UNIVERSIDADE TÉCNICA DO ATLÂNTICO
INSTITUTO DE ENGENHARIA E CIÊNCIAS DO MAR

WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE

Master Thesis

EFFECT OF EDDIES ON PLANKTON PRODUCTIVITY IN THE CABO VERDE REGION

PATRÍCIA HELENA FERREIRA SILVA

Master Research Program on Climate Change and Marine Sciences

São Vicente
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Patrícia Helena Ferreira Silva

Master's thesis presented to obtain the master's degree in Climate Change and Marine Sciences, by the Institute of Engineering and Marine Sciences, Atlantic Technical University in the framework of the West African Science Service Centre on Climate Change and Adapted Land Use

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Panel defense

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Examiner 1

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Examiner 2

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Resumo

O objetivo deste estudo foi avaliar e quantificar a distribuição do plâncton à volta de Cabo Verde e determinar como os redemoinhos afetam a sua produtividade. Isso foi feito usando medidas acústicas conduzidas no mar, utilizando uma ecossonda científica, operando com um transdutor de 200 kHz, visto que, com base nas características de refletância de organismos "semelhantes a fluidos", como o zooplâncton, eles produzem um eco mais forte nessa frequência. Também usamos a refletância integrada (*NASC*) como um indicador da abundância do plâncton. Os dados foram coletados durante a missão *ATL2MED*, de outubro a dezembro de 2019. Condições ambientais (Salinidade, Temperatura e Radiação Fotossinteticamente Ativa - *PAR*) foram analisadas de forma a determinar os seus efeitos na distribuição da biomassa do plâncton. A clorofila a foi analisada como um indicador da distribuição do fitoplâncton. A salinidade variou de 35,6 a 37,2, com uma média de 36,4, a temperatura variou de 20,5 a 27,3 °C, com uma média de 24,1 °C, *PAR* variou entre 0 e 1921 e a clorofila variou de 0,06 a 4,1 mg/m^3, com os maiores valores dentro do redemoinho 1. Foram visíveis dois *hotspots* de produtividade: um na região impactada pelo redemoinho 1 e outro perto do extremo sul da ilha do Sal. Dentro e fora do redemoinho, *NASC* apresentou valores maiores durante a noite comparado ao dia. Foram gerados os gráficos de *NASC* em relação a distância ao núcleo do redemoinho, à costa do Sal e ao monte submarino Nova Holanda. A correlação entre *NASC* e variáveis ambientais também foi feita para verificar o efeito das mesmas na distribuição do plâncton.

Palavras-chave: produtividade primária, hidro-acústica, plâncton, redemoinhos, Cabo Verde.

Abstract

The aim of this study was to assess and quantify the plankton distribution in the Cabo Verde region and determine how eddies do affect its productivity. This was done using acoustic measurements conducted at sea utilising a scientific echosounder operating with a 200 kHz transducer, because based on the backscattering characteristics of “fluid like” organisms such as zooplankton, they yield a stronger echo at this frequency. We also used the integrated backscatter (NASC) as a proxy for plankton abundance. Data were collected during the ATL2MED mission, from October to December 2019. Environmental conditions (Salinity, Temperature and Photosynthetically Active Radiation - PAR) were analysed in order to determine their effects on plankton biomass distribution. Chlorophyll a was analysed as a proxy for phytoplankton distribution. Salinity varied from 35.6 to 37.2, with an average of 36.4, temperature ranged from 20.5 to 27.3 °C, with an average of 24.1 °C, PAR ranged between 0 and 1921 and chlorophyll ranged from 0.06 to 4.1 mg/m^3, with highest values within eddy 1. Two productivity hotspots were visible, one in the region impacted by eddy 1 and the other close to the southern tip of Sal. Within and outside the eddy, NASC was higher during the night compared to the daytime hours. NASC was plotted against distance to the eddy core, to the coast of Sal and against to Senghor seamount. The correlation between NASC and surface environmental conditions was also done to check the effect of them on plankton distribution.

Keywords: primary productivity, hydroacoustics, plankton, eddies, Cabo Verde.

Abbreviations and acronyms

ACME	Anticyclonic Modewater Eddies
ADCP	Acoustic Doppler Current Profiler
ATL2MED	Atlantic to Mediterranean
BNR	Background Noise Removal
CC	Canary Current
Chl-a	Chlorophyll a
CVFZ	Cape Verde Frontal Zone
dB	Decibel
DVM	Diurnal Vertical Migration
EBUS	Eastern Boundary Upwelling Systems
ETNA	Eastern Tropical North Atlantic
GD	Guinea Dome
GPS	Global Positioning System
ITCZ	Intertropical Convergence Zone
MC	Mauritanian Current
MOCNESS	Multiple Opening and Closing Nets and Environmental Sampling System
NACW	North Atlantic Central Water
NASC	Nautical Area Scattering Coefficient
NEC	North Equatorial Current
NECC	North Equatorial Counter-Current
NEU	North Equatorial Undercurrent
NPP	Net Primary Productivity
OMZ	Oxygen Minimum Zone
PAR	Photosynthetically Active Radiation

