

**Françoise Meyer**

**Two weeks of vertical profiles on the inner shelf of the  
northern margin of the Gulf of Cadiz: what do they say  
about the ecosystem?**



**UNIVERSIDADE DO ALGARVE**

Faculdade de Ciências e Tecnologia

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about the ecosystem?**

**Master of Marine and Coastal Systems (MaCS)**



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**UNIVERSIDADE DO ALGARVE**

Faculdade de Ciências e Tecnologia

2023

## **Declaration of Authorship of Work**

Declaration of Authorship of “Two weeks of vertical profiles on the inner shelf of the northern margin of the Gulf of Cadiz: what do they say about the ecosystem? “.

I, Françoise Meyer, declare I am the author of this work, which is original and unpublished. Authors and works consulted are properly cited in the text and are included in the listing of references.

Françoise Meyer

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## Abstract

The inner continental shelf is a favourable environment for primary productivity due to its shallow water column, light and nutrient availability. Its environment is both ecologically and commercially important as it is suitable not only for photosynthetic primary producers but also for aquacultures, yet seldom studies are focused on the complex inner shelf dynamics. This study proposed an insight into the relationship between physical forcings occurring at the inner shelf and the base of its ecosystem, phytoplankton. The study site was at an artificial reef at the inner shelf of the Northern Margin of the Gulf of Cadiz, South Portugal, during 12 consecutive days in the spring 2022. Multiple datasets were used for comparing changes in wind, currents, and water properties. High resolution vertical profiles (2Hz, ~120 profiles/hour) were recorded from an automated wave-powered profiler (Wirewalker) deployed at the reef, monitoring physicochemical (temperature, salinity, turbidity, dissolved oxygen) and biological properties (chlorophyll-a, Chl-a) of the shallow water column (< 15 m). The set of *in-situ* data was analysed along with sea surface temperature and Chl-a satellite imagery, wind (ERA5 Reanalysis), and current (Acoustic Doppler Current Profiler). The results show 3 oceanographic events occurring during the deployment: coastal counter current (CCC), upwelling, and a current inversion. High seasonal spring Chl-a concentrations (~4 mg m<sup>-3</sup>) were observed during CCC and flow inversion to a westward flow, under periods of low intensity winds (< 5 m s<sup>-1</sup>), reduced current (< 0.2 m s<sup>-1</sup>) and thermal stratification of the water column. During upwelling, Chl-a was ~2 times lower (1.5 mg m<sup>-3</sup>), with stronger wind and an increased eastward flow (0.4 m s<sup>-1</sup>). Overall, the dominant alongshore current was eastward, except during the lowest wind stress period, during which the current turned westward from the bottom for 20 hours, suggesting the presence of a background alongshore pressure gradient. The analysis revealed the rapid changes in the phytoplankton biomass and its dynamics at the inner-shelf, dependent also on cross-shore exchanges, and the potential isolation from other parts of the shelf during the upwelling flow, limiting primary production development, as found in other areas, e.g., the South Californian bight, during upwelling and downwelling conditions.

**Keywords:** Inner shelf – Phytoplankton variability – Coast counter current – Coastal upwelling – Current inversion

## Sumário

O fitoplâncton está na base dos ecossistemas marinhos, transferindo energia para níveis tróficos superiores, até às populações de peixes e mamíferos marinhos. Compreender a flutuação da sua densidade é uma informação fundamental para a gestão das pescas, a aquacultura e a gestão costeira, assim como a previsão de potenciais florescências de algas nocivas. Presentes em todos os tipos de ambientes marinhos, desde o oceano aberto até às águas costeiras pouco profundas da plataforma continental interna, a distribuição temporal e especial destes organismos unicelulares é sensível às alterações oceanográficas, tais como os ventos, as correntes oceânicas, a estratificação térmica da água, a ressurgência, a turbulência e as concentrações de nutrientes inorgânicos. Em ambientes tão dinâmicos como a plataforma interna, a interação destas forças altera-se rápida e drasticamente. O ambiente associado a uma elevada disponibilidade de nutrientes provenientes da costa, com penetração da luz em toda a coluna de água até ao fundo marinho e condições de turbulência baixa longe da rebentação das ondas é favorável ao desenvolvimento do fitoplâncton

Esta tese teve como objetivo analisar um conjunto de alta resolução de dados físicos, químicos e biológicos adquiridos durante quase duas semanas, registados *in-situ* num recife artificial na plataforma interna da Margem Norte do Golfo de Cádiz (NMGoC). O conjunto de dados excepcionalmente finito permitiu a observação das variações da biomassa fitoplanctónica, através da concentração de clorofila-a (Chl-a) usada como proxy, durante eventos oceanográficos de relaxamento da afloramento costeiro, afloramento costeiro e inversão da corrente. Os dados foram registados por um perfilador vertical automático fundeado no recife artificial de Cacela Velha, a ~7 milhas náuticas da costa, a oeste da foz do rio Guadiana. Durante 12 dias em abril de 2022, foram registados a cada hora ~120 perfis verticais da coluna de água pouco profunda (> 15 m). Durante este período de primavera, as imagens de satélite da temperatura da superfície do mar (L2 Aqua Modis e VIIRS-SNPP) e da clorofila-a (L3 VIIRS-SNPP) permitiram detetar, respetivamente, águas quentes e elevada concentração de clorofila-a e águas frias com menor biomassa de fitoplâncton ao longo da NMGoC. Para associar as características oceanográficas aos dados adquiridos pelo do perfilador, foi recolhido *in-situ* um conjunto de dados de medições de correntes com um perfilador acústico de correntes Doppler (ADCP) a cerca de 24 km a oeste do recife artificial na plataforma interna. Para medir

a influência dos ventos locais na variável concentração de fitoplâncton, foram recolhidos registos de vento do conjunto de dados da reanálise ERA5 "ERA5 hourly data on pressure levels from 1940 to present", uma base de dados do Copernicus que combina a reanálise de medições e modelos *in-situ*, melhorada pela assimilação de dados. Dada a natureza dos conjuntos de dados, observou-se uma distribuição não-Gaussiana e os diferentes parâmetros foram correlacionados utilizando o teste de correlação de Spearman.

Os resultados mostraram três eventos oceanográficos distintos com impacto na variação da concentração de fitoplâncton - um evento de relaxamento de afloramento de 5 dias (também designado por Contra-Corrente Costeira, CCC), um evento de afloramento de 6 dias e uma inversão de corrente costeira de 20 horas após o afloramento - foram sinónimo. As concentrações mais elevadas de Chl-a ( $3-4 \text{ mg m}^{-3}$ ) foram observadas durante a CCC e a inversão de corrente costeira, enquanto as concentrações durante a ocorrência de um evento de afloramento ( $< 1,5 \text{ mg m}^{-3}$ ) foram observados em simultâneo com águas mais frias e menos salinas afloradas, transportadas para oeste ao longo da costa sul portuguesa. Durante os períodos de afloramento, o fluxo de corrente foi mais forte (62.5%) e foi acompanhado por ventos mais fortes de norte ( $6-12 \text{ m s}^{-1}$ ). Enquanto a corrente foi reduzida durante a CCC, uma estratificação intermitente induzida pela radiação solar surgiu à superfície e afundou até ao fundo do mar ao meio-dia. Curiosamente, a concentração de Chl-a foi sempre mais elevada durante a tarde, sob os estratos de água mais quentes. A maior concentração a este nível pode dever-se à migração vertical do fitoplâncton a fim de evitar a fotoinibição solar durante a exposição solar do meio-dia. Outro fenómeno ocorreu durante os períodos de relaxamento de afloramento costeiro, à medida que a superfície da água aqueceu, ocorreram mudanças diurnas na direção do vento, de oeste matinal para norte vespertino. Dada a orientação da costa perto do recife artificial (virada a noroeste), a brisa terrestre da tarde, induzida pela diferença de aquecimento terra/oceano, poderia promover o transporte de fitoplâncton perpendicular à costa. O caso da inversão de corrente de 20 horas, no dia 25 abril, que ocorreu após o afloramento mostrou concentrações semelhantes de Chl-a elevadas como durante a CCC, no entanto, desta vez, a corrente para oeste induziu a presença de maior biomassa de fitoplâncton, bem misturada ao longo de toda a coluna de água. O fluxo inverso começou no fundo durante os períodos de menor intensidade do vento ( $< 4 \text{ m s}^{-1}$ ). A água advectada pode ter transportada uma elevada concentração de fitoplâncton presente nas proximidades do rio Guadiana. No

entanto, durante a instalação do perfilador vertical, os níveis de caudal do rio foram muito baixos ( $< 10 \text{ m}^{-3} \text{ s}^{-1}$ ), o que sugere que a principal fonte de fitoplâncton não será causada por níveis elevados de nutrientes provenientes do rio, mas sim da advecção de níveis elevados sazonais de Chl-a (florescência primaveril) junto desta zona, alternados com a baixa concentração de Chl-a a medida durante o período anterior, de afloramento costeiro.

Esta análise de dados alta frequência, num prazo de quase duas semanas, relativa aos eventos oceanográficos permitiram avaliar resposta da biomassa fitoplanctónica a estes processos na plataforma interna do NMGoC. As condições preferenciais envolveram uma redução dos ventos e da corrente dominante de leste que permitiram uma estratificação térmica diurna da água, e conseqüentemente uma redução da turbidez da água, um tempo de residência mais longo para o desenvolvimento do fitoplâncton, enquanto as ocorrências de brisa terrestre durante a tarde permitiram também um transporte perpendicular à costa com mistura do fitoplâncton ao longo da coluna de água.

**Palavras-chave:** Plataforma interna - Variabilidade do fitoplâncton - Contracorrente costeira - Ressurgência costeira - Inversão de correntes.

## Table of contents

<b>DECLARATION OF AUTHORSHIP OF WORK .....</b>	<b>I</b>
<b>COPYRIGHT ON BEHALF OF FRANÇOISE MEYER AND THE UNIVERSITY OF THE ALGARVE .....</b>	<b>II</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>III</b>
<b>ABSTRACT.....</b>	<b>IV</b>
<b>SUMÁRIO .....</b>	<b>V</b>
<b>TABLE OF CONTENTS .....</b>	<b>VIII</b>
<b>TABLE OF FIGURES.....</b>	<b>XI</b>
<b>TABLE OF TABLES.....</b>	<b>XIII</b>
<b>CHAPTER 1: GENERAL INTRODUCTION.....</b>	<b>1</b>
1.1 Motivation for the topic .....	1
1.1.1 The inner shelf dynamics.....	1
1.1.2 The under documented artificial reef of Cacela.....	1
1.1.3 The effects of coastal currents on biological activity	2
1.2 Objectives .....	3
1.3 Master thesis' Structure .....	3
1.4 State of the art review .....	4
1.4.1 Inner-shelf studies.....	4
1.4.2 Northern margin of the Gulf of Cadiz studies .....	5
Sea surface circulation .....	5
Coastal counter-currents characterisation.....	6
Bio-physical interaction at the inner-shelf.....	6
Sediment transport of the inner-self .....	7
1.4.3 Innovative data collection Equipment .....	8
1.5 Case study settings.....	10
1.5.1 Satellite imagery .....	10

Sea Surface Temperature .....	10
Chlorophyll-a .....	12
1.5.2 In-situ data sources investigation.....	12
Sea surface temperature .....	12
Surface currents .....	13
1.5.3 Notes on dataset processing.....	13
References.....	14

**CHAPTER 2: SCIENTIFIC ARTICLE MANUSCRIPT TO BE SUBMITTED. 19**

Abstract.....	20
2.1 Introduction.....	21
2.2 Data and methods.....	24
2.2.1 Datasets: Wind, Current and water properties .....	24
ECMWF Reanalysis v5 (ERA5 Reanalysis) .....	24
Acoustic Doppler Current Profiler (ADCP) .....	24
Automated vertical profiler: the Wirewalker.....	25
2.2.2 Pre-processing.....	25
2.2.3 Data processing.....	26
Water column density computation .....	26
Water column stratification .....	27
Statistical testing: variables correlations .....	27
2.3 Results.....	29
2.3.1 NMGoC circulation setting.....	29
2.3.2 Physical forcings.....	30
Wind .....	30

	Alongshore current .....	31
2.3.3	Vertical Profiler .....	33
	Physical parameters .....	33
	Density and stratification .....	34
	Chemical and biological parameters.....	34
2.3.4	Correlations between parameters.....	37
2.4	Discussion.....	41
2.4.1	Oceanographic context .....	41
	Water masses thermohaline signature .....	41
	Inner-shelf circulation.....	42
	Local wind and thermal circulation at the inner-shelf .....	44
2.4.2	Phytoplankton biomass fluctuations .....	46
	Phytoplankton signature response to oceanographic changes .....	46
	Diurnal phytoplankton biomass variability .....	50
	Phytoplankton and cross-shelf transport.....	53
2.5	Conclusion .....	55
2.6	Acknowledgments.....	56
2.7	Data availability .....	56
	References.....	57
	<b>CHAPTER 3: CONCLUSIONS .....</b>	<b>68</b>

## Table of figures

Figure 1-1. The 7 Artificial reefs implemented between 1990 and 2000 along the coast of the Algarve, Portugal. Map adapted from Monteiro & Santos (2000). The orange circle indicates the location of the Cacela reef. ....	2
Figure 1-2. The Wirewalker profiler and its set up (source: <a href="https://www.delmarocean.com/ww-how-it-works">https://www.delmarocean.com/ww-how-it-works</a> ).....	9
Figure 1-3. Daily sea surface temperature satellite images from NASA World Viewer (L2 AQUA-MODIS and L2 Terra-MODIS) at the NMGoC (13-25.04.2022). ....	11
Figure 1-4. ERA 5 daily SST at the nearest point to the vertical profiler at the Cacela reef (14-26 April 2022).....	11
Figure 1-5. Daily satellite images of surface Chlorophyll-a concentration (L2 AQUA-MODIS and SPP-VIIRS) at the NMGoC (14-27 April 2022).....	12
Figure 2-1. Maps of the study area, southeast NMGoC, Sea Surface Temperature from L2 Aqua Modis and L2 Terra-MODIS the 15.04.22 (a), the 20.04.22 (b), and location of the in-situ monitoring equipment (c). Key location: Cape Santa Maria (CSM), Gu (Guadiana River), vertical profiler and artificial reef location (WW, for Wirewalker), and the town of Cacela Velha (CV).	23
Figure 2-2. Monthly composite satellite images from NASA Oceancolor Aqua-Modis Level 3 for chlorophyll-a (Chl-a) at the Northern Margin of the Gulf of Cadiz (March - April 2022) processed with Mirone software. Key reference locations are marked: Cape St. Vincent (CSV), Cape St. Maria (CSM) and Gu (Guadiana River). ....	29
Figure 2-3. Wind rose from ERA5 hourly wind at Cacela Velha artificial reef (14-26 April 2022). ....	30
Figure 2-4. Stick plot of hourly ERA5 Wind at the location of the vertical profiler 14-26 April 2022. The direction of the wind reads "from" the corresponding cardinal point. Here mainly from North and North-west. ....	31

Figure 2-5. Time series of (a) the Alongshore, (b) Cross-shore current from the ADCP at Armona in April 2022. Positive values in figure (a) represent north-eastward flow, and negative values, the south-westward flow. For figure (b), positive values represent the flow going towards the shore (north-westward), and negative values the flow going offshore (south-eastward). Depth here is expressed as increasing away from the bottom mounted ADCP..... 32

Figure 2-6. Time series of *in-situ* parameters through the water column (14-26 April 2022, Cacela Velha artificial reef). In order: Conservative temperature, Absolute Salinity, Turbidity, Chlorophyll-a, Dissolved Oxygen (DO), Brunt Väisälä frequency (N) and density ( $\rho$ ). ..... 36

Figure 2-7. Correlation heatmaps of *in-situ* parameters from the vertical profiler during (a) total observation period (14-26 April), (b) costal counter-current (14-18 April), (c) upwelling (19-24 April), and (d) flow inversion (25 April).  $R^2$  between parameters are presented (all  $p < 0.01$ ). The parameters correspond to: (CT) Conservative Temperature, (Sa) Absolute Salinity, (Chl-a) Chlorophyll-a, ( $\rho$ ) Density, (Osat) Dissolved Oxygen Saturation, (Tu) Turbidity..... 39

Figure 2-8. Time series of the mean alongshore current velocity on 25<sup>th</sup> April 2022 at the Armona ADCP. Data points are represented per hour by cells of 0.5 m. The blue sticks indicate north-eastward flow and the red arrows a south-westward flow. The dataset is represented de-tide, filtered with a Lanczos-window Cosine Filter (40 h cut off frequency)..... 44

Figure 2-9. T-S-Chl-a diagram of the vertical profiler deployment (14-26 April 2022). Three dotted ellipses show the water masses and chlorophyll-a concentration during different oceanographic events: CCC (red), upwelling (blue), and current inversion (pink). The black lines represent the isopycnic lines expressed in  $g\ cm^{-3} - 1000$ ..... 48

Figure 2-10. Daily time series at the Cacela Velha reef of local wind, buoyancy frequency, Density and Chlorophyll-a for: (a) 17<sup>th</sup> of April under CCC, and (b) 25<sup>th</sup> of April under current inversion. .... 51

## Table of tables

Table 2-1. Details on the loggers and their respective recorded parameters on the vertical profiler at the Cacela Velha reef deployment in April 2022.....	25
Table 2-2. Physical forcings speed ( $\text{m s}^{-1}$ ), Chl-a ( $\text{mg m}^{-3}$ ) and Osat (%) correlations during changing oceanographic features. All values have a corresponding p value $< 0.001$ , unless specified. ....	40

# Chapter 1: General Introduction

## 1.1 MOTIVATION FOR THE TOPIC

### 1.1.1 THE INNER SHELF DYNAMICS

The interest in this topic lied in acquiring a greater knowledge of oceanographic processes occurring within the continental inner-shelf and their effect on the local ecosystem. The inner shelf is defined as the submerged coastal zone offshore of the surf zone and extends to the mid-shelf. It is the region further defined vertically by the overlap of the water column surface and bottom layers (Grant & Madsen, 2003). The surface layer is subject to wind friction and the bottom layer to bottom friction, induced by variable processes (Fewings et al., 2008). The wide range of processes, from the breaking action of surface gravity waves to the Ekman transport, sways the water circulation and biological activity (Sánchez et al., 2006). Among the inner shelf's frequently cited processes are wind induced surface drift, upwelling or downwelling events, internal waves, tides, thermally induced stratification, momentum exchange, and sediment fluxes originating from rip currents. While the surf zone and the mid to outer shelf have been the subject of numerous studies, the transiting region of the inner shelf, with its complex dynamics, has not (Kumar et al., 2021).

