layers when the westward current 580 speed (towards the Gulf of Cádiz) is higher (Figures 5, 6, 8 b-d). In Figure 8 b-d, it 581 can be observed that the tidal pumping of saltier, colder and NO_3 -rich waters takes 582 place several days before uvel achieves its maximum speed during spring periods; 583 when the tidal current speed is strong enough to cause a significant upwelling of deep 584 waters. Figure 11b shows the temporal dynamics of the average uvel (m s^{-1}) and 585 salinity, computed for the whole water column at 6.11 $^{\circ}W$ - 36.06 $^{\circ}N$ (red circle in 586 Figure 1b) over two tidal cycles. It should be noted that the semi-diurnal tidal cycle 587 in Trafalgar, with two high tides and two low tides per day, shows a diurnal inequality 588 with one high-low tidal cycle more intense than the other. It also should be noted 589 that during a semi-diurnal tidal cycle, due to the expected time delay between the 590 maximum westward current flow (negative uvel) and the horizontal displacement of 591 the water mass (high tide), the maximum upwelling of salty waters is observed 2 - 3592 hours after the maximum flow. Thus, each peak of maximum salinity is caused by 593

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



Figure 11: (a) Temporal evolution of mean nitrate concentration (NO₃, 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 °W - 36.06 °N (red circle in Figure 1b).

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

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

For all the analysed variables, salinity, temperature, NO_3 concentration and total 619 phytoplankton biomass, the time-averaged WPS shows a peak at the fortnightly tidal 620 cycle, explaining $\sim 21\%$, $\sim 26\%$, $\sim 12\%$ and $\sim 21\%$ of the total variance respectively 621 (right-hand panels in Figure 9). Although the time-averaged WPS peak observed at 622 the \sim 15-day signal period for temperature is smaller than for salinity, it explains a 623 higher percentage of the total variance (Figure 9d). However, the local WPS analysis 624 shows statistically significant results for salinity at certain time periods of the simu-625 lated year but not for temperature (Figure 9 a and c), confirming that temperature is 626 not a good proxy to identify tidally driven upwelling events in this region. Salinity and 627 temperature are intrinsic properties of the upwelled water, and no biological activity 628 can alter them. However, upwelled nutrients may be assimilated by phytoplankton, 629 weakening the fortnightly periodicity component of NO_3 concentration, which would 630 explain the absence of statistically significant peaks in the WPS analysis (Figure 9e). 631 Furthermore, the lack of a statistically significant fortnightly periodicity component 632 may also be related to the lack of continuity in the upwelling events, which are less 633 intense during neap periods (Figure 8). In fact, the WPS analysis with daily aver-634 aged time series results in stronger fortnightly signals, statistically significant over 635 longer periods (data not shown). Supporting these findings, the WCo analysis be-636 tween state variables (drivers against responses) identifies the strongest statistically 637 significant covariation patterns at the fortnightly tidal period (see left-hand panels 638 in Figure 10). However, only in very few certain moments of the temporal domain, 639 the driver variable (uvel) is in synchrony with the response variables (i.e., salinity, 640 temperature, NO_3 concentration and total phytoplankton biomass). For most of the 641 year, the time delay between driver and response variables varies back and forth. Al-642 though the tidal-topography interaction is the main responsible for the temporal and 643 spatial variability in the Trafalgar region, it is not until the westward uvel reaches a 644 threshold value of $\sim 0.42 \text{ m s}^{-1}$ that deep water is pumped to the most superficial 645 layers. Moreover, the tidal cycle is also responsible for the horizontal displacement 646 of water masses that modifies the properties of the water column. Finally, the sea-647 sonal variability, the Gulf of Cádiz circulation pattern, and the wind regime will also 648 introduce changes (Vargas-Yáñez et al., 2002; Sala et al., 2018). Therefore, this asyn-649 chrony between driver and response variables is conceptually expected but difficult to 650 anticipate before performing the simulations, due to non-linearities in the dynamics. 651 The WCo analysis between uvel (as driver variable) against NO_3 concentration 652 and phytoplankton biomass (as response variables) shows an opposite pattern (disre-653 garding May) (Figure 10 f, h). When NO_3 oscillations appear later than the driver, 654 the phytoplankton biomass oscillations appear earlier than the driver, and vice versa. 655 In any case, the maximum of phytoplankton biomass must be a response to the pre-656 vious NO_3 tidal pumping. This is explicit in the primary production equations of the 657 ecosystem model used to perform these simulations. In the Cape Trafalgar region, 658

there seems to be always a phytoplankton community ready to assimilate nutrients when there is a new input. After a neap tide period with a minimum nutrient input

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

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

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

Finally, it is worth mentioning that several authors have described a secondary impact of the tidal cycle in the Strait of Gibraltar that would increase the primary production in the Alborán Sea. Due to the velocity divergences developed in the surface layer when undulatory features are generated over the Camarinal Sill, a lateral advection of patches with high chl-*a* concentration was observed from coastal areas to the centre of the Strait (Macias et al., 2006; Vázquez et al., 2009; Ramírez-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

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

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

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

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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.

AppendixA. 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, $^{-1}$ C) climatology derived from remote sensing images corresponding to the period 2001 - 2010. (b) Model-derived climatology of SST for the 3^{rd} -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.

AppendixB. 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:

$$R_{t} = R_{max} - (R_{max} - R_{min}) \cdot (\frac{I_{max} - I_{t}}{I_{max} - I_{mix}}),$$
(C.1)

R represents the C:Chl ratio. R_{max} and $R_m in$ 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 (uvel; 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.



Figure D.2: Nitrate concentration (NO₃, 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 (uvel; 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. 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 (uvel; 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.



AppendixE. 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 (u10, 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 u10 reference delimiting positive (negative) values that indicate westerly (easterly) winds.

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