SACW	South Atlantic Central Water
SD	Saildrone
SQL	Structured Query Language
SST	Sea Surface Temperature
Sv	Volume Backscattering Strength
USV	Unmanned Surface Vehicle
VGPM	Vertically Generalized Production Model

General index

Figure index

Table index

1. Introduction

1.1. Background and Context

The Central Tropical Atlantic Ocean is an oligotrophic "blue ocean" area with very low productivity and complex pelagic food webs. At its eastern boundary, however, it is home to the Canary Current, an upwelling region that features high primary productivity that provides the food for the large stocks of sardinella and tuna, which play key roles in the fishery (Piontkovski *et al.,* 2003 and references therein). Out of the four Eastern Boundary Upwelling Systems (EBUS), this one is the least studied one, with still large uncertainty on the spatial and temporal dynamics governing its productivity (Chavez and Messié, 2009).

Apart from the seasonality in the trade wind system and associated upwelling intensity, it also features mesoscale eddies that can create and maintain local upwelling that is carried far offshore into the oligotrophic open ocean. These eddies are created both at the Capes of the African west coast (Schütte *et al.,* 2016) as well as in the wake of the tallest islands of the Cape Verdean archipelago, Fogo and Santo Antão. Eddies are divided into cyclones that rotate counter clockwise, and anticyclones that rotate clockwise in the northern hemisphere. Classically, cyclones are thought to result in shoaling of the mixed layer and upward transport of nutrients, enhancing biological productivity under favourable conditions, even in regions that can be presumed as oligotrophic regions, and anticyclones to result in downward transport of nutrients, decreasing nutrient availability (Cardoso *et al.,* 2020 and references therein). However, there are two types of anticyclones. Although normal anticyclones are generally relatively warm and unproductive, cyclonic and anticyclonic modewater eddies (ACMEs) are characterized by a negative sea surface temperature (SST) and positive surface chlorophyll a (chl-a) anomaly. In particular, ACMEs have been observed to exceed cyclones in terms of upwelling nutrients and productivity in the subtropical Atlantic (Hauss *et al.,* 2016 and references therein).

Diverse biotic and abiotic factors, such as light, prey density, temperature, oxygen concentration, among others, vertically structure the habitat of pelagic marine organisms. In the mesopelagic region of the Eastern Tropical North Atlantic (ETNA), a permanent Oxygen Minimum Zone (OMZ) is found, where oxygen concentrations are not lower than 40 µmol O_2 kg^{-1} (Karstensen *et al.,* 2008), but are low enough to exclude high active top predators such as billfishes from the OMZ. In the pelagic habitat various organisms perform vertical migration. Diurnal vertical migrations (DVMs), are performed by many zooplankton and nekton taxa, usually spending the daylight hours in the mesopelagic OMZ and migrating into the productive surface layer at night to feed. These taxa comprise, for example, euphausiids, sergestid and penaeid shrimp, myctophid fishes, and also several large calanoid copepods (e.g., *Pleuromamma* species, Hauss *et al.*, 2016 and references therein).

Plankton is a microscopic community of plants (phytoplankton) and animals (zooplankton), usually found free-floating, swimming with little or no resistance to currents, suspended in water, immobile or insufficiently mobile to overcome current transport. Phytoplankton (microscopic algae) usually occur as unicellular, colonial or filamentous forms and are primarily photosynthetic and are fed by zooplankton and other organisms that occur in the same environment. Zooplankton are mainly composed of microscopic protozoans, rotifers, cladocerans and copepods. For their short life spans, plankton respond quickly to environmental changes (Ramachandra & Solanki, 2007).

There are several methods to analyse plankton, which can be quantitative or qualitative. One of the quantitative methods is hydroacoustics that, besides widespread use in fishery surveys, has been widely used as a tool for surveying the spatial distribution or phenology of zooplankton biomass (e.g., Greenlaw, 1979; Stanton *et al.*, 1994), and recent advances in the field of autonomous vehicles (e.g., Ohman *et al.*, 2019) have been made in conjunction with the development of multifrequency and/or broadband methods that allow for more sophisticated discrimination of scattering layers.

1.2. Problem Statement and Research Questions

It is known that there are a lot of eddies that form at the eastern margin of the ocean and then move westward in the West African Upwelling System. Looking at the satellite altimetry, there are either hills or valleys that represent anticyclonic or cyclonic eddies, respectively, having different characteristics, and they can be very productive or very unproductive. Based on the satellite altimetry, temperature signature and chlorophyll signature it is possible to distinguish two productive kinds of eddies in the region, the Anticyclonic Modewater Eddies (ACME) and the cyclonic eddies.