### 1.1.2 THE UNDER DOCUMENTED ARTIFICIAL REEF OF CACELA

In this case study, measurements of the water column's physical, chemical, and biological properties have been monitored ~7 nautical miles southwest of Vila Real de Santo António, on a wider part of the continental shelf fringing the southwest border of the Iberian Peninsula. The analysis of physical processes, as bottom control of primary producers, is particularly valuable as the deployed vertical profiler measured the changing processes during the recognised upwelling season at the location of an artificial reef system (Leitão et al., 2019; Ruiz & Navarro, 2006). The reef, offshore from Cacela Velha, is one of the 7 artificial reefs created off the coast of the Algarve (Fig. 1-1). Concrete modules were used to build the reef system: small modules (2.7 m<sup>3</sup>) and large modules (174 m<sup>3</sup>) (Boaventura et al., 2006). Although placed in 1990 by the Portuguese Institute of Marine Research (IPIMAR) – presently the Portuguese Institute for the Sea and Atmosphere (IPMA), the artificial reef system of Cacela, has had little to no reviews on its yielding. Many studies focused on the reefs near Faro and Olhão. This thesis initiated the analysis of oceanographic

data at the location of the Cacela reef. It may bring insight into the coastal processes and their possible impact on the bottom food chain of the reef's ecosystem.

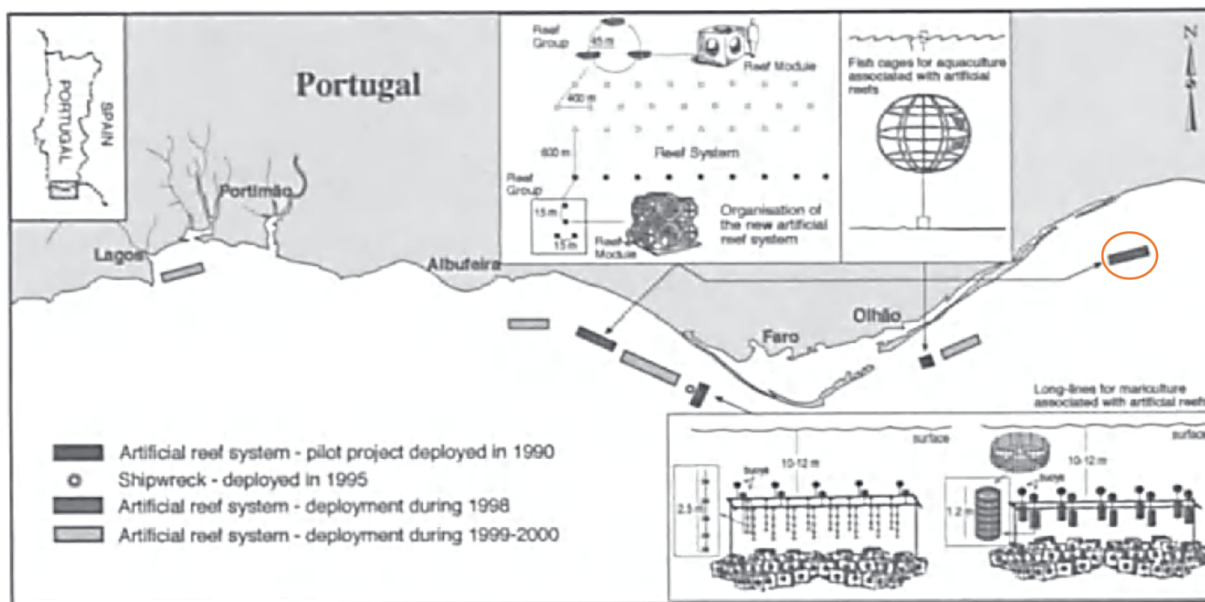


Figure 1-1. The 7 Artificial reefs implemented between 1990 and 2000 along the coast of the Algarve, Portugal. Map adapted from Monteiro & Santos (2000). The orange circle indicates the location of the Cacela reef.

### 1.1.3 THE EFFECTS OF COASTAL CURRENTS ON BIOLOGICAL ACTIVITY

Another motivation for the topic was the added knowledge on the influence of Coastal Counter Currents (CCC) on the inner-shelf's ecosystem at the Northern Margin of the Gulf of Cadiz (NMGoC). Indeed, it is still relatively unknown in terms of chemical and biological impact, unlike the upwelling mechanism of the region. The CCCs have been characterised on the South Coast of Portugal as broadly westward coastal currents or the relaxation of broadly eastward upwelling currents. These currents occur when upwelling-favourable winds relax – westerlies at the South Coast - or reverse – easterlies or Leventer (de Oliveira Júnior et al., 2021, 2022; Garel et al., 2016; Relvas & Barton, 2002; Sánchez et al., 2006; Teles-Machado et al., 2007). The coastal flow of the NMGoC is described in literature as alternating between warm CCC and cold eastward nutrient rich upwelled currents. Therefore, the currents translate into colder and warmer events of Sea Surface Temperature (SST), typical of respectively upwelling and downwelling conditions (Garel et al., 2016; Cravo, 2010). Although the coastal surface water circulation has been widely

researched, there is a need for subsurface measurements to understand the reactivity of the inner-shelf ecological and biogeochemical processes altered by these environmental changing factors, *i.e.*, CCCs (Lucas et al., 2011; Washburn & McPhee-Shaw, 2013).

The high-resolution measurements recorded from the vertical profiler for 12 days in April 2022 offered an opportunity to further complete the characterisation of CCCs with their possible interaction with biological and chemical processes, and the implications on the phytoplanktonic activity of the inner-shelf during upwelling spring times.

## 1.2 OBJECTIVES

The goals for this research master thesis were to better understand the intrinsic relation between the physical forcings of the coastal circulation, and their impact on phytoplanktonic development at the inner-shelf. Here the key information recorded by a vertical profiler were the variables of chlorophyll-a (Chl-a) and dissolved oxygen (DO) concentration, as a proxy for primary producers' biomass (Huot et al., 2007; Lorenzen, 1967), in relation to temperature (T), salinity (S) and turbidity (Tu). The analysis compared these subsurface measurements along with current and local wind measurements to get an insight into the functioning at the base of the ecosystem.

This study provided further analysis characterising natural coastal events that occur on the inner-shelf off South Portugal, namely the effect of CCCs (westward flow) and upwelling (eastward flow) on the bottom-up control of ecosystems. These events have been characterised from a physical (Sánchez et al., 2006) and chemical standpoint (Cardeira et al., 2013; Cravo et al., 2013) but further research on the subject is needed.

## 1.3 MASTER THESIS' STRUCTURE

This master thesis is presented under the format of a manuscript-type journal article. Its structure follows guidelines applicable for the deliverance of a PhD proposal adapted to the requirements of a master thesis. Hence, the thesis is divided in chapters. Chapter 1 corresponds to a general introduction, with the motivations for the topic, a state-of-the-art review, and additional

case study setting details (such as further information on the equipment the *in-situ* data is from). Chapter 2 is a scientific article, proposed to be submitted using the data from the thesis, and Chapter 3 presents the overall conclusions of the thesis. The references are included for each respective chapter.

The formatting of the article manuscript was tailored for a publication to a continental shelf specialised journal. The scientific journal publishes articles focused on research conducted within the shallow marine environment, for coastal and estuarine waters to the shelf break. This study falls within the scopes the journal focuses on: Interactions between physical dynamics (waves, currents, mixing, etc.) and biogeochemical cycle; and benthic, phytoplankton and zooplankton ecology. Furthermore, an important angle to consider that influenced the formatting of the manuscript is the emphasis on the broad, international, and inter-disciplinary character of their readers. As a result, it is worth noting that the style of the manuscript has been directed with this focus.

## 1.4 STATE OF THE ART REVIEW

### 1.4.1 INNER-SHELF STUDIES

Comprehensive research studies on the circulation and the interaction of processes on inner-shelves are scarce. In 2017, the Inner-Shelf Dynamics Experiment (ISDE) was conducted off the Californian coast as an extensive inner-shelf's processes characterisation project. The experiment incorporated in-situ measurements, satellite images and numerical models. The inter-connection between physical parameters of the inner-shelf is complex, and an attempt to describe a spatial heterogeneity of inner-shelf's properties has been described in the ISDE study of the Californian coast (Kumar et al., 2021). In the same context, but in a much more restricted study, this thesis provided insights into the correlation of physical, chemical, and biological parameters with a short time and local scale.

Both part of Eastern Boundary Upwelling Systems (EBUS), the Portuguese and Californian coastal processes are often discussed in a similar manner, also when comparing the processes of the South Coast of Portugal and the South Californian bight, due to their somewhat similar South facing coastal tilt and topography. The processes at the inner shelf, as the cross-shelf circulation

of the South Californian System has been studied (Fewings et al., 2008; Horwitz & Lentz, 2014; Kumar et al., 2021; Lentz & Fewings, 2012; Washburn & McPhee-Shaw, 2013; Wu et al., 2021), as well as the alongshore circulation (Feddersen et al., 2020; Kumar et al., 2021; Lentz & Fewings, 2012), and from a biological standpoint (Goodman et al., 2012; Lucas et al., 2011; Washburn & McPhee-Shaw, 2013). Studies at the Portuguese southern coast observes similar circulation patterns, as mentioned in detail in the following subsection.

#### 1.4.2 NORTHERN MARGIN OF THE GULF OF CADIZ STUDIES

##### SEA SURFACE CIRCULATION

The surface water circulation at the NMGoC, South Portugal, has been extensively researched (Criado-Aldeanueva et al., 2006; de Oliveira Júnior et al., 2022; García-Lafuente et al., 2006a). The water flow is influenced by broad scale circulation, with the Canary Current Upwelling System to the West boundary, and the exchange through the Strait of Gibraltar to the East. At the inner shelf, these large-scale processes are mitigated by regional winds and the presence of the seafloor, that influence upwelling events and mesoscale structures (Criado-Aldeanueva et al., 2006; García-Lafuente et al., 2006a; Relvas & Barton, 2002; Sánchez et al., 2007).

Along the South Coast of Portugal, the upwelling mechanism and seasonality has been broadly investigated under different viewpoints (Cardeira et al., 2013; Correia et al., 2020; Cravo et al., 2013, 2014; Fiuza, 1983; Leitão et al., 2019; Relvas & Barton, 2002, 2005; Rosa et al., 2019). Off the western Iberian coast, the seasonality of the wind-induced processes is broadly divided into upwelling (spring-summer) and a non-upwelling season (autumn-winter), due to the interplay of the Azores high and the Iceland low pressure cells, whose location and intensity determine the wind regime. Off the southern coast, this regime is distorted. The equatorward cold flow (EF) associated to upwelling off the western coast, overshoot the Cape São Vicente and progress eastward along the shelf break, often mixed with local upwelled water (Relvas and Barton, 2002). Although eastward, this flow is seen as an equatorward flow (EF) due to its continuity with the west coast flow. However, a contrasting warm costal counter current (CCC) pattern, flowing westward (assumed to be poleward, PF) interleaves with the equatorward flow (Sánchez et al., 2006) for more than 40% of the time, without noticeable seasonality (Garel et al., 2015). The development of the EF along the NMGoC results from the geostrophic adjustment to the upwelling

of cold subsurface Eastern North Atlantic Central Water (ENACW) (Fiuza, 1983; Wooster et al., 1976) along the coast and consequent offshore Ekman transport. With irradiance increase throughout the water column and mixing from reduction of the bathymetry, ENACW becomes Surface Atlantic Water (SAW) on the continental shelf (Navarro et al., 2006).

The study focused on the inner-shelf at the Eastern part of the Gulf of Cadiz, East of Cape Santa Maria, where the *in-situ* measurements were taken. The location, although at shallow depth, close to the coast, follows the water mixing of SAW influenced by the coastal flow and mixing of modes water, the tides, the shallow bathymetry and the interaction with the seabed and the surface, and thermally induced stratification. To compliment the knowledge of the sea surface circulation of the inner-shelf, this thesis study provided observations on the influence of these horizontal circulation events on the vertical mixing of a shallow water column.

#### COASTAL COUNTER-CURRENTS CHARACTERISATION

CCCs are generated by a background alongshore pressure gradient (Garel et al., 2016). The counterflow to the eastward equatorward current develops during upwelling relaxation events, when the alongshore pressure gradient becomes unbalanced (de Oliveira Júnior et al., 2021; Teles-Machado et al., 2007). On a weekly basis, without seasonality, warm surface waters are carried westward along the south coast of Portugal. These poleward flows are associated with downwelling events (Garel et al., 2016). On occasions, the flow turns clockwise around Cape São Vicente along the west coast (Fiúza et al., 1982; Relvas and Barton, 2002). The counterflow is intensified during wind forcing from the East (Levanter) (Teles-Machado et al., 2007).

The study of CCCs has however been focused on physical characterisation and requires complementary research. As upwelling events have been under the “radar” for their importance on the primary productivity, the downwelling conditions associated with CCCs are inversely meaning of lower nutrients availability, possibly limiting phytoplankton growth at the NMGoC (Navarro & Ruiz, 2006).

#### BIO-PHYSICAL INTERACTION AT THE INNER-SHELF

The relation between the concentration of chlorophyll-a (Chl-a) pigments, as a proxy of phytoplankton biomass (Lorenzen, 1967), and meteorological settings has been thoroughly researched for the continental shelf via satellite images and oceanographic cruises along the coast (Cravo et al., 2013; Navarro & Ruiz, 2006; Ruiz & Navarro, 2006), as well as their influence on

the productivity of the bottom of the food chain (Prieto et al., 2009). In an extensive study analysing the highest phytoplanktonic productivity in respect to physical settings (Navarro et al., 2006), the bio-physical relationship of the Gulf of Cadiz was characterised. Generally, coastal filaments of upwelled water are temporarily linked with low concentration of Chl-a ( $< 1 \text{ mg m}^{-3}$ ), followed by increase concentration during upwelling relaxation, during which favourable conditions due to a reduced current flow promote phytoplankton development (Cardeira et al., 2013; Cravo et al., 2010). Zooming to the scale of the inner-shelf, further study of the vertical mixing from causal physical forcings, and their chemical characterisation is needed (Cardeira et al., 2013). Some studies have been carried out in the Californian inner shelf, on the effect of cross-shelf and alongshore transport (Goodman et al., 2012; Lucas et al., 2011; Washburn & McPhee-Shaw, 2013), but further studies at the southern Portuguese inner-shelf would add further insight on the regional mechanisms.

#### SEDIMENT TRANSPORT OF THE INNER-SELF

The deposition of sediment on the inner-shelf plays an important role in establishing the equilibrium of shallow depth aquatic ecosystems. The sediment composition, texture and its turbidity in the water column influence the growth and diversity of both, pelagic and benthic communities of primary producers (Dolbeth et al., 2007). At the location studied, the sediment composition of the inner-shelf is known to be medium to coarse sand (Dolbeth et al., 2007; Rosa et al., 2013).

Influence from the Guadiana River has been recorded at the 10 m isobath, near the deployment site, with the highest concentration of suspended particulate matter (SPM) and nutrients during winter periods under and high river outflow ( $> 100 \text{ m}^3 \text{ s}^{-1}$ ) (Cravo et al., 2006). The river is situated roughly 11 km ( $\sim 6 \text{ nm}$ ) northeast from where the *in-situ* measurements were taken. This means that the impact of the river outflow on the study area might be felt in terms of phytoplankton biomass if the Guadiana River flow had been high during the study.

Monitoring the rapid changes in the water column physical and chemical composition to analysis the interplay with phytoplankton fluctuations requires high resolution and accuracy *in-situ* measurements. Here, the analysis was made possible owing to the deployment of an automated equipment that could monitor the seawater continuously for almost two weeks. The equipment's specifics are detailed in the following subsection.

### 1.4.3 INNOVATIVE DATA COLLECTION EQUIPMENT

The Wirewalker (WW) vertical profiler, used for the collection of data, was the first of its kind moored along the Portuguese coast. Short and long period variability of the characteristics of the coastal ocean through several oceanographic parameters were continuously recorded along the water column for 12 days. The inexpensive autonomous equipment allows for short- and medium-term deployments with high resolution dataset collection (Rainville & Pinkel, 2001).

Its implementation was part of the EMSO-PT (European Multidisciplinary Seafloor and water column Observatory) project aimed to promote knowledge of the functioning of the ocean off Europe and the coastal zones and to assess the consequences of climate change on the structure of the water column. It was part of the EMSO - European Research Infrastructure Consortium (ERIC). The objective of the cooperative initiative being the establishment of a permanent ocean observatory, including the "Iberian Margin node", one of the several observatories along the European coast.

In preparation for longer monthly deployments at greater depths off the Southwest Coast of Portugal on the continental platform off Cape St. Vincent (~200 m deep), the WW was deployed at the Cacela artificial reef on the inner-shelf (Fig. 1-1). The recording time of the WW was from the 14.04.2022 at 18:00:05s to the 26.04.2022 at 17:58:08s.

Ocean waves power the profiling instrumentation-platform (Fig. 1-2). Once deployed, the sensors mounted on the profiler continuously recorded several oceanographic parameters (Temperature (T), Salinity (S), Turbidity (tu), Chlorophyll-a (Chl-a), Dissolved Oxygen (DO), and Pressure (p)) along the water column. Being an autonomous device, it represents an invaluable source of data to draw the simultaneous changes in the physical-chemical-biological environment. With a buoyant ascent rate of about  $0.4 \text{ m s}^{-1}$  during the deployment, in such shallow waters (< 15 m), ~120 profiles per hour were retrieved.