The aim of this study is to assess and quantify the plankton distribution in the Cabo Verde region and determine how eddies do affect plankton productivity. This will be done using acoustic measurements conducted at sea utilising a scientific echosounder operating with a 200 kHz transducer, because based on the backscattering characteristics of “fluid like” organisms such as zooplankton, they yield a stronger echo at this frequency. The integrated backscatter (NASC) will also be used as a proxy for plankton abundance, to answer the following questions: How is phyto- and zooplankton biomass distributed in the Cabo Verde region? How do environmental conditions affect phyto- and zooplankton distribution around Cabo Verde? Can surface environmental conditions be used to predict plankton biomass in the Cabo Verde region? Is plankton biomass increased in the vicinity of the islands, in certain eddies, and at Senghor Seamount?

1.3. Relevance and Importance of the Research

Due to the importance of the plankton community in the pelagic food web, including serving as a trophic link, and transferring energy from primary producers to the larger invertebrate predators, as well as fish through the food chain, identifying productivity hotspots around Cabo Verde is essential to understand fish distribution, and thus relevant to sustainable management of marine living resources. Also due to the limitation of studies that do not allow us to know about the distribution of plankton in the region and the effect of eddies on its productivity, knowing hotspots of plankton productivity in the Cape Verde region and how they are affected by eddies can help to gauge the fish availability/distribution in this area.

1.4. Objectives of the work

The aim of this study is to assess and quantify the plankton distribution in the Cabo Verde region and determine how eddies do affect plankton productivity, and the specific objectives are:

- To determine how phyto- and zooplankton biomass is distributed in the Cabo Verde region;
- To determine how environmental conditions affect phyto- and zooplankton distribution around Cabo Verde;
- To determine if surface environmental conditions can be used to predict plankton biomass in the Cabo Verde region;
- To determine if the plankton biomass increases in the vicinity of the islands, in certain eddies, and at Senghor Seamount.

1.5. Structure of the work

This work is structured as follows: a contextualization in order to facilitate the understanding of the work, the objectives and its importance are presented in section 1, a brief review concerning the regional setting and the main concepts is presented in section 2. The section 3 discusses the data used and how they were obtained, along with the subsequent processing methods, the main results are presented in section 4 and subsequent discussion in section 5, and the main conclusions are summarized in section 6. The literature cited for this work is shown in section 7, and finally, the appendix section shows the settings used in noise removal and some of the scripts used for the analyses.

2. Literature review

2.1. Characterization of the Cabo Verde archipelago

2.1.1. Geomorphology

Cabo Verde is an archipelago with ten deep water islands located in the Eastern Tropical North Atlantic (ETNA), between 450 and 600 km off the western African coast. It lies between latitudes 14° and 18° North, and longitudes 22° and 26° West. The archipelago is organized in a west-facing horseshoe disposition and can be divided in two main groups: the windward islands at the north and the leeward islands at the south. The local bathymetry reveals the existence of two major structures, characterized by shallow depths between islands: the first structure is the northern chain, with a west–east orientation, consisting of islands from Santo Antão to São Nicolau, and the second structure is the east–south west chain, formed by two detached edifices composed of islands from Sal to Santiago and from Fogo to Brava (Ramalho, 2011).

2.1.2. Oceanographic setting

The archipelago's regional context is characterized by a zone of large-scale interactions (Figure 1) between the Canary Current (CC), the North Equatorial Current (NEC), the North Equatorial Counter-Current (NECC), and the seasonal Mauritanian Current (MC; Mittelstaedt, 1991). This large-scale interactions of currents and features is strongly affected by the seasonal meridional migration of the Intertropical Convergence Zone (ITCZ; Stramma & Schott, 1999).

The CC, one of the prominent oceanic features influencing circulation patterns in Cabo Verde, transports cold water from north to south off the African coast, that turns south-westward near Cape Blanc to become the NEC (Stramma *et al.*, 2005). The NEC has a weakening during winter and maximum speed in summer. The NECC has an eastward mean flow speed of approximately 42 cm s^{-1} (Fratantoni, 2001). It also exhibits seasonality, being strong during summer and early autumn (Mittelstaedt, 1991), when the ITCZ reaches its northernmost position (Lázaro *et al.*, 2005), and it is also during this time that the NECC can have an influence in the Cabo Verde archipelago (Fernandes *et al.*, 2005). The MC forms as a result of the interaction of the NECC with the African coast. It reaches approximately 14° N during winter/early spring, and can extend up to approximately 20° N during summer/early autumn, and has been documented to be partly responsible for the suppression of the regional coastal upwelling (Mittelstaedt, 1991). Southwest of Cabo Verde, there is the Guinea Dome (GD), a permanent cyclonic geostrophic feature, associated with the NEC, the NECC, and the North Equatorial Undercurrent (NEU; Siedler *et al.,* 1992). It is defined by a cold dome of isotherms and low hydrostatic pressure (Faye *et al.,* 2015), developed by divergent wind-stress curl (Siedler *et al.*, 1992).

Two different water masses meet around the archipelago and extend the entire length of the Atlantic Ocean (Lozier *et al.,* 1995), forming a basin-wide frontal system between Cape Blanc and the northernmost Cabo Verde islands termed the Cape Verde Frontal Zone (CVFZ; Zenk *et al*., 1991). This strong thermohaline front (Zhang *et al*., 2003) separates the relatively young, salty and warm water mass with nutrient-poor and oxygen rich concentrations North Atlantic Central Water (NACW) from the older, fresher and cooler water mass with nutrient-rich and oxygen poor South Atlantic Central Water (SACW; Mittelstaedt, 1991; Meunier *et al.,* 2012).

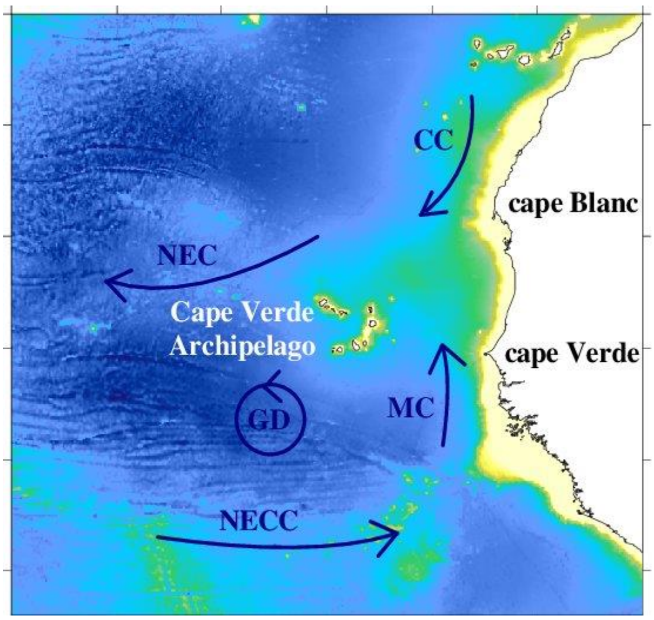

Figure 1. Schematic representation of the major ocean circulation features presented in Cape Verde Archipelago region (acronyms explained in the text). Also shown is the location of capes Verde and Blanc. From Fernandes *et al.,* 2005.

2.2. Conceptual bases

2.2.1. Plankton

The word "plankton" derives from the Greek word *planktos* that means "to drift" and comprises organisms able to move in water but unable to swim against the currents (McEnnulty *et al.,* 2020). In the oceanic realm, the majority of species are holoplankton, meaning they spend their entire life cycle as plankton. Species where only early life stages are planktonic and later either nekton (such as fishes) or benthos (such as echinoderms and many molluscs), are called meroplankton. Plankton organisms are further divided into size groups (pico-, nano-, micro-, meso-, macro) for practical reasons as this reflects different observation methods that are needed to quantify them, and into autotrophic and heterotrophic organisms, depending on their energy source (e.g., microphytoplankton comprises photoautotrophic cells between 20 and 200µm in size).

2.2.2. Phytoplankton

Phytoplankton is composed of aquatic microscopic plants suspended in water: various species of prokaryotic (blue-green alga) and eukaryotic algae (Ramachandra & Solanki, 2007). Phytoplankton are the autotrophic components of plankton and an important part of the oceanic and freshwater ecosystems, forming the basis of marine food webs and are responsible for about half of global photosynthetic activity and oxygen production (Karlusich *et al.,* 2020). In the oligotrophic open ocean, the phytoplankton community is dominated by pico- and nanoplankton (e.g., Prochlorococcus and Synechococcus). Diazotrophy (the ability to fix atmospheric N_2) is a competitive advantage, but is often iron limited, so that dust input leads to extensive blooms of the filamentous cyanobacterium *Trichodesmium* (e.g., Hauss *et al.,* 2013; Sandel *et al.,* 2015). Under upwelling of nutrient-rich deep water at the eastern boundary or in productive eddies, however, diatoms also contribute substantially to the primary producers (Fischer *et al.,* 2016; Marañén *et al.,* 2016). They have much larger cells, which leads to higher trophic transfer efficiency (because the microbial loop is not so dominant) as well as higher export flux (meaning that carbon is transported away from the surface into the deep ocean). Thus, the structure of the base of the food web impacts the entire pelagic ecosystem (see Figure 2).

2.2.3. Zooplankton

Zooplankton is the heterotrophic constituent of plankton and is the main link between phytoplankton and higher trophic levels. Zooplankton communities are very diverse and nearly all phyla are represented. They extent from microzooplankton such as heterotrophic flagellates, foraminifera and radiolarians, to metazoans, such as crustaceans, chaetognaths, molluscs, cnidarians and chordates including fish salps and larvae (McEnnulty *et al.,* 2020). Zooplankton are very abundant, and one group, the copepods, can be more abundant than insects (Schminke, 2007).

A study carried out by Lima (2014) on the zooplankton communities in the Cabo Verde archipelago associated with an anticyclonic eddy, showed that the most abundant group at the core of the eddy were the copepods Calanoid, followed by the Eucalanid with greater abundance outside the eddy compared to inside the eddy, the *Macrosetella* group was more abundant from around 100 to 150 meters depth at the eddy core. *Oithonid* were more abundant at the more superficial layers of the nucleus. Organisms belonging to the genus *Oncaeaid*, crustaceans Euphausiid, the Ostracod and Chaetognath were also found, with the crustaceans Euphausiid having the lowest abundance.