The profiler (Fig. 1-2) was composed of:

- a surface buoy: equipped with real-time satellite GPS tracking
- a profiling wire: linking the surface buoy to the down-weight on the seafloor. This wire transmits surface wave energy through its mechanical ascending/descending motion in contrast with the surrounding water.
- the profiler: with the cam mechanism driving the profiler downward through wave action to the end of the profiling wire, at which point the cam releases, allowing the profiler to float freely up to the surface. The WW is shaped by asymmetric cowlings that allows it to align its body to the passing current.
- two steel down-weight plates
- three loggers: [RBRmaestro<sup>3</sup> CTD Multi-Channel Logger](#) (Salinity, Pressure, Temperature), [RBRcoda<sup>3</sup> T.ODO](#) (Dissolved Oxygen), [Turner Designs Cyclops-7F fluorometer](#) (Chlorophyll-a, Turbidity)

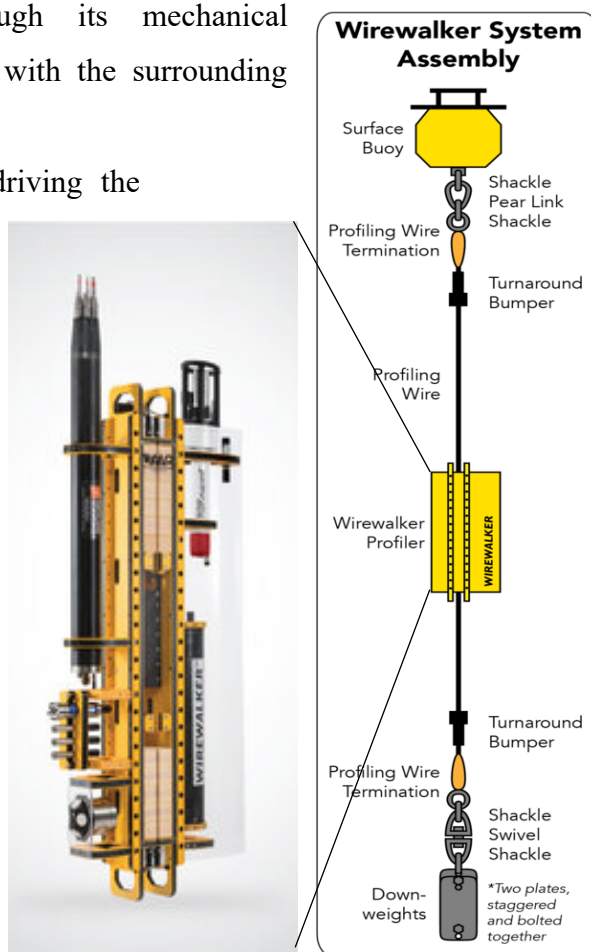


Figure 1-2. The Wirewalker profiler and its set up (source: <https://www.delmarocean.com/ww-how-it-works>)

The WW profiler can be mounted with different sensors' setting depends on the targeted physical, chemical or biological properties. In the presented study, each parameter was recorded with vertical spatial coordinates (depth in m), as the profiler was moored at a fixed location, and temporal information (in seconds). Latitude and longitude were recorded at the mooring point (37°6'25.848N 7°29'48.444W).

## 1.5 CASE STUDY SETTINGS

### 1.5.1 SATELLITE IMAGERY

For a first look at the regional water circulation and the impact on the phytoplankton development during the vertical profiler's deployment, satellite images of the SST and Chl-a were acquired through NASA web tool Worldview (<https://worldview.earthdata.nasa.gov>):

- Sea Surface temperature: from L2 Aqua Modis and L2 Terra-MODIS
- Chlorophyll-a: Level 3 VIIRS-SNPP images

As the dataset was retrieved in April, the cloud cover did not allow for clear satellite images for the entire deployment time. 50% of the days were gathered for SST. No weekly composite images could be retrieved in the week preceding the deployment of the equipment due to the cloud cover.

#### SEA SURFACE TEMPERATURE

At the study area (Fig. 1-3), for the 12 days of data, there was a confirmed coastal water circulation shift: from warmer water (14-19.04) to cooler water (19-25.04), with roughly a decrease of SST up to 2°C in 6 days. Prior to the profiling, the SST in the Gulf of Cadiz would have been generally cooler (13.04), then warmer waters were observed along the south coast, warmest at the eastern bight (East of Cape Santa Maria).

In addition, the ERA 5 reanalysis (European Centre for Medium-Range Weather Forecasts Re-Analysis 5<sup>th</sup> generation) of 'ERA5 hourly data on single levels from 1959 to present', which combines models with recorded observations allowed the retrieval of daily recordings of SST at the nearest point closest to the deployment of the vertical profiler (Fig. 1-4).

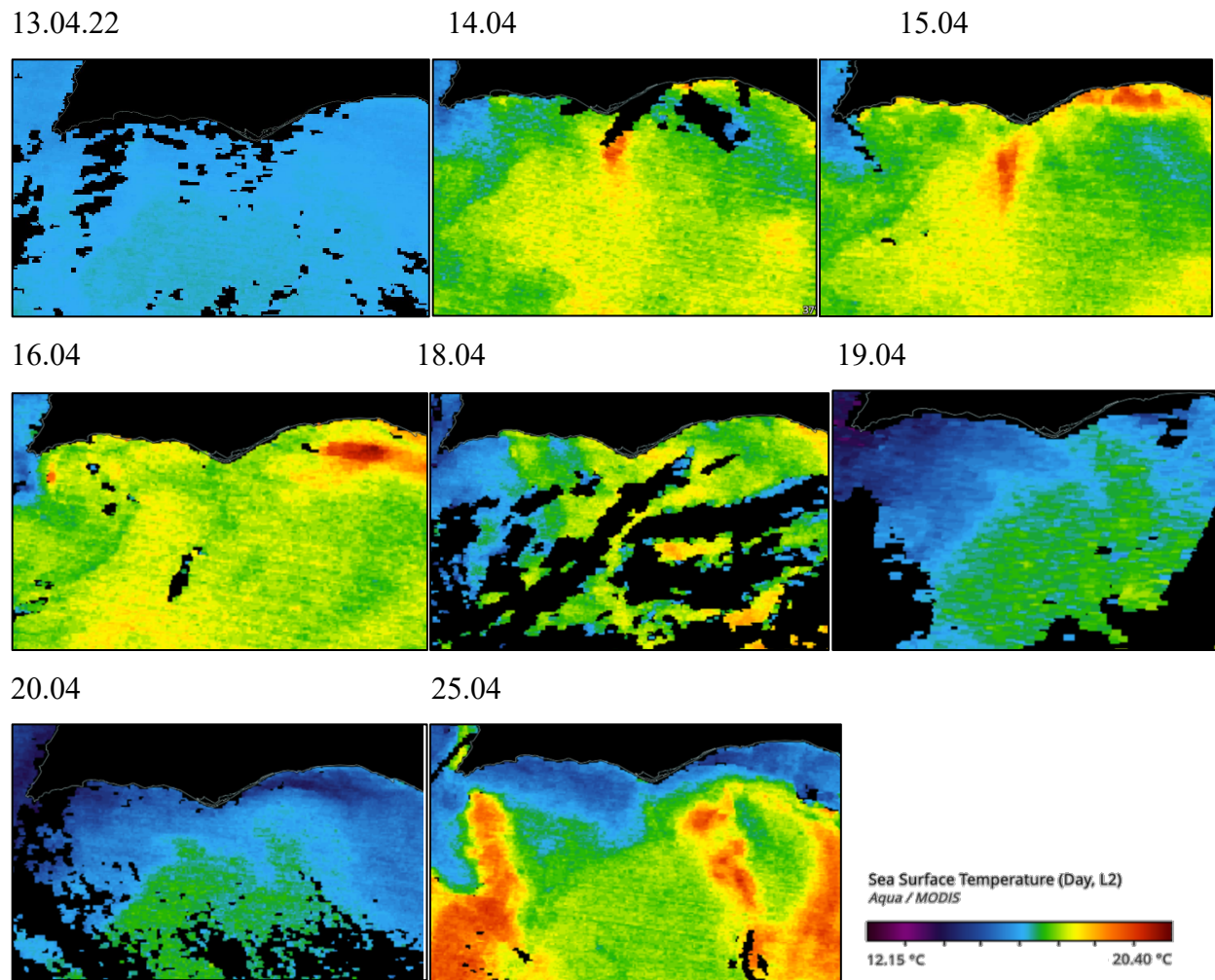


Figure 1-3. Daily sea surface temperature satellite images from NASA World Viewer (L2 AQUA-MODIS and L2 Terra-MODIS) at the NMGCoC (13-25.04.2022).

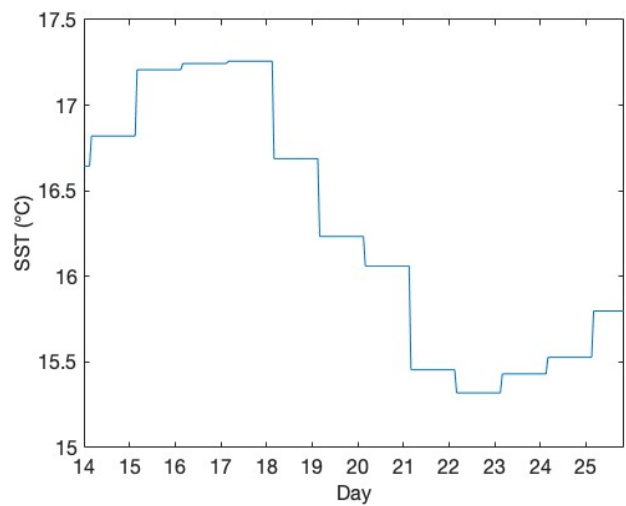


Figure 1-4. ERA 5 daily SST at the nearest point to the vertical profiler at the Cacela reef (14-26 April 2022)



## SURFACE CURRENTS

The High-Frequency Radar of the Portuguese Hydrographic Institute located at Vila real de Santo António PL019 records the surface currents, wave height, period, and direction. Unfortunately, the study area is in a “shadow zone”, East of the Cape Santa Maria, so no HFR data could be recovered - see illustrated zone in the 2016 – 2020 dataset (de Oliveira Júnior et al., 2022).

### 1.5.3 NOTES ON DATASET PROCESSING

Given the format of the master thesis, some extra notes that could not be included in the synthetic scientific manuscript (Chapter 2) are detailed in this part.

To avoid “Not a Number” (NaN) values that could influence statistical analysis results, NaN values found in the ADCP dataset (7 values) were removed. No NaN values were found in the ERA5 and the vertical profiler datasets. However, the profiler had a couple of ‘failures’, where it remained near the bottom stopper, that resulted in a couple of hours without profiles. To avoid NaN values when averaging the dataset (both in time, per hour, and depth, per meter), a linear interpolation was applied.

Cross-correlation tests were carried out between the current, wind and profiles’ parameters datasets to account for any time lags. When necessary, datasets were resampled to allow fitting correlations. However, no significant time lags were recorded between the datasets (< 1 hour, not statistically significant).

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## Chapter 2: Scientific article manuscript to be submitted

Title: High resolution observations on short term fluctuations of phytoplankton biomass with changing physical forcings at the inner-shelf of the Northern Margin of the Gulf of Cadiz.

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## ABSTRACT

The relationship between currents shifts at an artificial reef in shallow inner-shelf waters at the Northern Margin of the Gulf of Cadiz (NMGoC) and the impact on the phytoplankton development is examined. Under a high-resolution observational mode and finite analysis of 12 days of *in-situ* deployment, a relaxation of upwelling flow (coastal counter currents, CCC), an eastward flow (upwelling), and westward flow (current inversion) occurred and are analysed together with the changing biological activity. A vertical profiler (Wirewalker) continuously logged an average of ~120 of high-resolution profiles (2 Hz) every hour through the 15 m deep water column, rendering an incredibly finite view of the changing water column properties (temperature, salinity, dissolved oxygen, turbidity and chlorophyll-a, Chl-a). Additionally, hourly current and local wind velocities were respectively retrieved from an Acoustic Doppler Current Profiler (ADCP) moored nearby and from the ERA 5 Reanalysis database. Results show that phytoplankton concentration varied greatly depending on the simultaneous action of current velocity and origin, as well as the wind, namely the local land breeze, cross-shelf transport, and tidal conditions. While a 6-day upwelling event was observed, with a colder and less saline water signature, the intensity of the surface current was the highest ( $0.4 \text{ m s}^{-1}$ ), the water column was mixed, and the phytoplankton concentration was at its lowest ( $< 1.5 \text{ mg m}^{-3}$ ). High spring seasonal levels of Chl-a ( $3\text{-}4 \text{ mg m}^{-3}$ ) were observed during events of CCC/ wind relaxation and current inversion to a westward alongshore current. The CCC setup was synonym of a reduction of the dominant eastward flow ( $0.2 \text{ m s}^{-1}$  at surface), allowing an intermittent thermal stratification. A thermal gradient of up to  $2.5 \text{ }^{\circ}\text{C}$  along the entire water column, partially resulted in the localised increase in phytoplankton biomass underneath the warmer strata, along with afternoon land breeze enhancing cross-shelf mixing. Strong midday irradiance inhibited phytoplankton development that systematically dropped at midday and increased only after 3 pm. Only when the alongshore current reversed to a westward flow for 20 h, did the Chl-a concentration appeared homogenously mixed in the water column, suggesting an advection of phytoplankton rich waters from the retention “shadow” area in the vicinity of the Guadiana River. While upwelled nutrient rich waters may be a major source enabling phytoplankton development, rapid dynamic changes in the biomass leaves speculations on the importance of current relaxation, enhancing thermal stratification, hence promoting the residence time and growth of aggregating phytoplankton, and the importance of local wind on cross-shelf mixing and advection of near-shore, mid-shelf communities.

## 2.1 INTRODUCTION

The inner shelf of the NMGoC is located within a productive Eastern boundary upwelling system (EBUS) (Carr & Kearns, 2003). The Canary current system supplies the coast with nutrients that promote the growth of primary producers, i.e., the phytoplankton. During upwelling season (roughly from April to September) (Fiuza, 1983; Sánchez & Relvas, 2003), the nutrient rich waters circulate southward off the west coast of Portugal and is advected eastward (broadly referred to as equatorward flow, EF) along the NMGoC under favourable westerly wind (Cravo et al., 2010; Criado-Aldeanueva et al., 2006). All the way to the inner shelf, the large-scale physical forcing balances with Coastal Counter Currents (CCCs) or poleward flow (PF), travelling westward along the south coast, induced by an alongshore pressure gradient (Garel et al., 2016; Relvas & Barton, 2002, 2005). The warmer water mass forms a narrow band (10-20 km wide) at the inner shelf advected from a retention pool located around the Guadalquivir mouth and Cadiz area (de Oliveira Júnior et al., 2021; García-Lafuente et al., 2006b, 2011; Teles-Machado et al., 2007). The PF is observed during period of relaxation of the upwelling favourable wind (northerlies at the West Coast of Portugal, and westerlies at the South Coast), inverting the upwelling driven EF (de Oliveira Júnior et al., 2021). All year round, the shift in current direction has been observed on average once a week, without significant seasonality of the CCC events duration of at least 3 days (Garel et al., 2016).

The alternated circulation pattern forms an inner shelf environment where phytoplankton population may benefit from nutrient-rich waters, from upwelled coastal waters, or proximity to the coast, and reduced current flows, particularly in the eastern region of the NMGoC beyond the Cape of Santa Maria (CSM) that can be considered a retention bay (Fig. 2-1). This extended residence time in the bight further enhances optimal growth conditions (Krug et al., 2017; Lachkar & Gruber, 2011). The continental shelf holds 90% of the world fisheries production, and the inner shelf has the highest primary producer concentration of the shelf (Schilling et al., 2023). The physical and chemical conditions of the inner shelf waters make it an enabling environment for coastal ecosystems. The shallow bathymetry allows light penetration through the neritic zone, making photosynthesis possible for pelagic and benthic phytoplankton, resulting at times into blooms (Behrenfeld & Boss, 2014). Away from the turbulent water movement of the surf zone and extending to the mid shelf, the inner shelf is however a dynamic environment made of complex mixing processes.

The primary production from phytoplankton supports the productivity of higher trophic levels. As such, the study of phytoplankton biomass is a valuable information for coastal management of aquaculture production and understanding further the biological and chemical processes occurring at the inner shelf (Tweddle et al., 2018). The Iberian upwelling ecosystem has been the subject of many studies (Trainer et al., 2010), however there is a need for subsurface measurements to understand the reactivity of the primary producers altered by environmental changing factors at the inner shelf, *i.e.*, CCCs (Lucas et al., 2011; Washburn & McPhee-Shaw, 2013), that could potentially lead to Harmful Algal Blooms (Lima et al., 2022).

In 1990, IPMA, the Portuguese Institute for the Sea and Atmosphere (at the time IPIMAR) installed an artificial reef system ~7 nm from Cacela Velha (Fig. 2-1c). The shallow reef (< 15 m water depth) is formed of small (2.7 m<sup>3</sup>) and large concrete modules (174 m<sup>3</sup>). It is one of the 7 artificial reefs created off the coast of the Algarve (Boaventura et al., 2006). The installation of the reefs was part of an incentive to measure economically important fish populations to better manage the intensive fishing activities of the coast (Monteiro & Santos, 2000; M. N. Santos & Monteiro, 2007). Nonetheless, unlike the Faro and Olhão reefs, Cacela has had little to no reviews on its yielding.

To contribute expanding the limited knowledge of the bio-chemical-physical processes at the reef, an innovative automated vertical profiler was deployed for 12 days in April 2022 (Fig. 2-1, c) to record fine scale (2Hz sampling rate) *in-situ* parameters of the water column. During the deployment, processes of CCC (Coastal Counter Current) (Fig. 2-1, a), coastal upwelling (Fig. 2-1, b), and current inversion were observed. This study proposed a fine-scale (temporal and spatial) analysis of the response of primary producers to changing environmental conditions occurring at the shallow waters of the Cacela Velha artificial reef. The analysis focused on water physical properties (temperature, salinity, density), chemical (dissolved oxygen, and turbidity), and biological parameters (chlorophyll-a), and local environmental drivers (current, local wind). The relationship between phytoplankton biomass and the changing environmental conditions was discussed.