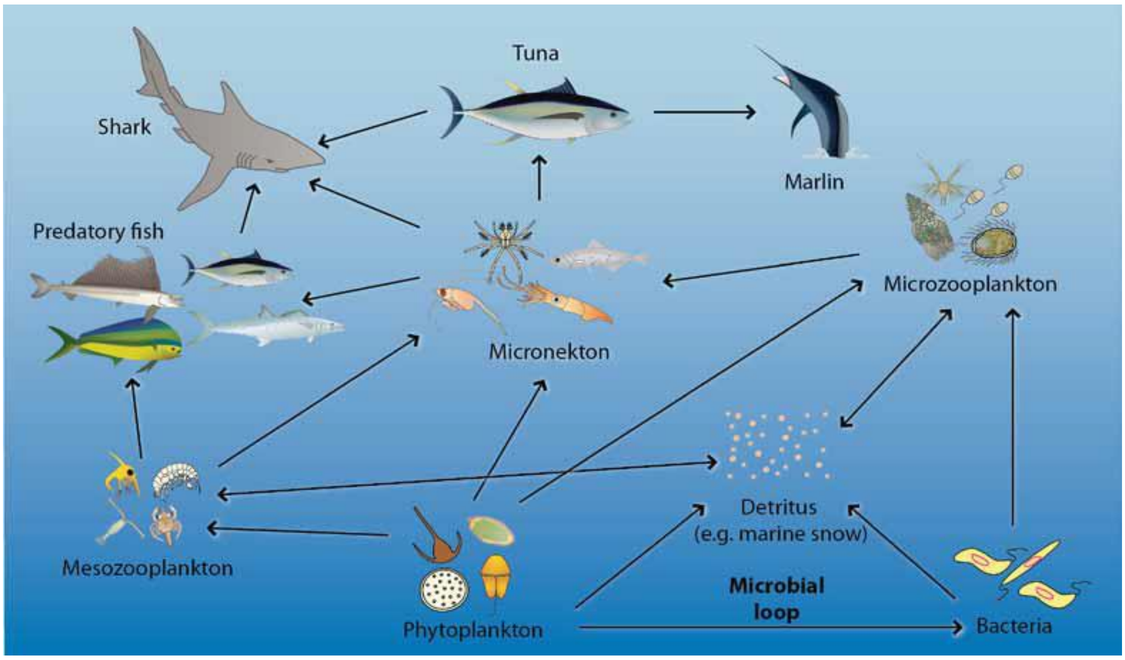

Figure 2. The pelagic food web in the tropical ocean (from LeBorge *et al.,* 2011).

2.2.4. Eddies

Eddies are defined as self-rotating coherent bodies of water that propagate through the ocean mostly from self-advection and planetary vorticity effects (Chelton *et al.*, 2011), but their propagation can be influenced by several other factors (Andres & Cenedese, 2013).

There are two types of eddies, the anticyclones that rotate clockwise, they have a positive sea level anomaly, being a mountain or a hill in the ocean, and the cyclones that rotate counter clockwise, and they are a valley in the ocean. Eddies have a typical horizontal scale from around 50 km to 500 km and a time scale of a few days to hundreds of days. They are characterized by considerable kinetic energy that is a significant peak of the ocean's kinetic energy spectrum, and can directly influence the distribution of current velocity, the thermohaline structure, and also transport heat and momentum, and can strongly affect the physical properties of the upper ocean (Li *et al.*, 2012).

The regular anticyclones are very unproductive (Palacios *et al.*, 2006), being not so interesting in terms of zooplankton biomass, but there are two productive kinds of eddies, the anticyclonic modewater eddies (ACMEs) and the cyclonic eddies. Both are cold in their cores, with a negative SST and positive surface chl-a anomaly (Goldthwait and Steinberg, 2008; McGillicuddy *et al.*, 2007), presumably affecting plankton production.

The Canary Current Upwelling System is associated with several mesoscale features including filaments (Lange *et al.*, 1998), and eddies, that can create and maintain local upwelling that is carried far offshore into the oligotrophic open ocean (e.g., Löscher *et al.*, 2015; Fiedler *et al.*, 2016; Schütte *et al.*, 2016a, 2016b). The part of this upwelling system in close proximity to Cabo Verde is the Northwest Africa upwelling system which even though it is situated in waters relatively close to the coast, the associated eddies and filaments, and the propagation of Rossby waves could lead to the impact of this cold SST to be felt 300 to 600 km offshore, or other regions elsewhere (Mittelstaedt, 1991).

Eddy generation can be driven by various physical mechanisms acting in the ocean, including the effect of topography (Heywood *et al.*, 1990); current shear (Perret *et al.*, 2011; Schütte *et al.*, 2016a); ocean-atmosphere interaction (Ioannou *et al.*, 2017); eddy-eddy interactions (Chelton *et al.*, 2011); and the island induced processes (Cardoso *et al.*, 2020). Most of these features are present around the archipelago and influence the dynamics of this area.

2.3. Plankton analysis

Quantitative zooplankton research dates back approximately 150 years. Since then, fine-meshed nets with a defined mouth area have been used to filter a certain amount of seawater and to enumerate the organisms within (ICES Zooplankton Methodology Manual). One of the first researchers to use such nets was Victor Hensen, who also led the first Atlantic Plankton expedition in 1889, which also visited Cabo Verdean waters. Since then, nets have been developed for different applications (e.g., multiple closing nets such as MOCNESS or the Hydro bios multinet) and remain a primary tool for plankton research. More recently, in situ optical techniques have been increasingly used (Lombard *et al.,* 2019). Another technique is the use of active acoustics, so-called echosounders or fish finders, that were first used in fishery research. Acoustics are frequently cited for being a non-invasive survey technique capable of acquiring high-resolution spatio-temporal data with reduced sampling effort and a potential capacity for surveying large areas (Simmonds and MacLennan, 2005). Limitations of hydroacoustic surveys include taxonomic ambiguity that requires biological data to verify species composition, acoustic range and data quality may be adversely affected by environmental conditions (e.g., wind, waves, entrained air), and successful data collection and interpretation require highly trained personnel (Boswell *et al.*, 2007 and references therein). Thus, it is crucial to complement the acoustic surveys by using ground truth methods (trawling, gillnets, seining, etc; Draštík *et al.*, 2009).

3. Materials and Methods

3.1. Data collection

The dataset was collected during the first Atlantic to Mediterranean (ATL2MED) mission which had the goal to explore mesoscale eddies in the Cabo Verde region, and was led by the Helmholtz Centre for Ocean Research (GEOMAR) from October to December 2019. Two eddies were surveyed, one northeast of Sal that was a cyclone generated on the west coast of Africa and then moved westward, and the other one was generated on the wake of Fogo. These eddies were found and sampled in a work done by Tim Fischer, based upon satellite altimetry and shipboard ADCP data during M160 cruise. Data obtained during the RV Meteor "M160" cruise during November/December 2019 using a CTD rosette were also used in order to help to set more context apart from the surface signatures.

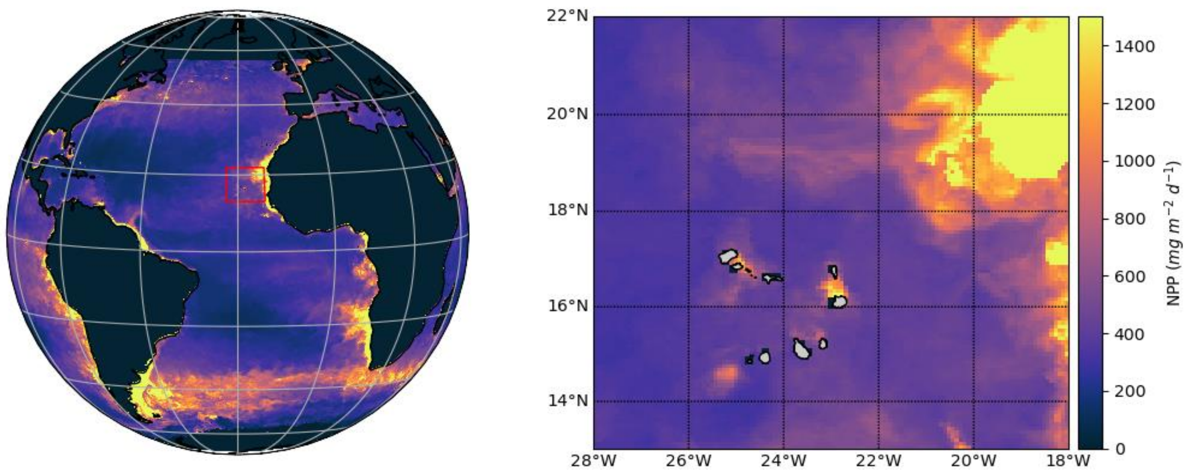

Figure 3. Satellite-based Net Primary Productivity (NPP, mg C m^{-2} d^{-1}) in November 2019 globally (left, red box indicates area enlarged) and in the Cabo Verde region (right). Data are standard VGPM according to Behrenfeld & Falkowski, 1997 and downloaded from the Ocean Productivity Home Page (http://sites.science.oregonstate.edu/ocean.productivity/standard.product.php).

Two saildrone unmanned surface vehicles (USVs), SD1030 and SD1053, were employed in parallel, sailing from the Canary Islands to Cabo Verde and then went back to Trieste, Italy (see Figure 4). SD1030 was equipped with a Teledyne RDI Workhorse WHM300-I-UG1 Acoustic Doppler Current Profiler (ADCP) operating at a frequency of 300 kHz, the SD 1053 with a Simrad WBT Mini (EK80) scientific echosounder transceiver operating a combi-transducer Simrad at 38 kHz and 200 kHz (17.1° X 17.1° and 16.9° X 17.3° beam angle, respectively) to record acoustic data. Configuration was set at 1.024 milliseconds pulse duration, and the power at 500 W for 38 kHz and 215 W for 200 kHz, and one ping every 2 seconds.