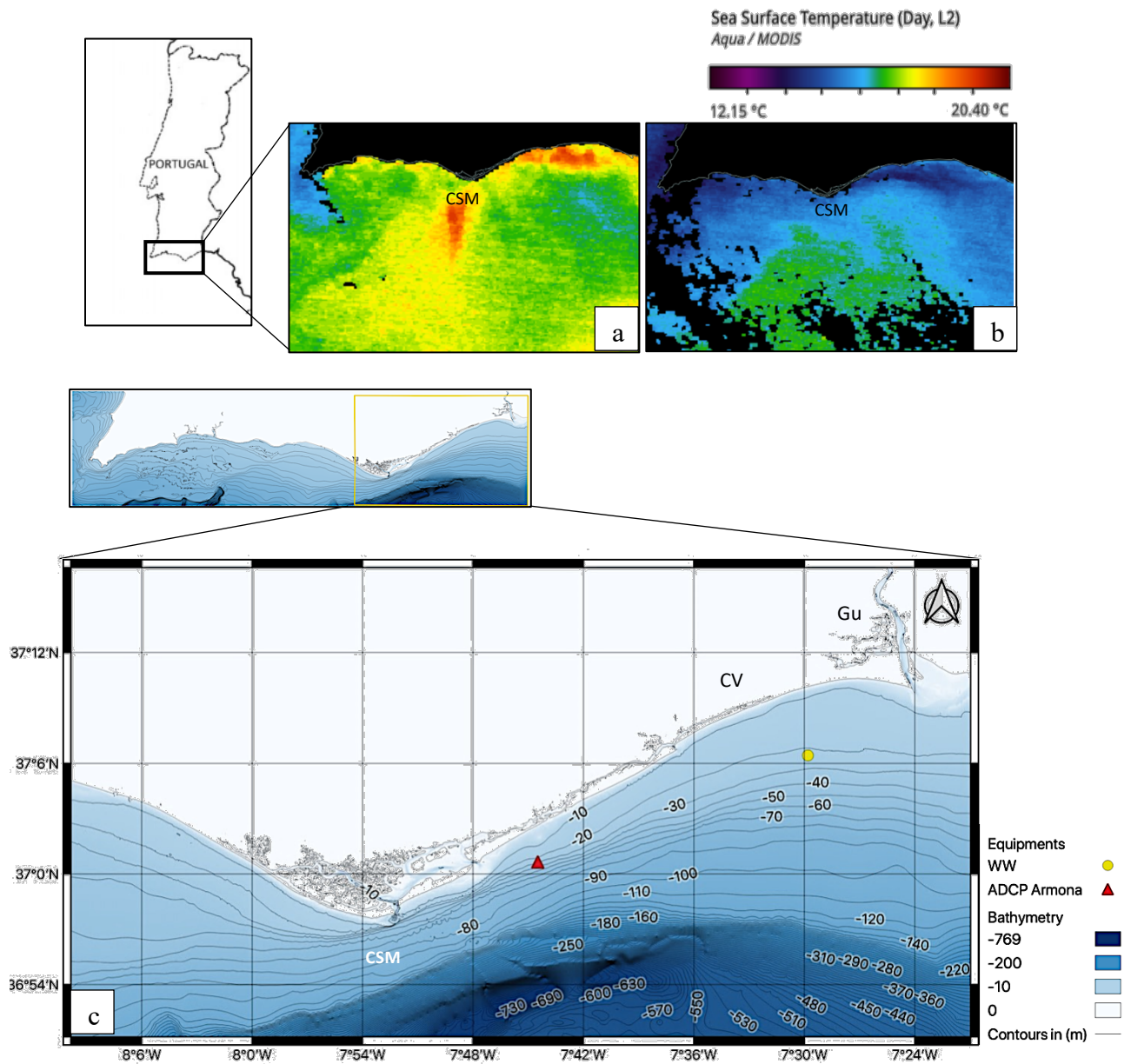


Figure 2-1. Maps of the study area, southeast NMGoC, Sea Surface Temperature from L2 Aqua Modis and L2 Terra-MODIS the 15.04.22 (a), the 20.04.22 (b), and location of the in-situ monitoring equipment (c). Key location: Cape Santa Maria (CSM), Gu (Guadiana River), vertical profiler and artificial reef location (WW, for Wirewalker), and the town of Cacela Velha (CV).

## 2.2 DATA AND METHODS

Multiple *in-situ* datasets were collected to identify the different modes water recorded: from an automated vertical profiler, the Wirewalker (WW), for different physical, chemical, and biological parameters detailed in section 2.2.1, and from an Acoustic Doppler Current Profiler (ADCP) for current speed and direction in the water column located near the profiler. The wind direction and speed were collected by remote sensing with the ERA5 Reanalysis Hourly recordings. The data analysis and visualisation figures were generated using MATLAB software.

### 2.2.1 DATASETS: WIND, CURRENT AND WATER PROPERTIES

#### ECMWF REANALYSIS V5 (ERA5 REANALYSIS)

The wind data was obtained from the Climate Data Store database of Copernicus (Hersbach et al., 2023). Hourly wind recordings were used from the ERA5 Reanalysis from the “ERA5 hourly data on pressure levels from 1940 to present” dataset with a resolution of 4 km<sup>2</sup>. The zonal component, *u* (west-east), and meridional component, *v* (north-south), were recorded at a height of 10 meters above sea surface with units of m s<sup>-1</sup>. For the analysis, upwelling favourable winds for the south coast (westerlies), alongshore winds (parallel to the coast) and sea-land breezes (northerlies) were separately analysed to observe possible correlation with the current and water properties.

#### ACOUSTIC DOPPLER CURRENT PROFILER (ADCP)

Currents velocities throughout the water column were gathered from an ADCP near the vertical profiler’s location (Fig. 2-1c). During deployments at the Armona station, the instrument is fixed on an artificial reef concrete structure at 1.4 m from the seafloor (de Oliveira Júnior et al., 2021). 31 cells of 0.5 m from 3.5 m to 18.5 m away from the ADCP were collected. The ADCP was deployed at about 23 m depth, 24km southwest from the profiler. Some degree of caution must be taken when comparing the WW and ADCP datasets as, although relatively close to one another, the distance between the two equipment may have mitigated the correlations between the observed parameters. The recordings were acquired through a partnership between IPMA and CIMA (Centre for Marine and Environmental Research). The dataset has been quality checked before retrieval and the surface layers affected by the surface boundary were removed. The standard deviation of the horizontal velocity was generally less than 0.07 m s<sup>-1</sup>.

The 12 days of vertical profiles were retrieved during the spring of 2022. Moored on a buoy attached to the artificial reef (37°6'25.848N, 7°29'48.444W), the vertical profiler (Rainville & Pinkel, 2001) recorded high resolution profiles of the water column down to ~15 m, with data acquisition every 0.5 s (2 Hz). The velocity of the upward cast (free floating) was constant at ~0.4 m s<sup>-1</sup>, at the difference of the down cast which moved with a variable velocity. Three different loggers were mounted with sensors that recorded - physical parameters of salinity (S), temperature (T), and sea pressure (p), - chemical parameters of dissolved oxygen (DO), dissolved oxygen saturation (Osat), turbidity (Tu), – and a biological parameter of chlorophyll-a (Chl-a) (Table 2-1). Each parameter was recorded with spatial coordinates (depth in m) and temporal information (in seconds). The profiles were on average 8 m in length, oscillating from ~1 to 9 m below sea surface.

Loggers	Parameters	Unit	Accuracy
<a href="#">RBRmaestro<sup>3</sup> CTD Multi-Channel Logger</a>	Salinity	Unitless, derived from conductivity expressed in S m <sup>-1</sup> (Siemens per m)	±0.0003
	Pressure	dbar	±0.05% full scale
	Temperature	°C	±0.002°C
<a href="#">RBRcoda<sup>3</sup> T.ODO</a>	Dissolved Oxygen	mmol m <sup>-3</sup>	±8µM
		%	±2%
<a href="#">Turner Designs Cyclops-7F fluorometer</a>	Chlorophyll-a	mg m <sup>-3</sup>	±3%
	Turbidity	1 (Nephelometric Turbidity)	±3%

Table 2-1. Details on the loggers and their respective recorded parameters on the vertical profiler at the Cacela Velha reef deployment in April 2022.

### 2.2.2 PRE-PROCESSING

The profiler dataset underwent several pre-processing steps to ensure data quality and reliability. The initial dataset of the vertical profiler was made up of 1,027,167 samples over 285 hours. Using histograms and boxplots for identifying the distribution of the data points, outliers were removed. Data points beyond three standard deviations from the mean were cleared from all

parameters (Emery & Thomson, 1997). As expected, given the nature of the dataset, with diurnal, physical-event linked and depth changes, a non-Gaussian distribution was observed, hence non-parametric statistical tests were computed. Given the changing environmental conditions during the deployment, when necessary, analysis was performed separating the dataset into 3 sub-datasets: (14-18 April) CCC, (19-24 April) upwelling, and (April 25) current inversion.

Only upcast samples were kept, maintaining a spatial and temporal regularity of the data points. MATLAB software was used to index the position of upcast and downcast based on the difference in depth of the profiler. The resulting finite dataset had a high sampling frequency (2 Hz), and numerous profiles (~120 profiles per hour), with depth interval between 15 to 20 cm. After removing outliers and down casting, 59% of the initial dataset remained. Two WW failures of over 1 h gaps were found where the profiler remained near the bottom stopper. 40% of the initial dataset remained after all pre-processing (399 367 samples). The ADCP dataset was filtered through a low-pass Lanczos-window Cosine Filter with a cut off frequency at 40h to de-tide the current velocity and focus the analysis on the alongshore/ cross-shore currents' impact on phytoplankton biomass.

### 2.2.3 DATA PROCESSING

#### WATER COLUMN DENSITY COMPUTATION

Seawater density and Brunt Vaisala frequencies, necessary for the analysis of the stratification of the water column, were derived from the *in-situ* recordings. According to the standards of TEOS-10 (Thermodynamic Equation of Seawater 2010) from the Intergovernmental Oceanographic Commission (25th assembly of June 2009), the Absolute Salinity ( $S_A$ ) was used instead of Practical Salinity  $S_P$  and the Conservative Temperature (CT or  $\theta$ ) over the *in-situ* temperature.  $S_A$  is defined as the mass fraction of dissolved material in seawater. It is preferred to Practical Salinity ( $S_P$ ) as it considers the direct influence of the mass of solutes (e.g.,  $SiO_2(s)$ ,  $CO_2$ , nutrients like  $NO_3^-$  and  $PO_4$  from the oxidation of plant material) on the thermodynamic properties of seawater, whereas  $S_P$  is characterized by conductivity (McDougall & Barker, 2011). The unit used is  $g\ kg^{-1}$ .

The density of the water column was inferred from the measurements of  $S_A$ ,  $\theta$ , and  $p$  (pressure) using the equation of state (Eq. 1):

Equation 1. 
$$\rho = \rho(\theta, S_A, p)$$

The Gibbs-SeaWater (GSW) Oceanographic Toolbox was used in MATLAB to compute the  $S_A$  and  $\theta$ , the density of the water column and Brunt-Väisälä frequencies.

#### WATER COLUMN STRATIFICATION

The Brunt-Väisälä frequency was computed (Eq. 2) to analyse the stratification of the water column.

Equation 2. Brunt Väisala frequency equation (expressed in radians per seconds)

$$N^2 = g^2 \cdot \rho \frac{\beta^\theta \Delta S_A - \alpha^\theta \Delta \theta}{\Delta p}$$

where  $g = 9.8 \text{ m s}^{-1}$  is the gravitational acceleration,  $\Delta S_A$  and  $\Delta \theta$  are the differences between  $S_A$  and  $\theta$  of vertically adjacent seawater parcels separated in pressure by  $\Delta p$ , measured in Pa. The density  $\rho$  and the saline contraction and thermal expansion coefficients  $\beta^\theta$  and  $\alpha^\theta$  are evaluated at the average values of  $S_A$ ,  $\theta$  and  $p$  of the adjacent seawater parcels (Ioc et al., 2010; Roquet et al., 2015). The highest Brunt-Väisälä frequency determines the depth at which a parcel of water is more stable and therefore may indicate the presence of neighbouring water masses with different densities.

#### STATISTICAL TESTING: VARIABLES CORRELATIONS

Environment parameters of wind and current were cross correlated to confirm and analyse the different physical processes with the inclusion of possible time lags (Holmes et al., 2020). However, no significant time lag was observed ( $< 1 \text{ h}$ ) so the Spearman's rank correlation coefficient was used.

The Spearman rank correlation's test (non-parametric) was computed at the significance level of 0.05. To generate correlations between the high-resolution *in-situ* parameters (2Hz) and the current dataset resolution (1 sample per hour per 0.5 m), both 2-dimensions time series datasets were subsampled into averaged cells of 1 meter (1.5 m for the ADCP) per hourly increments. Both

datasets resulted in 10 bins for 285 hours. The ADCP original dataset being 15.5 m, the first bin was 1 m and the following 1.5 m. Additionally, to translate the corresponding modes water to the different physical events (i.e., CCC, upwelling, current inversion) occurring with the highest resolution, the parameter of mean hourly temperature was chosen to correlate the *in-situ* parameters to the environmental events. The datasets were resampled accordingly to be tested.

Physical forcings are drivers of change for chemical and biological processes (Navarro et al., 2006). The correlation of phytoplankton biomass concentration to changes in environmental forcing was computed using the strength of monotonic relationships between Chl-a increase depending on modes water density. Physical parameters were correlated with biological and chemical parameters of Chl-a and DO, and turbidity, respectively, that are intrinsically affected by biological activity.

The main hypothesis tested was whether there was an interconnection between the ecosystem's phytoplankton primary producer biomass and the types of currents involved, i.e., CCCs or EF. Based on the results of hypothesis testing, conclusions were drawn. Further interpretations were made regarding the best suitable depths of phytoplankton communities in relation to different oceanographic features.

## 2.3 RESULTS

### 2.3.1 NMGoC CIRCULATION SETTING

To infer the oceanographic context during the studied period, monthly Chl-a surface concentration from satellite images at the NMGoC before and during the studied period (March - April 2022) and are presented in Figure 2-2.

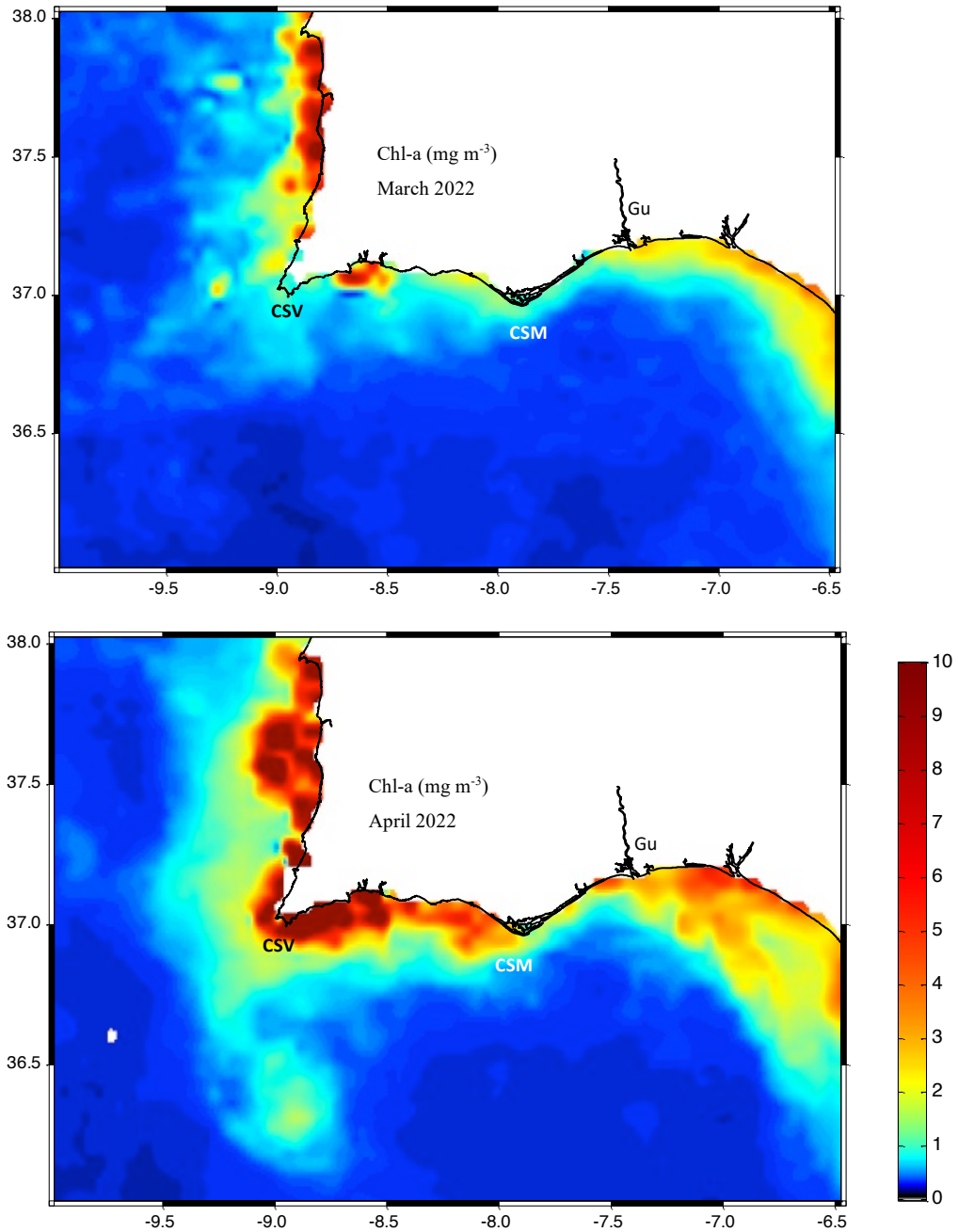


Figure 2-2. Monthly composite satellite images from NASA OceanColor Aqua-Modis Level 3 for chlorophyll-a (Chl-a) at the Northern Margin of the Gulf of Cadiz (March - April 2022) processed with Mirone software. Key reference locations are marked: Cape St. Vincent (CSV), Cape St. Maria (CSM) and Gu (Guadiana River).

The monthly composite images reflect seasonal high levels of Chl-a concentrations on the coast ( $>2-3 \text{ mg m}^{-3}$ ). From March to April, there was a noticeable increase of Chl-a along the west coast of Portugal that may be identified as an indicator of the start of upwelling season (roughly April – September). These composite images show the Chl-a signature in April ( $> 3 \text{ mg m}^{-3}$ ) at the coast and even more so, zones of particular abundance, respectively in the retention bay east of CSM all along the easter bight, where the study area was located, and along the west coast to CSM.

### 2.3.2 PHYSICAL FORCINGS

#### WIND

The local wind regime throughout the 2 weeks varied from low to high intensity (daily average speed from  $3.14$  to  $7.36 \text{ m s}^{-1}$ , with a range  $\sim 0-12 \text{ m s}^{-1}$ ), from westerlies and northerly wind (Fig. 2-3). The wind speed almost doubled on the 5<sup>th</sup> deployment day and stronger northerlies lasted for 6 days (19-24 April). A daily shift in the direction at midday was recorded outside of the strongest wind period (Fig. 2-4). During that time (14-19, 25-26 April), the wind followed a diurnal shift pattern: lowest intensity in the morning with westerlies (some occasional low southerly winds), higher intensity in the afternoon/night from northerlies. Strongest winds ( $8$  to  $12 \text{ m s}^{-1}$ ) were coming from the North (Fig. 2-4) with no diurnal variations (19-24 April).

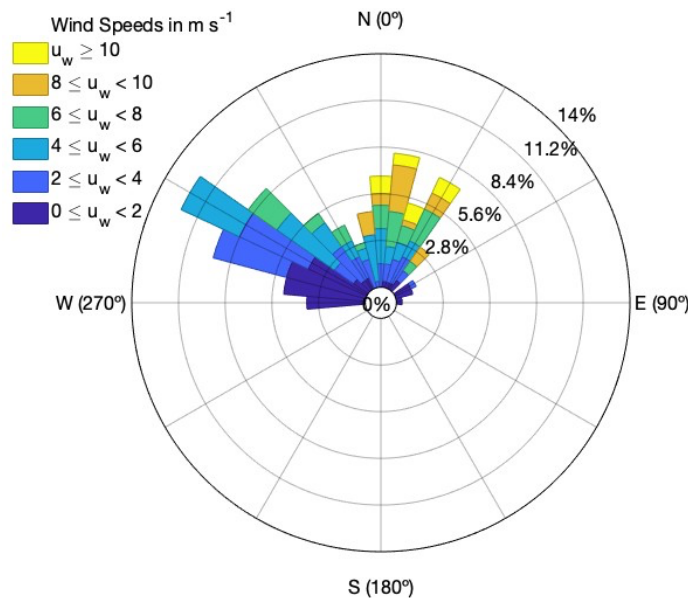


Figure 2-3. Wind rose from ERA5 hourly wind at Cacela Velha artificial reef (14-26 April 2022).

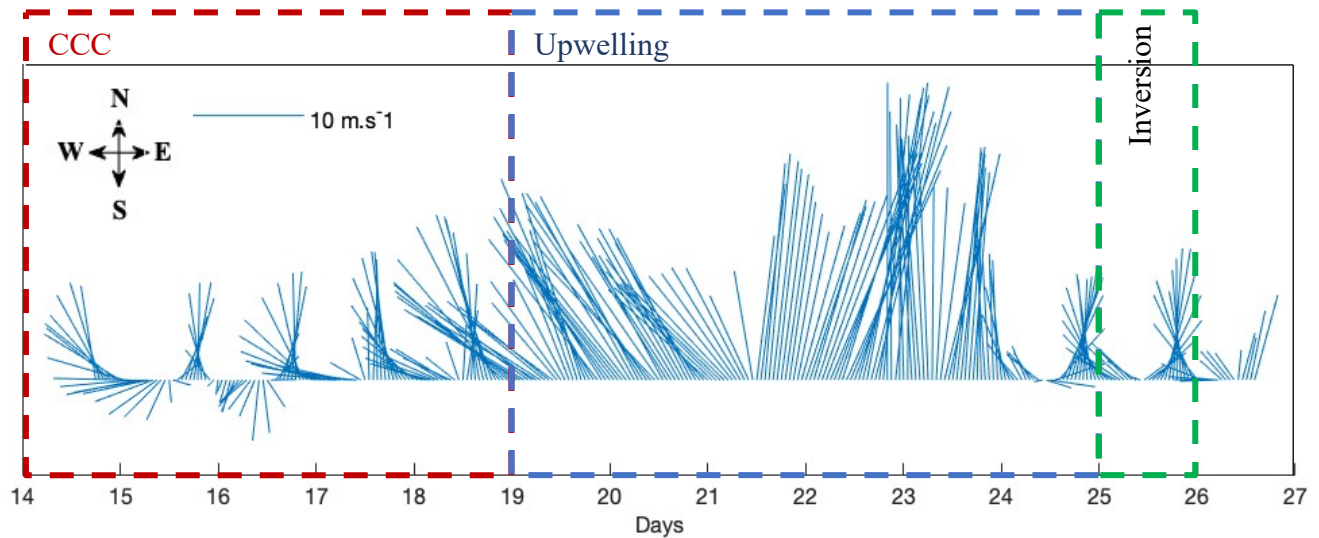


Figure 2-4. Stick plot of hourly ERA5 Wind at the location of the vertical profiler 14-26 April 2022. The direction of the wind reads "from" the corresponding cardinal point. Here mainly from North and North-west.

Although there was a statistically significant correlation between alongshore wind speed and direction with the alongshore current (Fig. 2-4 and 2-5), the correlation strength was weak ( $r < 0.3$ ,  $p < 0.001$ ). This suggests that, even if local wind was a partial driver of the inner shelf's alongshore current, other drivers, on a larger scale, might have been of predominant influence as suggested in previous research on the inner shelf's circulation (de Oliveira Júnior et al., 2022; Garel et al., 2016). Here, the wind with some west component was upwelling favourable during the 14-21 April at midday, then the east component in the wind from the 21<sup>st</sup> onwards became downwelling favourable.

#### ALONGSHORE CURRENT

The cross-current flow (roughly northwest - southeast), and the alongshore current flow (following the northeast-southwest axis of the coastline,  $55^\circ$  from true North) are depicted in Figure 2-5 (a and b). The alongshore current, as predicted from literature was mainly due to the overpowering eastward EF. Despite the shallow depth, the current was mostly homogeneous with an average variance of  $0.005 \text{ m s}^{-1}$  when the surface cells recorded a velocity higher than  $0.3 \text{ m s}^{-1}$ , but under, the bottom shear stress was felt throughout the water column and a flow of  $0.01 \text{ m s}^{-1}$ .

<sup>1</sup> was recorded. The general current velocity fluctuated from a daily average of  $0.16 \text{ m s}^{-1}$  to an increase of 62.5 % for the 6 days (19-24 April) described as synonym of upwelling event. Lowering of the current intensity occurred at both ends of the event (18-20, 24-25 April). The average current velocity after upwelling relaxation increased by  $\sim 48\%$  (from  $0.21$  to  $0.31 \text{ m s}^{-1}$ ) and reduced to an average of  $0.03 \text{ m s}^{-1}$  during the post-upwelling current inversion to a westward PF.

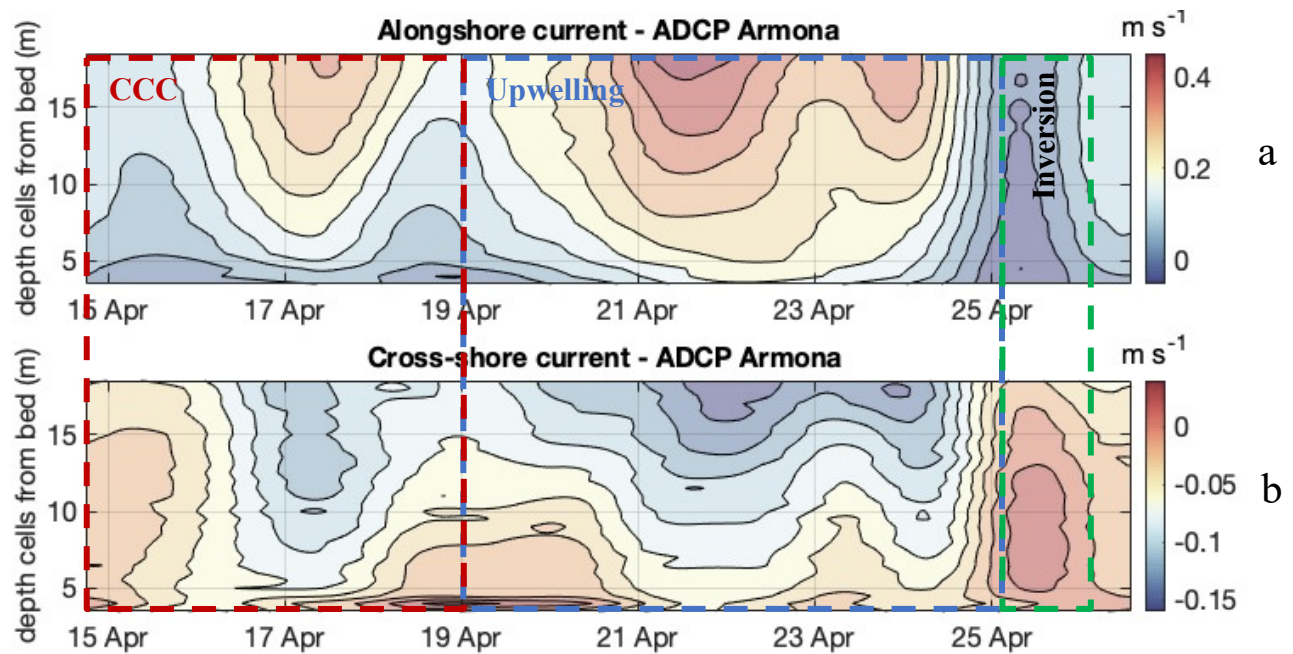


Figure 2-5. Time series of (a) the Alongshore, (b) Cross-shore current from the ADCP at Armona in April 2022. Positive values in figure (a) represent north-eastward flow, and negative values, the south-westward flow. For figure (b), positive values represent the flow going towards the shore (north-westward), and negative values the flow going offshore (south-eastward). Depth here is expressed as increasing away from the bottom mounted ADCP.

The alongshore current direction only shifted westward once, under low wind stress ( $< 5 \text{ m s}^{-1}$ ). On occasions, when the surface current velocity decreased, the bottom alongshore current shifted south-westward on the last meters, most probably due to increased bottom shear stress. While this occurred, a cross-shore current flowing onshore was observed (see Fig. 2-5, 18-21 April, and 23 April). At the upper part of the water column, when EF was stronger (17, 20-24 April), an offshore current was recorded ( $0.1$ - $0.15 \text{ m s}^{-1}$ ). On a much more homogenous pattern, the flow observed during April 25<sup>th</sup> showed an inversion of the current (detailed in sub-section

2.4.2, see Fig. 2-8), starting from the bottom. The westward flow appeared at the deepest part of the water column (deeper than 6 m) with a consistent velocity for ~17 hours.

### 2.3.3 VERTICAL PROFILER

The high-resolution time series of *in-situ* parameters retrieved from the vertical profiler's measurements – Conservative Temperature (CT or  $\theta$ ), Absolute Salinity ( $S_A$ ), Turbidity (Tu), Chlorophyll-a (Chl-a), Dissolved Oxygen (DO), Oxygen Saturation (Osat), Brunt Väisälä frequency (N) and Density ( $\rho$ ) - recorded along the water column from the 14 to 26<sup>th</sup> April 2022, in Cacela Velha artificial reef are shown in Figure 2-6. The correlations between the parameters during the mentioned events are presented in Figure 2-7 and Table 2-2.

#### PHYSICAL PARAMETERS

Striking oceanographic patterns were discernible. A shift, from relatively warm ( $> 16^\circ\text{C}$ ) and more saline water ( $>36.4 \text{ g kg}^{-1}$ ) was recorded for just over 4 days (18:00 14 to 19 April) - characteristic of an upwelling relaxation (or Coastal Counter Current, CCC) event, to colder ( $<15^\circ\text{C}$ ), less saline water ( $<36.2 \text{ g kg}^{-1}$ ) – typical of a spring upwelled flow. At both ends of the upwelling event (19 and 25 April), less pronounced oceanographic features were observed in the salinity and temperature, however the Osat and Chl-a levels distinctly shifted. These changes will be further discussed.

Characteristic of CCC, the period of lower wind range ( $< 6 \text{ m s}^{-1}$ , see Fig. 2-4) and reduced EF current velocity (Fig. 2-5) translated into ~4 days of warm water temperature range ( $15.61\text{-}16.8^\circ\text{C}$ ) (Fig. 2-6). The increase, said eastward EF (19-24<sup>th</sup> April), translated into cooler temperatures with a drop of the mean water temperature of  $2.21^\circ\text{C}$ , typical of upwelling events and mixing throughout the shallow water column. The period of stronger mixing was reflected in the turbidity recordings, with higher Tu during upwelling and lower concentration of Chl-a, as will be discussed in the following sub-section.

The  $S_A$  (Fig. 2-6) illustrates the events shifts with a homogeneously higher salinity in the mode water during CCC, decreasing of  $0.78 \text{ g kg}^{-1}$  during upwelling. The salinity of the water column was homogenous until midday where a daily occurring layer of less saline water appeared at the surface and extending deeper as the day unfolded. A possible explanation for this phenomenon

could be the diurnal irradiance changes, from highest during midday to sundown, that could induce evaporation at the surface (Feddersen et al., 2020).

For better coherence, all presented time-series have been marked with dashed separation lines to delimited named periods of: - (red) upwelling relaxation, - (blue) upwelling, and - (green) current inversion (distinguished in subsection 2.3.2). Time delimitations have been set to following the striking changes in CT and  $S_A$ : CCC (14-18 incl. April), upwelling (19 – 24 incl. April) and current inversion (25<sup>th</sup> April).

#### DENSITY AND STRATIFICATION

The identified period of warmer water, CCC, showed an intermittent stratification of the water column with a higher Brunt-Väisälä frequency at the surface at midday descending to the seafloor by the evening (Fig. 2-6). With increased flow velocity, as expected, the stratification of the water column during periods of upwelling was non-existent as the water was well mixed ( $Turb > 0.8$  NTU). The day of current inversion (25<sup>th</sup> April) showed an intermittent stratification similar to the period of CCC. The stratification was linked with higher temperature gradients throughout the water column. During the warmer event, the gradient was 2.89°C, and was non-existent with the well mixed waters of the upwelling event.

#### CHEMICAL AND BIOLOGICAL PARAMETERS

During upwelling (Fig. 2-6), the concentration of Chl-a was homogeneously low ( $< 1.5$  mg  $m^{-3}$ ). The highest concentration (3-4 mg  $m^{-3}$ ) was recorded at the time of flow decrease (17-19, 24-25 April) and flow inversion (25<sup>th</sup> April). In both instances, the highest concentration was recorded in the afternoon with lower flow intensity ( $< 2$  m  $s^{-1}$ ) in the deepest half of the water column and low wind intensity ( $< 6$  m  $s^{-1}$ ) (Fig. 2-5, and 2-4). These patches of higher concentration occurred always highest at depth  $> 4$  m. In the case of the CCC, the concentration remained localised there. In contrast, the 19-20 April, before the upwelling flow, and after, when the inversion of current occurred (April 25), the concentration did not follow the same pattern and was homogenous along the water column, except at the middle of the day, where the Chl-a was homogeneously lower (similar to upwelling concentration level). However, on the morning of April 26 it increased again to maximum values, but at surface down to 3-4 m. This suggest that although both events occurred during periods of lower wind, the -pre and -post upwelling times observed slightly different results in the phytoplankton biomass and its location in the water column.

During CCC and the current inversion, DO was overall higher than during upwelling (respectively 274 - 249 mmol m<sup>-3</sup>), with a drop to 235 mmol m<sup>-3</sup> during upwelling event (Fig. 2-6). Oxygen supersaturation (110-120%) occurred during CCC and to a lower extent (100-110%) during the pre- and post-upwelling (19 and 25 April). The latter being associated with relatively higher concentration of Chl-a (~3 mg m<sup>-3</sup>), signature of the phytoplankton producing more oxygen than was being consumed in the respiration process (Cravo et al., 2010). Hence, then, the Osat was higher at the surface than at the bottom, when oxygen was partially used in the respiration process. Osat was lowest during upwelling (< 100%), corresponding to stronger current and wind velocity, bringing water from deeper levels where consumption of DO is higher than that produced by photosynthesis.

The water column Tu was generally low (< 1 NTU), but variations followed 2 recognisable patterns during the deployment (Fig. 2-6). Tu was higher (> 0.8 NTU) during the increased water flow during upwelling and to a lower extent (> 0.5 NTU), outside of the upwelling flow, when Chl-a concentration was higher (3-4 mg m<sup>-3</sup>). For the starting stages of CCC (14- midday 18 April), with a relatively low current and wind flows, and a lower concentration of Chl-a, Tu was notably lower (< 0.3 NTU).