Both saildrones carried a suite of sensors with underway observations of sea surface temperature, salinity, chlorophyll-a, photosynthetically active radiation (PAR), and others (carbon, current velocity and direction, wind speed and direction, dissolved oxygen, acoustic backscatter). Chlorophyll a was estimated using a WET Labs ECO-FLS G4 fluorometer, salinity and temperature were collected using a Sea-Bird Scientific SBE 37, dissolved oxygen was measured using a Sea-Bird Scientific SBE 37-SMP-ODO Microcat and PAR was measured using a LI-COR LI-192SA. Unfortunately, the 1053 unit had to skip the southern portion of the survey area due to biofouling issues, as it had to enter the port of Mindelo for a service.

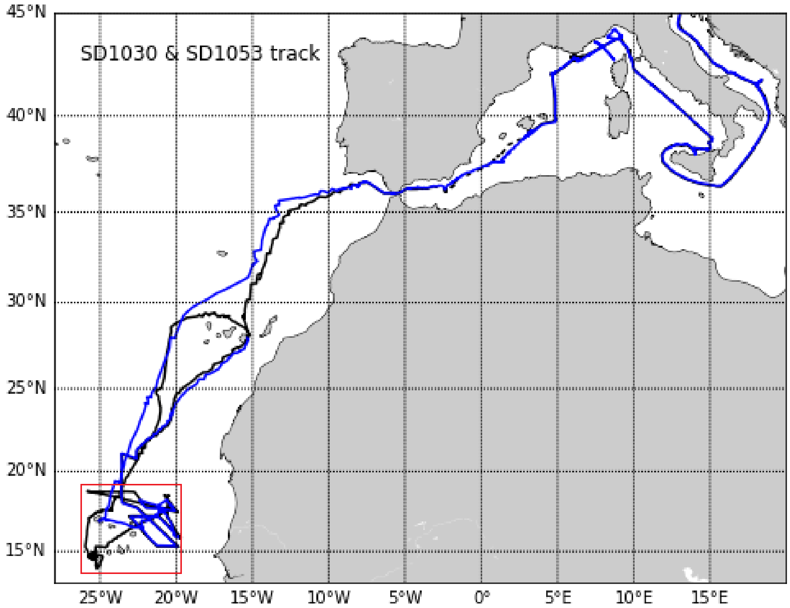

Figure 4. Map of the way travelled by the saildrones. The red box indicates the Cabo Verde region.

3.2. Data analysis

Acoustic echo sounders have been used relatively successfully for several decades in the detection and possible classification of simple populations of fish. In those studies, the authors have assumed that the energy of the acoustic echo of a school of fish is related to animal biomass through a simple linear regression curve. However, as a result of the natural diversity of species within zooplankton aggregations, the use of acoustic methods to quantify zooplankton populations pose a challenge because the acoustic scattering properties of each gross anatomical class of zooplankton are very unique. Thus, large errors can occur if one relies on a simple regression curve to describe the echo energy/biomass relationship (Stanton *et al.*, 1994). Because based on the backscattering characteristics of "fluid like" organisms such as zooplankton, they yield a stronger echo at 200 kHz, in this work we used data from the 200 kHz transducer instead of the 38 kHz transducer.

Acoustic data were visualized, organized and stored on an external drive and later processed and analysed using the post-processing and analysis software Echoview 12. Different Echoview files were created for each month, starting from October until December 2019, and the raw data loaded in different file sets, subtracting 7 hours from it in order to get the correct time, since there was an offset of 7 hours, and the GPS data loaded using the minutes GPS as comma separated values file, for each month into the corresponding file set, since the raw data did not have GPS signal and they had been recorded separately, and were connected by Echoview based on the timestamp.

Data from the surface to a depth of 8 meters were excluded from analysis due to bubble interference and the acoustic near-field, and analyses were limited to 200 m in depth. False bottoms were visually detected and manually excluded. Different algorithms to remove background noise were implemented following Ryan *et al*. (2015). Background noise was removed through defining the Background Noise Removal level based on a Time Varied Gain curve per ping and then this level was implemented in the BNR operator from Echoview (Settings, see table 1). Different band tools were used in the cleaned echogram to mark all the sections where position data and time data did not match up or where there was still a lot of noise as bad data regions, excluding those parts from the analysis. A minimum threshold of -70 dB, an interval of 15 minutes and depth cells of 5 meters were used for integration. Integration reports were generated for each analysis cell in Echoview and exported into csv files. All data were then written to relational databases (SQL) to allow joining of the different datasets by timestamp or position. All analyses were conducted using Python (packages used: psycopg2, numpy, matplotlib, Basemap, datetime, pandas, os, Path, x array, Geod). The main metrics used were the volume backscattering strength Sv (in dB re $1m^2/m^3$) and its integral, the nautical area scattering coefficient NASC (in m^2 n mi^{-2}) which can be interpreted as a proxy for abundance/biomass (MacLennan *et al.*, 2002).