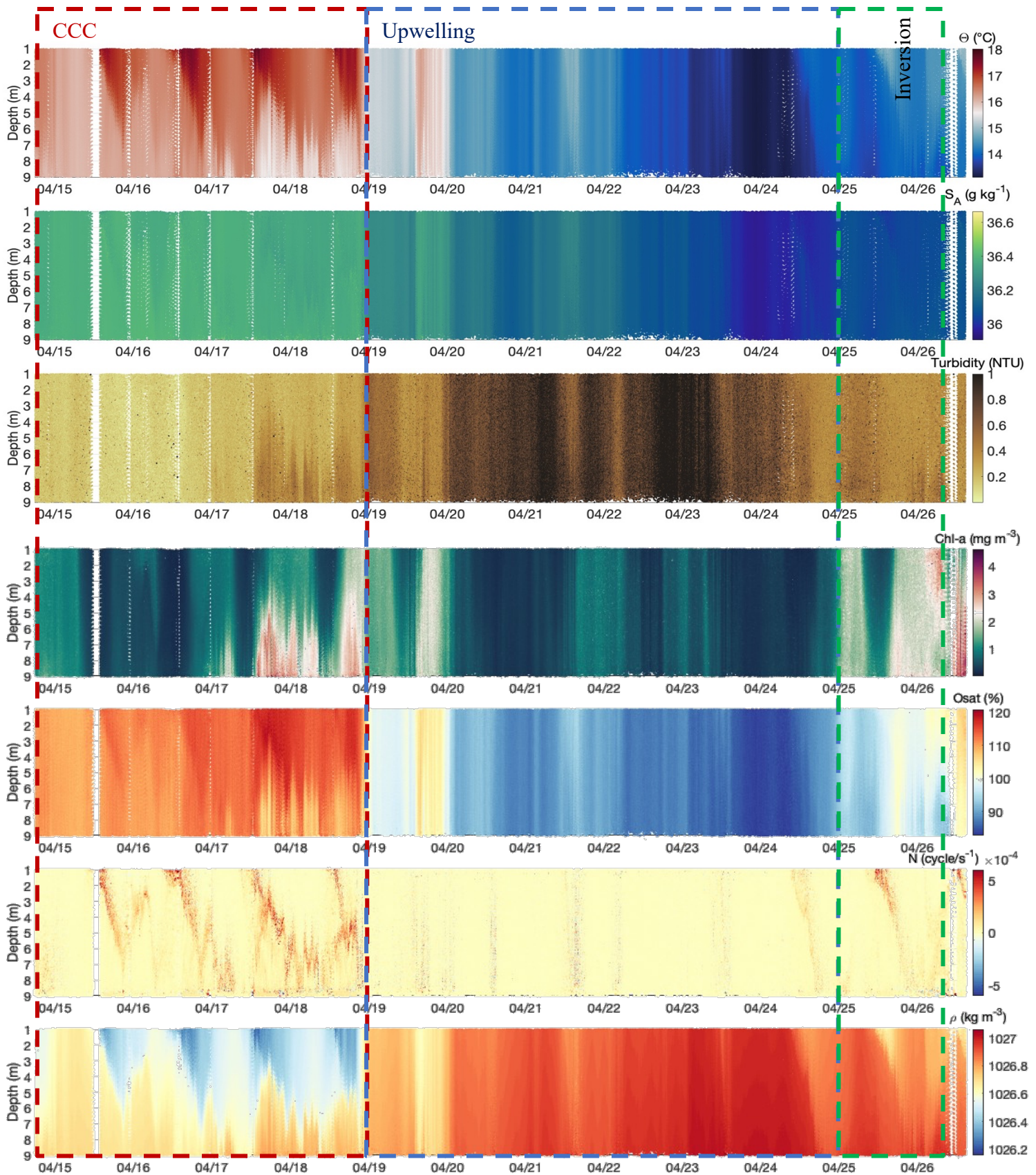


Figure 2-6. Time series of *in-situ* parameters through the water column (14-26 April 2022, Cabela Velha artificial reef). In order: Conservative temperature, Absolute Salinity, Turbidity, Chlorophyll-a, Dissolved Oxygen (DO), Brunt Väisälä frequency (N) and density ( $\rho$ ).

#### 2.3.4 CORRELATIONS BETWEEN PARAMETERS

Trying to understand how the different physical-chemical-biological processes interplayed and were coupled in the identified three periods of different oceanographic features in comparison with the global period, a comprehensive analysis was conducted and resulting correlations are presented in Fig. 2-7. Respectively during the whole period, CCC, upwelling and current inversion, chemical and biological parameters of Chl-a, Osat were correlated to the general current and wind, and are presented in Table 2-2, with also correlations with the alongshore and cross-shore components of current, and wind u and v component. p values are informed in Fig. 2-7 and Table 2-2, r values are mentioned in the analysis.

Overall (Fig. 2-7a),  $S_A$  and CT were strongly correlated (+0.94). However, during CCC (Fig. 2-7b) probably due to a stronger stratification of the water column (Fig. 2-6), and possible evaporation at the surface, the properties were inversely correlated (-0.14), which also corresponded with the only time Chl-a was negatively correlated with CT (-0.35),  $S_A$  (-0.47), as the water column separated into a warmer, less saline surface strata with lower Chl-a, and a lower, denser, strata, with a higher concentration of Chl-a. In this case, the lower Chl-a concentration at surface also corresponded with higher dissolved oxygen (Fig. 2-6) due to more oxygenated waters from the interaction of the wind, and the accumulation of Chl-a at lower depth where lower Osat was found, was depicted in the Chl-a and Osat correlation (-0.12). During upwelling (Fig. 2-7c), the correlation between CT and  $S_A$  was very strong (0.98) and shifted during the current inversion (Fig. 2-7d) (-0.29) as the water was once again stratified (Fig. 2-7, and 2-6). This reflects the presence of difference modes water during the studied period and the importance of short-term processes affecting the density gradient of the water column, as a function of CT and  $S_A$ .

Globally (Fig. 2-7a and Table 2-2), the alongshore current and Chl-a were moderately negatively correlated (-0.46), as well as with Osat (-0.40). This would imply that Chl-a and Osat were highest when the current velocity was lower. Nonetheless, Chl-a was positively correlated to the cross-shore current velocity (0.30), meaning that an increased onshore (north-westward) current, advected water from further seaward towards the land, with increased Chl-a concentration. Correlations between Chl-a and the wind were negative and very weak (-0.06) throughout the whole period but stronger when separating the different oceanographic features.

During CCC and current inversion (Table 2-2), Chl-a and the wind were strongly correlated (+0.68 and +0.69), particularly with the u component of the wind. In contrast, no significant correlation during upwelling was recorded. During these periods, the link with the wind was more significant than the current, while during upwelling, the relation with the wind was neglectable.

From the three situations (Fig. 2-7), the weakest correlations were found for the current inversion and CCC. The biological parameter of Chl-a can be associated with Osat and for the different observed periods it was: Globally a)- positively related (+0.57), CCC b)- no correlated, upwelling c) – strongly positively related (+0.71), current inversion d) – moderately positively related (+0.39).

When CCC was observed (Fig. 2-7b), the correlation between Chl-a and Tu was positively strong (+0.68) and inverted to be negative during upwelling (-0.56), and weaker during inversion (-0.12). These correlations demonstrate the connection between current intensity and the developing phytoplankton biomass. Overall, Tu and Osat were strongly negatively correlated (-0.80), however, the correlation was notably very weak during CCC (+0.066) in contrast with upwelling (-0.71) and the current inversion (-0.61). This Osat correlation represented the upwelled stronger flow, lower in Osat, while during CCC and the current inversion, the lower alongshore current flow was positively correlated (+0.63 and +0.72) to an also decreasing Osat (Table 2-2).

During upwelling (Fig. 2-7c), Chl-a was the most strongly correlated with CT (+0.68),  $S_A$  (+0.70), and Osat (+0.71) and most negatively correlated with  $\rho$  (-0.60) and Tu (-0.56). Then, Osat was most strongly correlated with CT (+0.98) and  $S_A$  (+0.95). This illustrated a general decrease in all parameters with the advection of upwelled water, more dense, colder, less saline, less saturated in oxygen, with a lower phytoplankton biomass and higher turbidity.

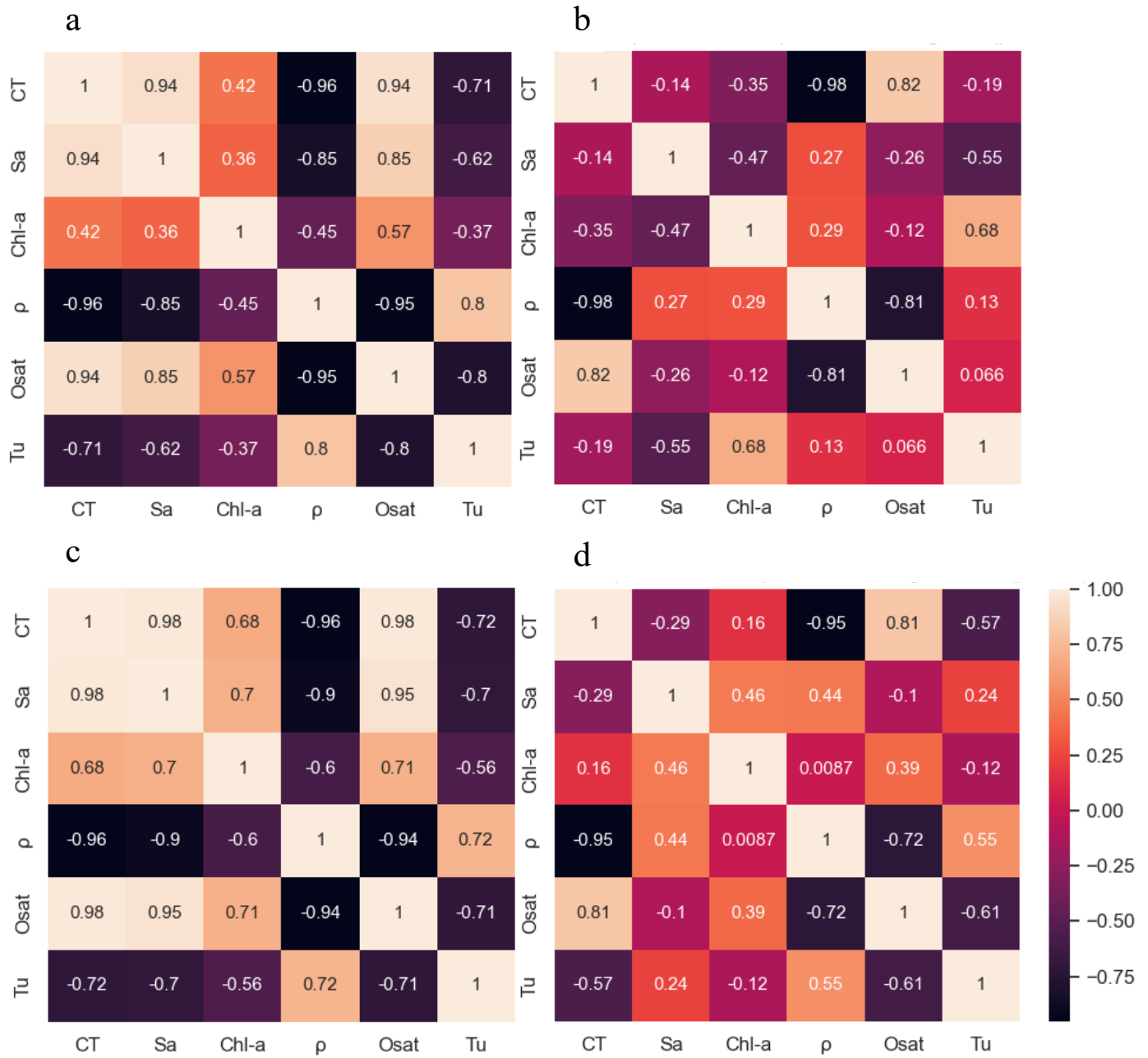


Figure 2-7. Correlation heatmaps of *in-situ* parameters from the vertical profiler during (a) total observation period (14-26 April), (b) coastal counter-current (14-18 April), (c) upwelling (19-24 April), and (d) flow inversion (25 April).  $R^2$  between parameters are presented (all  $p < 0.01$ ). The parameters correspond to: (CT) Conservative Temperature, (Sa) Absolute Salinity, (Chl-a) Chlorophyll-a, ( $\rho$ ) Density, (Osat) Dissolved Oxygen Saturation, (Tu) Turbidity.

Table 2-2. Physical forcings speed ( $\text{m s}^{-1}$ ), Chl-a ( $\text{mg m}^{-3}$ ) and Osat (%) correlations during changing oceanographic features. All values have a corresponding p value  $< 0.001$ , unless specified.

	Whole study period		CCC		Upwelling		Inversion	
	Chl-a	Osat	Chl-a	Osat	Chl-a	Osat	Chl-a	Osat
<i>Physical forcings speed</i>								
<b>Current</b>								
General	-0.48	-0.44	x	0.68	-0.24*	-0.3	0.52*	0.74
Alongshore	-0.46	-0.4	x	0.63	-0.3	-0.25*	0.45**	0.72
Cross-shore	0.3	-0.22	x	-0.48	x	0.28	-0.61	-0.4**
<b>Wind</b>								
General	-0.06	-0.41	0.68	x	0.2**	x	0.69	0.84*
u	x	-0.49	0.6	0.54	x	x	0.71	0.83
v	-0.2	-0.22	-0.44	x	x	-0.47	x	0.52*

\*p<0.01

\*\*p<0.05

x not statistically significant

## 2.4 DISCUSSION

### 2.4.1 OCEANOGRAPHIC CONTEXT

#### WATER MASSES THERMOHALINE SIGNATURE

The high resolution of a short-term period of 12 days allowed the observation of modes water advection. In previous studies, different water masses have been characterised in the Gulf of Cadiz (Criado-Aldeanueva et al., 2006). At the eastern inner shelf of NMGoC, Warm Shelf Waters (SW) have a thermohaline signature above  $14.0 \leq T \leq 18.0^\circ\text{C}$  and  $35.9 \leq S \leq 36.5 \text{ g kg}^{-1}$  (Criado-Aldeanueva et al., 2006). The shallow waters were defined as modified water masses from the Surface Atlantic Waters (SAW) due to the influence of short-term coastal thermal stratification, wind induced variability due to shallow water column depth, sea-air interaction, and fluvial discharge. During the deployment, two distinct mode waters can be characterised that fall with the range of SW (Fig. 2-6, and 2-9): (14-19 April)  $> 15.5^\circ\text{C}$  with  $36.4\text{-}36.6 \text{ g kg}^{-1}$ , (20-26 April)  $13\text{-}15.5^\circ\text{C}$  with  $36\text{-}36,4 \text{ g kg}^{-1}$ . This range is similar to findings from Cardeira et al. (2013) in 2006 at the surface layer close to the mouth of the Guadiana River.

Figure 2-6 displays the evident occurrence of the physical phenomenon of coastal upwelling and CCC with significant changes in modes of seawater. In this case study, a drop of  $4.87^\circ\text{C}$  of the mean water column CT occurred between CCC and upwelling periods. Such a change in the water physical property, and an increase in the mean alongshore current velocity of (62.5 %), undoubtedly signaled the presence of advected upwelled waters, as found by other authors in the NMGoC (e.g., Fiuza, 1983; Folkard et al., 1997; Relvas & Barton, 2002; Vargas et al., 2003). Along with the CT drop, simultaneously the water column salinity decreased by  $0.78 \text{ g kg}^{-1}$ . Both parameters were correlated at (+0.94) for the total observed time (Fig. 2-7a). The physical and chemical characteristics at the inner shelf have been previously reported (Cardeira et al., 2013; Cravo et al., 2010; de Oliveira Júnior et al., 2022; Garel et al., 2016). In literature, the temperature difference of the inner shelf's water has been observed to vary as strongly as  $6^\circ\text{C}$  in 3 days (Garel et al., 2016). The overall strong correlation between  $S_A$  and CT (+0.98) was however reversed during CCC and a current flow inversion (respectively -0.14 and -0.29, see Fig. 2-7b, d), suggesting the presence of different modes water influenced by coastal processes.

## INNER-SHELF CIRCULATION

Several studies have been conducted to explore the interplay between coastal winds and current flows, such as the one from Whitney & Garvine (2005). At the inner shelf, wind intensity can intensify or diminish the flow (Criado-Aldeanueva et al., 2006; Navarro et al., 2006). The eastward alongshore current along the water column was responsive to the intensity of the wind, notably between 19-24 April (Fig. 2-4 and 2-5), while a counter-flow westward happened during relatively low winds intensity (25 April), driven by an alongshore pressure gradient. As stated previously, the current recorded by the Armona ADCP station was predominantly flowing north-eastward throughout the deployment of the vertical profiler, except for an inversion event on April 25 that will be discussed further.

Although there was a dominant eastward flow, a reduction of the current velocity ( $0.4 \text{ m s}^{-1}$  at surface, see Fig. 2-5) was observed when warmer water occurred (see Fig. 2-6, 14-19 April). During CCC, as characterised in literature, an actual westward flow is only occurring when Leventer, easterly winds, are present (Criado-Aldeanueva et al., 2006). CCC are more generally described as upwelling relaxation events, during which there may not always be an actual flow traveling westward (Teles-Machado et al., 2007). In this study, we were able to observe the reduction of the eastward flow, but no Leventer winds were blowing. Here, the CCC was recorded at no greater current speed than  $0.3 \text{ m s}^{-1}$  at the surface, still going eastward. During upwelling, the wind intensity was within the range of 6 to  $12 \text{ m s}^{-1}$ , which fits with the observations of Relvas & Barton, (2002), when upwelled waters were observed, coming from the west coast all the way to the area of Cape St Maria (CSM) under wind stress of  $\sim 8 \text{ m s}^{-1}$ .

The alternation between CCC and eastward flows (upwelling) has been described in literature as occurring on a weekly basis without much seasonality, apart from the fluctuation of the length of the events at times (Garel et al., 2016). Within the 12 days deployment, without surprise, current shifts were recorded (19-20 and 25<sup>th</sup> April). Cold, nutrient rich waters of coastal upwelling events are events that occur past CSM on the south coast of Portugal when upwelling favourable winds turn anticlockwise into westerlies at Cape St. Vincent (CSV, see Fig. 2-2) (Fiuza, 1983; Leitão et al., 2019; Lemos & Pires, 2004; Relvas & Barton, 2002, 2005; Ruiz & Navarro, 2006). Spring-

summer climatology of geostrophic surface flow (de Oliveira Júnior et al., 2022; Sánchez & Relvas, 2003) suggest the formation of a cyclonic cell centred off the eastern bight (east CSM) that connects the slope and coastal circulation, and result in an opposite dynamic to the eastward upwelling flow (de Oliveira Júnior et al., 2021, 2022; Sánchez & Relvas, 2003). In the south Portuguese coast upwelling events in front of CSM extending westward, until the Guadiana River mouth, have been previously analysed (Cardeira et al., 2013; Cravo et al., 2013; de Oliveira Júnior et al., 2022; Garel et al., 2016).

During the prior to last day of observation (April 25), as the wind was weaker ( $>4 \text{ m s}^{-1}$ ), the observed water current direction shifted south-westward (Fig. 2-8). This event of lowest wind showed an interesting event of current inversion. For 6 h, from midnight to 6 AM, a south-westward current was recorded, first at the top layer, and reaches the bottom layers with a delay of 4 h. For a total of 12 h, the bottom and top layers have currents of opposite direction. This is the only occurrence of inversion in the whole dataset. This confirms the discussed theory in literature stating that the flow, induced by the geostrophic balance, is leaning towards the south-west without the interference of the wind and, therefore, wind induced upwelling event (Wu et al., 2021). The shifted flow may have been the result of an episodic recirculation eddy described by (de Oliveira Júnior et al., 2021). Similar to what was observed in this study, previous research on the counter-flow from Garel et al. (2016) found that the current inversion started at the bottom (Fig. 2-5 and 2-8).

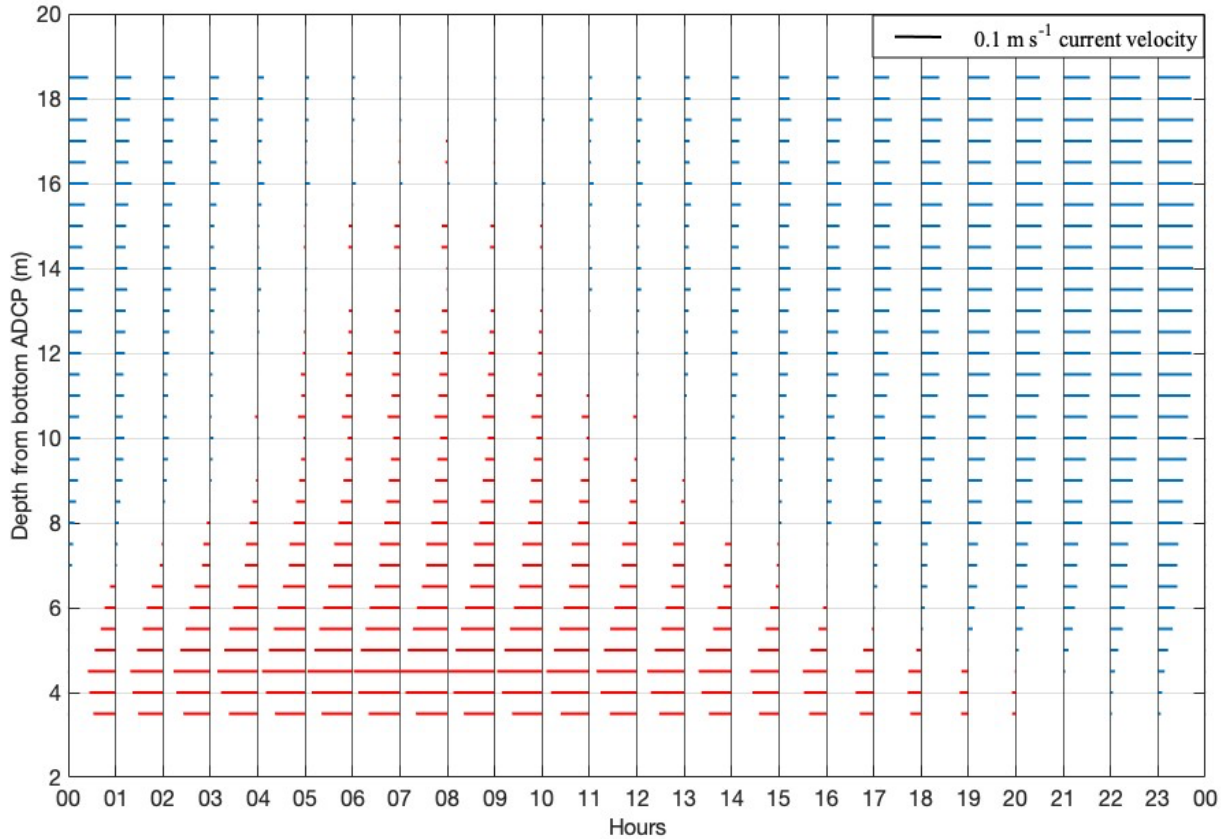


Figure 2-8. Time series of the mean alongshore current velocity on 25<sup>th</sup> April 2022 at the Armona ADCP. Data points are represented per hour by cells of 0.5 m. The blue sticks indicate north-eastward flow and the red arrows a south-westward flow. The dataset is represented de-tide, filtered with a Lanczos-window Cosine Filter (40 h cut off frequency).

#### LOCAL WIND AND THERMAL CIRCULATION AT THE INNER-SHELF

Coastal upwelling at the inner shelf of the NMGoC is primarily not the result of local winds (Sánchez et al., 2006) but rather of large-scale upwelling favourable winds (Garel et al., 2016). The local wind and current speed had, nonetheless, a statistically significant correlated pattern ( $r=+0.56$ ,  $p<0.001$ ), while there was a weak correlation between alongshore wind and alongshore current ( $r=0.28$ ,  $p<0.001$ ). This confirms that although local wind has an impact on the local circulation, other processes, most likely of larger scale intervened. During the studied upwelling event, recorded winds came from the north (with some west influence until 21 April, see Figure 2-4), but it seemed to have a big enough impact on the eastward flow intensity (Fig. 2-5 and 2-6). Notably, the shift in the zonal component of the wind from (north)west to (north)east observed in

the period of 21-26 April may have had an impact on the decay of the eastward current flow, turning into an inversion of the flow on April 25.

The warmer mode water, during CCC (Fig. 2-6), corresponded partially to a reduction of the cold eastward current with low local wind, hence the slower flow reduced heat advection and diffusion, but enhanced surface thermal heating, as described by García-Lafuente et al. (2006b). The origin of the noticeably warm mode water came from a warmed retention pool off the Guadiana River mouth area, observed in the satellite images in Figure 2-2. To a further extend, from the east of the retention bay, in the Guadalquivir River mouth area, the warmer coastal waters would have their source from land heating. The imbalance of the baroclinic geostrophic flow would come from the accumulation of warmer water at this east part of the shelf that creates an alongshore sea surface slope, observed in this study with the slowed eastward flow. Under easterlies and the warmwater pool travels along the south coast from the Guadalquivir River mouth area, near Cadiz (García-Lafuente et al., 2006b).

At the inner shelf, the shallow water column enables variability due to wind stress through the whole water column (Criado-Aldeanueva et al., 2006). A decrease of the current velocity (Fig. 2-5) was felt at depth greater than 8 m when weak wind stress occurred lower than  $6 \text{ m s}^{-1}$ , with a loss of 45 (during CCC) to 50% (during current inversion) relative to the surface velocity at the lower 7 m part of the water column. The vertical shear was less important during upwelling with 35% velocity reduction. Characteristic of an upwelling pattern, with winds stronger than  $8 \text{ m s}^{-1}$  and up to  $12 \text{ m s}^{-1}$ , for 6 days (19-24 April), the current was unequivocally north-eastward throughout the water column with a current speed reduction neglectable felt 4 m from the seafloor. The stronger surface current increase by  $0.1 \text{ m s}^{-1}$  on average from previous slower CCC. At surface, the eastward flow was linked with a cross-shore current going offshore, while the deepest part of the water column (deeper than 8 m), with a reduced alongshore flow, was linked with slow onshore flow ( $< 0.03 \text{ m s}^{-1}$ ). This flow could be due to a reduction of the current and the increased bottom shear stress.

The diurnal shift in wind direction (morning westerlies, afternoon/evening northerlies, see Fig. 2-4) most probably results from both topographic steering, and midday sun irradiance differences from land and coastal water heating, resulting in a mild land breeze as observed in

other studies (Walter et al., 2017). The breeze can have a significant impact on the inner shelf physical water properties (e.g., thermal and salinity/freshwater mixing) and biological activity (e.g., coastal phytoplankton population advection). Diurnal wind forcing is an important mechanism for temperature oscillation for inner shelf waters (Bonicelli et al., 2014; Feddersen et al., 2020), possibly from local scale diurnal upwelling (Woodson et al., 2007). In terms of biological activity mixing at the inner shelf, local winds have been studied to have a key role in phytoplankton dynamics (Lucas et al., 2014), and for higher trophic levels, in the transport of larvae (Satterthwaite et al., 2020).

Studies of the coastal circulation of the NMGoC are often compared to the South Californian Bight. The Wirewalker vertical profiler was previously used in a more in-depth study of phytoplankton community structures and productivity at the Californian shelf from changing environmental conditions (Lucas et al., 2011). During these spring conditions, where thermal stratification increases, upwelling events disrupt the seasonal cycle, which influences the phytoplankton community structures. This could help to explain the Chl-a results as will be presented in the next subsection. The determination of phytoplankton communities structure depending on environmental conditions as been described as hardly predictable (Vidal et al., 2017). Typically, stronger stratification benefits dinoflagellates (Lima et al., 2022), and lower stratified waters during upwellings benefit diatoms (Santos et al., 2021). Nevertheless, this study does not allow for the differentiation of phytoplankton communities and grazing patterns as we do not have information of the taxa of the phytoplankton observed (diatoms or dinoflagellates). Although increased stratification in shallow waters could profit motile dinoflagellates over diatoms (Jones & Gowen, 1990).

#### 2.4.2 PHYTOPLANKTON BIOMASS FLUCTUATIONS

##### PHYTOPLANKTON SIGNATURE RESPONSE TO OCEANOGRAPHIC CHANGES

Changes in the water column properties during the observed oceanographic events (CCC, upwelling and current inversion) and phytoplankton biomass coincide. The three events reveal different biomass concentrations in the different modes water (Fig. 2-6). If we consider the seasonal Chl-a concentration levels on the coast (Fig. 2-2), as previously reported in other studies (Brito et al., 2012; Navarro & Ruiz, 2006), spring is considered the most productive time of the

year for phytoplankton ( $> 3 \text{ mg m}^{-3}$ ). Therefore, the advected waters, observed previously, from different origin (roughly from the west for cold, low phytoplankton upwelled waters, and mixed, phytoplankton rich, warm water of the east part of the NMGoC), show an alteration in time and space of the phytoplankton concentration at the artificial reef. Freely drifting phytoplankton, and other organic particles, along with nutrients, are advected effectively for few to several days by coastal currents (Washburn & McPhee-Shaw, 2013), and shift in the wind regime (Reul et al., 2006). The different mode waters, and contribution from land and/or from offshore waters, will have different nutrients contents that will control the primary production. As the currents alternate at the reef, along with contribution or not from breezes, changes in Chl-a concentration in each mode water were observed.

Here, the mode waters represented in the T-S-Chl-a diagram (Fig. 2-9) were not defined as water masses in the strict sense (as North Atlantic Coastal Water (NACW) or Mediterranean water (MW)) as the seawater parcels were observed at much too shallow depths. However, the diagram revealed the presence of different advected waters that have been the result of mixing and coastal processes occurring at different zones along the coast, passing in front of the Guadiana” retention zone” that also encompass the study area. It is interesting to note that the highest values of Chl-a matched the isopycnic of 26.8-27, close to what was observed by Cardeira et al. (2013) close to this study area ( $\sim 26.5$ ) by the Guadiana River mouth transect, or (26.6 isopycnic) by Oliveira et al. (2009) and Navarro et al., 2006 in the Gulf of Cadiz, as noticeable isopycnic linked with a higher Chl-a concentration.

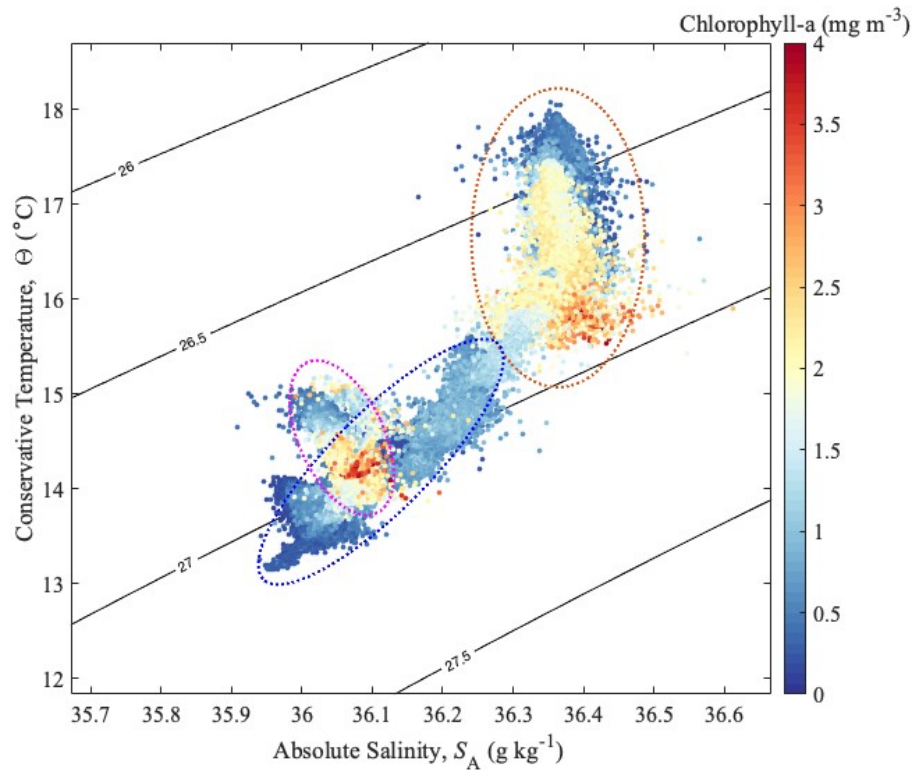


Figure 2-9. T-S-Chl-a diagram of the vertical profiler deployment (14-26 April 2022). Three dotted ellipses show the water masses and chlorophyll-a concentration during different oceanographic events: CCC (red), upwelling (blue), and current inversion (pink). The black lines represent the isopycnic lines expressed in  $\text{g cm}^3 \cdot 1000$ .

Upwelling water have been characterised in previous studies as having a signature of low temperature and Chl-a concentration ( $< 15^\circ\text{C}$ ,  $< 1 \text{ mg m}^{-3}$ , respectively) (Cardeira et al., 2013; Cravo et al., 2010). During the upwelling event, the water column was mixed with an increased alongshore current velocity ( $0.4 \text{ m s}^{-1}$  at surface, Fig. 2-5a). In this period, Chl-a concentration did not exceed  $1.5 \text{ mg m}^{-3}$ , three times lower than during relaxation events (CCC and current inversion; Fig. 2-6). The correlation of the alongshore current with Chl-a ( $-0.3$ ) and Osat ( $-0.25$ ) reflect this interplay, as an increase eastward flow meant the advection of phytoplankton poor, less oxygenated waters (see Table 2-2) from waters uplifting from deep levels. Different factors can affect the phytoplankton biomass. The increased turbidity during times of upwelling can reduce light availability, but it seems it was not the case since turbidity did not exceed 1 NTU. No stratification and a higher flow velocity leading to a shorter residence time (Vidal et al., 2017), conditions that are not favourable to phytoplankton growth, even under an increase of nutrients

provided by upwelled waters (Cardeira et al., 2013; Cravo et al., 2010, 2013; Simons & Catlett, 2023).

The highest concentration of phytoplankton biomass was observed during CCC (or post-upwelling event) and current inversion (Fig. 2-6 and 2-10) that were associated with periods of wind relaxation. During these days, the local wind velocity was low, and the water column intermittently stratified, promoting the growth of phytoplankton. This delay in time before and after upwelling could be a consequence of the phytoplankton demand of water stability for its development (Cardeira et al., 2013; Cravo et al., 2013, Simons and Catlett, 2023). In a recent study of Simons and Catlett (2023) at the Santa Barbara Channel, it was hypothesized that eddy circulation by the coast, when coupled with a relatively weak upwelling and therefore increasing the water residence time, amplified the seasonal Chl-a concentrations. In this study area, during CCC, the eastern bight of the NMGoC, close to Guadiana River mouth, may act as a “shadow” upwelling zone, like identified in similar systems, e.g., in California (Satterthwaite et al., 2020). This zone has been described by de Oliveira Júnior et al. (2022) as an area where a recirculation cyclonic eddy can occur, hence, this could have a favourable impact on the biological activity. The bight may be considered a retention bay, similar to the area in front of Portimão (Cardeira et al., 2013; Cravo et al., 2013). Correlations between *Osat* and the alongshore current were significantly high during CCC and current inversion (respectively +0.63 and +0.74), while inverted during the upwelling event (-0.25), reflecting the increase in oxygen in the water column particularly at the surface levels where the current is stronger, able to oxygenate the water. The opposite correlation between *Osat* and the alongshore current was found during the upwelling event (-0.25), meaning that under stronger currents and uplift of waters from deeper levels, the levels of oxygen decrease associated with increased respiration and organic matter remineralization processes.

During current inversion (Fig. 2-10), and after a wind relaxation period of about 12 h (Fig. 2-4), the response of the phytoplankton biomass was notably fast and homogeneous throughout the whole water column, suggesting the advected water from the east warmwater pool near the Guadiana River mouth resulted in a higher concentration (1.5 to 3 mg m<sup>-3</sup>), passing the vertical profiler. The Guadiana area is also considered a retention area, where concentrations in the spring period could benefit from nutrients from the estuary (Cravo et al., 2006). Nutrients concentration for different modes water were not collected during the study to establish whether the increased

biomass could have been partly due to an outflow of nutrients from the nearest river, the Guadiana, from the CCC or from upwelled waters. Although with spring conditions, the river outflow was very low in April with  $10.64 \text{ m}^3 \text{ s}^{-1}$  at Pulo do Lobo for the Guadiana River (see [recordings](#) from the Sistema Nacional de Informação de Recursos Hídricos) associated with very low precipitation recorded at the Cacela meteorological station (<https://www.drapalg.min-agricultura.pt/pt/servicos-e-produtos/servicos/fitossanidade/avisos-agricolas>), where precipitation was null in April 2023. The river discharge is generally low and constant, approximately  $10 \text{ m}^3 \text{ s}^{-1}$  throughout the year, except during intense rainfall events and potential water release from dams (Correia et al., 2020). Here, nutrients concentration would be expected to be low in opposition to winter conditions when river outflow can increase markedly. In fact, a study in the area during winter conditions showed that the surface waters of the study site (first 5 m) were mixed with higher nutrient driven from river discharge when the river outflow is  $> 100 \text{ m}^3 \text{ s}^{-1}$  (Cravo et al., 2006). Rather, here, high nutrients levels from upwelled waters may be a primary source, possibly even more so than from coastal influence, as it was observed in previous studies (García et al., 2002). Nevertheless, looking for the satellite images of Chl-a from March and April 2022 (Fig. 2-2), in the NMGoC, the highest values were consistently found in front of the main rivers, pointing for the contribution of nutrients availability in these areas.

When northerlies occurred in the afternoon (Fig. 2-10), alongside the intermittent stratification and a reversal back to an eastward EF (Fig. 2-8), the phytoplankton biomass was once again highest at the bottom ( $>3 \text{ mg m}^{-3}$ ). This time, however, the whole water column showed a mixed higher concentration of primary producers ( $\sim 2 \text{ mg m}^{-3}$ ). This occurrence could reflect the already phytoplankton-rich water passing back and forth by the vertical profiler, and not due to a fast growth attaining these concentration levels in periods shorter than 12 h. Typically for the Californian EBUS, a delay of 3-10 days after upwelling is needed for phytoplankton to deplete the new nutrients in the surface waters (Simons & Catlett, 2023).

#### DIURNAL PHYTOPLANKTON BIOMASS VARIABILITY

A closer analysis of the diurnal variation of the Chl-a reveal clear diurnal pattern of phytoplankton biomass fluctuations. For better visualisation, the time series of the two days with the noticeably highest Chl-a concentration are presented in Figure 2-10 (a) during CCC/ upwelling

relaxation, and (b) during current inversion. Here the hourly wind, Chl-a, density, and the buoyancy frequency are plotted to illustrate the changing stratification and phytoplankton biomass changes. In both instances, the Chl-a was highest in the afternoon (from ~3-9 pm), during periods of dominating afternoon land breeze from the North ( $< 5 \text{ m s}^{-1}$ ). A diurnal pattern was observed during CCC and current inversion, where the phytoplankton biomass was only rising to the surface slightly in the morning, then dropping at midday until 3pm ( $< 1.5 \text{ mg m}^{-3}$ ), to be at a peak until the evening (9 pm).

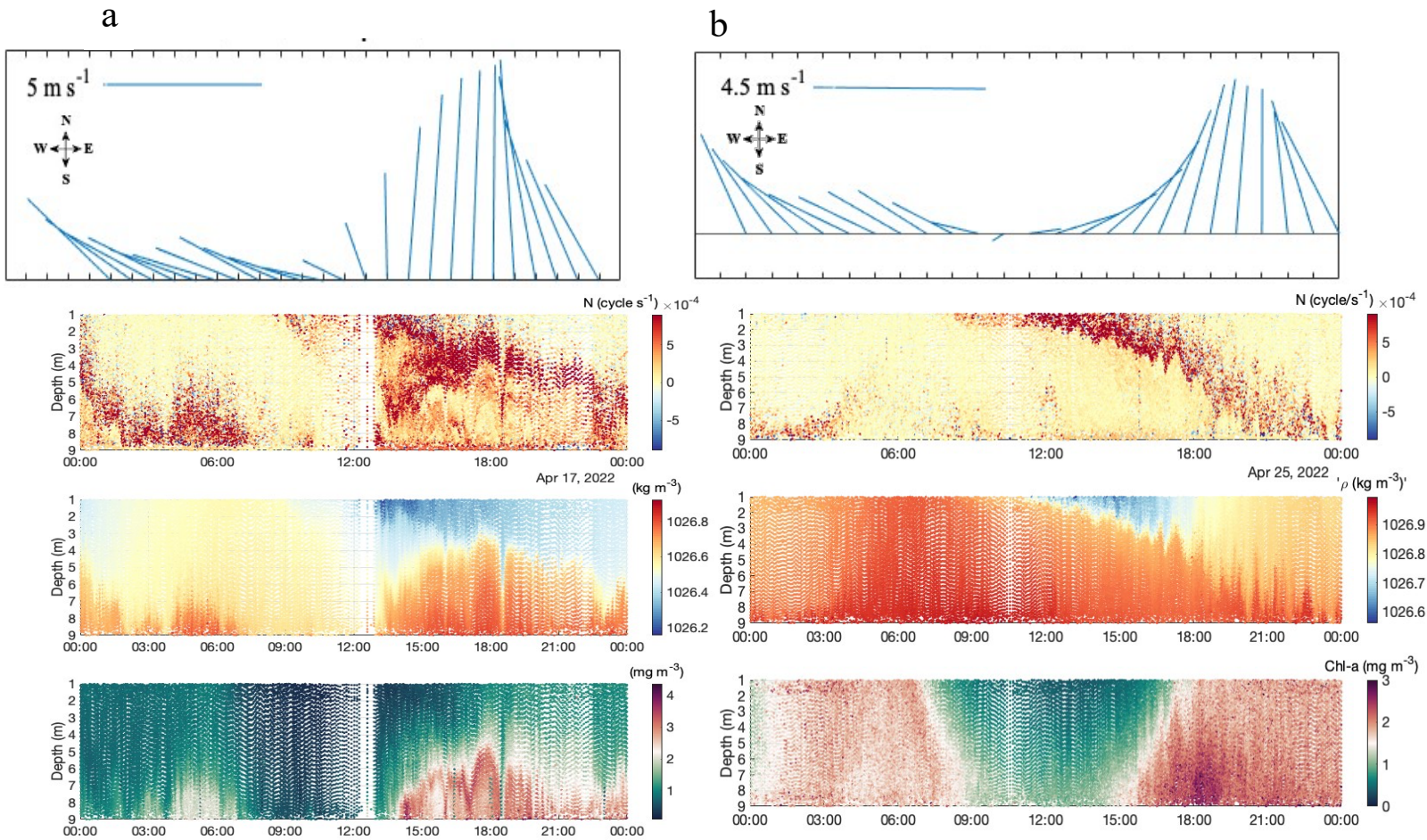


Figure 2-10. Daily time series at the Cacela Velha reef of local wind, buoyancy frequency, Density and Chlorophyll-a for: (a) 17<sup>th</sup> of April under CCC, and (b) 25<sup>th</sup> of April under current inversion.

The wind and current may have been of influence, but at midday, it can be assumed that the phytoplankton avoided photoinhibition (Domingues et al., 2005; Durham & Stocker, 2012; Platt et al., 1980; Raine et al., 2018). The sensitivity to overexposure from solar (ultraviolet) radiation may be one possible explanation for the phytoplankton distribution under the thermocline at this shallow water column. However, without knowing the phytoplankton composition, we cannot confirm it, only the biomass observation can be inferred. It has been observed in other studies that increased irradiance does not seem to have a drawback effect on phytoplankton growth (Häder et al., 2015). However, in a study of phytoplankton assemblage with increased UV exposure, in the shallow Ria Formosa coastal lagoon, on the south coast of Portugal, the composition changed (Domingues et al., 2017). Studies of the changing assemblage at the inner shelf in this region are yet to be conducted.

The diurnal stratification of the water column (midday till sundown) seemed to be a major factor in the peaks of phytoplankton biomass (Fig. 2-6 and 2-10a), as it was observed every day during CCC. In areas of stratified water column, the accumulation of phytoplankton biomass was observed under intermittent thermal strata present due to surface water heating from the diurnal sun cycle (Navarro et al., 2006). The intermittent surface layer descended from midday to the seafloor at the end of the day. As the stratification varied throughout the day, the highest Chl-a concentrations were felt at the bottom, up to ~4 m from the seafloor. During CCC and the current inversion, the Brunt Vaisala Frequency exacerbated the pycnocline (26.6-26.8) that followed the thermal heating of surface water from sun's irradiance intensity: from the surface (9 AM to midday) and descending (midday to midnight), resulting in the localisation of the phytoplankton under this layer to the seabed as found by other authors (Durham & Stocker, 2012). Similar results were found by Correia et al. (2020) at the mouth of the Guadiana River during a winter period, where lowest levels of Chl-a were observed from 10 am to 3 pm, under a river discharge of ~20 m<sup>3</sup> s<sup>-1</sup>. The phytoplankton biomass was observed always under the intermittent surface layer. Although at times the concentration was well mixed throughout the water column, the levels were predominantly highest at the bottom (Fig. 2-6, and 2-10). On two occasions, the shift between currents (CCC/ upwelling) resulted in the occurrence of uniform phytoplankton concentration from the surface down to the bottom (see 19-20 and 25 April in Fig. 2-6), once again, always between 3 and 9 pm, when the wind was lowest (< 5 m s<sup>-1</sup>; Fig. 2-10).

The combination of a reduced flow with increased residence time, stronger thermal stratification and land breeze favoured a higher phytoplankton concentration, as observed in previous studies, this could enhance the chances of algal bloom (Pitcher et al., 2010). Chl-a/ cross-shore wind correlation during CCC was negative (-0.44; Table 2-2), showing the importance of land breezes during upwelling relaxation, transporting water enriched in Chl-a that was captured by the vertical profiler from a current flowing offshore on April 17 (Fig. 2-5), despite the tidal flooding period (high water at 4 pm, peak of Chl-a from 3 pm). However, on April 25, during the current inversion there was a decay of the wind, while this time the alongshore current was flowing westward (00:00 to 20:00), and a low onshore current was present ( $0.03 \text{ m s}^{-1}$ ), Chl-a was homogeneously high in the water column, and while the tidal flooding period from 6:00 to 12:00 (high water) occurred, a decrease in Chl-a was observed, as seen in Fig. 2-10, suggesting the waters offshore from the study areas had lower Chl-a concentration. After the next ebb until 18:00 (low water), Chl-a concentrations started to increase again and were well mixed along the shallower water column, with a potential contribution from cross-shelf exchanges. This fact may denote that in a shallow environments tidal influence on a mesotidal system, interacting with the alongshore flow, might be also an issue to consider explaining diurnal variability of the water characteristics.

#### PHYTOPLANKTON AND CROSS-SHELF TRANSPORT

Outside of the upwelling period, changes in the local wind reflected the afternoon northerlies land breeze that were due to the difference in the heating of the land and the sea (Walter et al., 2017). Phytoplankton biomass increased appeared under the conditions of both diurnal thermal stratification and appearance of northerly winds. Only when the current inverted westward (Fig. 2-5, 2-8), did the phytoplankton spread throughout the water column (Fig. 2-6, 2-10b) and under westerlies (Fig. 2-4, 2-10b). This suggests that the advected phytoplankton communities are of different sources and probably, composition, and could also reflected different stages of growth (Simons & Catlett, 2023).

Studies have been conducted at the South Californian bight in the Californian Current System, where cross-shelf transport processes during periods of upwelling (spring) occurred with a certain isolation of the communities at the inner shelf (7 to 65 m) from the outer-shelf during downwelling

conditions (Goodman et al., 2012). In the experiment, the author observed better uniformity in diatoms across the shelf than during downwelling conditions. A cross-shelf gradient weakened during weak stratification, due to an exchange of water masses, with supply in Chl-a coming from offshore (Halewood et al., 2012). When there was a cross-shelf gradient, blooms of diatoms and then dinoflagellates occurred at the shelf of the Southern California Bight (Washburn & McPhee-Shaw, 2013). At the inner shelf of NMGoC, cross-shore currents ( $< 0.15 \text{ m s}^{-1}$ ), were observed going offshore when the eastward alongshore current was strongest ( $0.1- 0.4 \text{ m s}^{-1}$ ), and slowly onshore when eastward current was slower ( $< 0.1 \text{ m s}^{-1}$ ). Highest Chl-a concentration occurred when the cross-shore current at the deepest water depth ( $> 8\text{m}$ ) was onshore, which coincide with the findings from Goodman et al. (2012) and Halewood et al. (2012), and of Satterthwaite et al., (2020), for the transport of larvae at the northern Monterey Bay.

In this study, a multiplicity of environmental parameters acting together with the typical seasonal cycle of higher concentration in spring could have played a key role to control the higher phytoplankton concentration, during wind relaxation or current inversion, namely: lower wind stress; reduced flow with stronger thermal stratification, bringing laterally water from retention areas with higher concentrations of phytoplankton; afternoon northerlies that may have influenced shelf mixing; and some onshore flow at lower depths.

## 2.5 CONCLUSION

This study presented the high resolution (2Hz) vertical profiles from a wave-powered vertical profiler at the location of the Cacela Velha artificial reef at the Southeast Portugal inner shelf, at the NMGoC. The finite continuous recording for 12 days of ~120 vertical profiles per hour allowed for the observation of distinct physical processes occurring at the shelf: coastal counter current, upwelling and current inversion.

The key findings show that the seasonal spring levels of Chl-a ( $3\text{-}4\text{ mg m}^{-3}$ ), as a proxy for phytoplankton biomass, was ~2 times lower during the 6 days of upwelling ( $1.5\text{ mg m}^{-3}$ ), during which time, the eastward flow increased by  $1\text{ m s}^{-1}$  and may also reflect different stages of development for the freely drifting phytoplankton. Two noticeable events of high Chl-a concentration occurred during times of CCC and current inversion, with stratified water columns. The thermal stratification here was present due to diurnal solar irradiance at the surface water, and with lower current velocity (48% lower), hence increasing the residence time and higher water stability for phytoplankton at the inner shelf. The diurnal stratification happened from midday to the evening and a swift accumulation in the phytoplankton biomass was observed within a few hours from 3 pm to 9 pm. The phytoplankton concentration increased rapidly with changing environmental processes. Not only did the biomass increase outside of the higher current flow of the upwelling event, but the wind stress intensity had to be in all cases at its lowest ( $< 5\text{ m s}^{-1}$ ).

A key observation here was that the biomass was the highest at the deepest level of the water column, where a relatively low onshore current was occurring at similar depths. This finding may reflect the influence on cross-shelf transport that may supply the inner shelf ecosystem in phytoplankton biomass and nutrients from the outer-shelf.

A current inversion post-upwelling occurred within 24 hours and showed an opposite alongshore current going South-westward that only occurred during lower wind intensity throughout the water column and resulted in the advection of phytoplankton rich water, most likely from the seasonal productive pool of warm retained in the eastern bay of the NMGoC, close to the Guadiana River mouth. This event fits the theory seen in previous literature that states that the inner shelf flow alternates between stronger equatorward flows, and a counter-flow from an alongshore pressure gradient.

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## 2.7 DATA AVAILABILITY

The dataset from the vertical profiler is available on the ERDDAP server (<https://erddap.ccmар.ualg.pt/>) created in collaboration of NOAA and CCMAR to make oceanographic data globally accessible. The ADCP data is available upon request at CIMA (contact: Dr. Erwan Garel - [egarel@ualg.pt](mailto:egarel@ualg.pt)). ERA5 Reanalysis data are available from the Climate Data Store database of Copernicus, as part of the “ERA5 hourly data on pressure levels from 1940 to present” datasets.

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## Chapter 3: Conclusions

This Master thesis analysed two weeks of high resolution *in-situ* recordings of inner-shelf water physical, chemical and biological properties at the artificial reef of Cacela Velha (NMGoC), along with current and local wind datasets. From satellite imagery, a warmer water coastal counter-current (CCC), a colder coastal upwelled water was observed during the equipment deployment.

The analysis allowed a fine scale analysis of the effect of changing environmental processes in the water column water properties, notably the effect on the primary producers - the phytoplankton. Results showed differences in the advected water and the corresponding phytoplankton biomass. The warmer, more saline water during CCC were synonym of a reduction of the dominant current at the inner-shelf, eastward equatorward flow (EF). With flow decrease, the shallow water column (< 15 m) became intermittently stratified from solar radiation, with a pycnocline (isopycnic 26.6-26.9) descending from surface ~9 am to the seafloor in the evening. The consistent diurnal pattern was observed during CCC and post-upwelling, during a day long current inversion. Seasonal high phytoplankton biomass (3-4 mg m<sup>-3</sup>) was highest during CCC, from the bottom to the midday thermohaline strata (deeper than 4 m). During current inversion (for 20 hours), the phytoplankton concentration increased in relation to previous upwelled water (1.5 to 3 mg m<sup>-3</sup>) fully mixed in the water column that can be driven from the “shadow” retention bay in front of Guadiana River mouth, or even from further eastward within the NMGoC, by the Guadalquivir River mouth area. Despite the westward flow, then the reversal to an eastward EF in the afternoon, and diurnal thermal stratification, the biomass was homogeneous along the water column. During the periods of higher phytoplankton concentration, a sharp decrease (again upwelling biomass levels) occurred during midday to 3 pm. The sharp decrease reflected the avoidance of photoinhibition due to strong midday solar irradiance. During days of increased eastward flow with colder, less saline waters, under an upwelling event, no stratification was observed, along with a slightly increase of turbidity, decrease of dissolved oxygen saturation, and an overall well mixed but low phytoplankton biomass along the water column (< 1.5 mg m<sup>-3</sup>).

The interpretation of the results suggested the occurrence of advected phytoplankton biomass with their respective current, and the influence of local processes on phytoplankton accumulation (from stratification, cross-shelf transport, and higher residence time). The occurrence of CCC

seemed to facilitate phytoplankton development due to a set of favourable conditions. However, as observed from inner shelf dynamics studies, a multitude of environmental parameters played a time sensitive role in the increase of phytoplankton. The generally high Chl-a concentrations had their source in the retained warmer water pool from the Guadalquivir River area to CSM balancing against the nutrients rich eastward upwelled water. As this study was restricted to changes occurring in time at one location of the shelf, speculations were made on the weight of the diurnal cross-shelf transport of water properties and phytoplankton, from afternoon northerly land breeze, as well as tides, that may have an effect alongside the equatorward-poleward advection. The alongshore advection of the current was not significantly correlated to local alongshore wind, but the CCC and inversion of the current both occurred during lower wind stress, agreeing with previous studies stating the main driver of inner-shelf alternative flow is the alongshore pressure gradient. Further studies of similar resolution could help strengthen the present findings by notably discerning the changing phytoplankton communities at the inner-shelf of the NMGoC depending on cross-shelf and alongshore transport and diurnal environmental drivers.