Table 1. Settings used in noise removal

	Echoview noise removal settings	
Background Noise Removal	Averaging Cell	
	Horizontal extent (pings)	20
	Vertical units	Samples
	Vertical extent (samples)	5
	Vertical overlap (%)	0
	Thresholds	
	Maximum noise (dB)	-140
	Minimum SNR	10

4. Results

4.1. Environmental conditions

Environmental conditions recorded at the surface by the saildrone sensor suite (Salinity, Temperature and Photosynthetically Active Radiation - PAR) were analysed in order to determine their effects on plankton biomass distribution.

Salinity varied from 35.6 to 37.2, with an average of 36.4 (Figure 5).

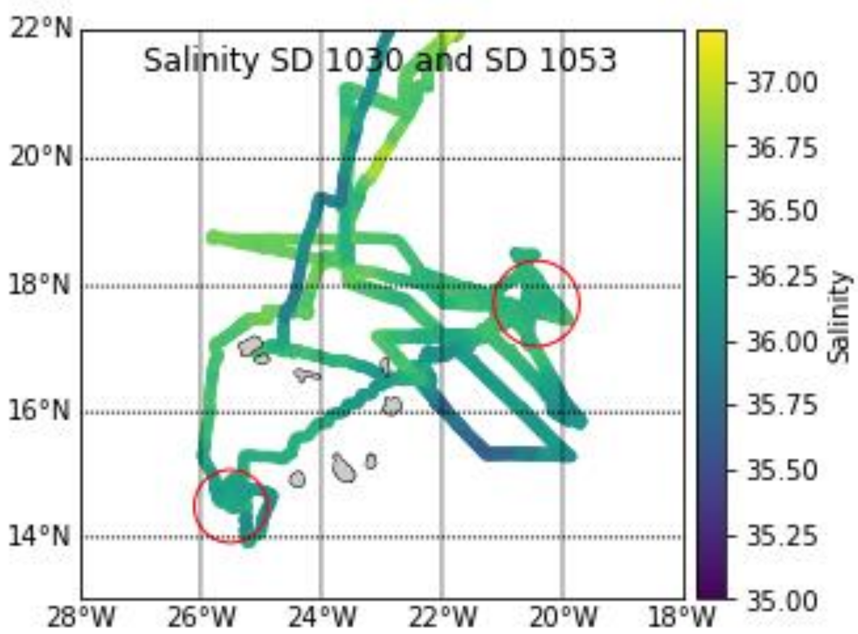

Figure 5. Along-track salinity around Cabo Verde from October to December 2019. The two red circles indicate the two eddies studied.

Temperature ranged from 20.5 to 27.3 °C, with an average of 24.1 °C (Figure 6). The difference between maximum and minimum temperature was around 7 °C. It has to be noted that there is a seasonality effect in there. When the saildrones sailed from Canaries to Cabo Verde in October, it was much warmer than when they left in December.

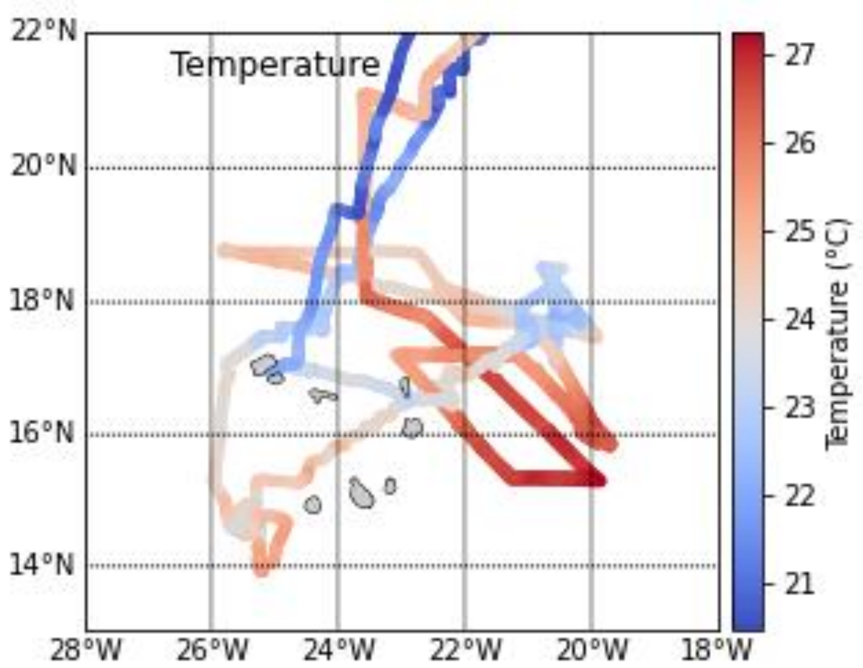

Figure 6. Along-track sea surface temperature around Cabo Verde from October to December 2019 in °C.

Photosynthetically active radiation varied according to the day/night pattern, with lowest values during the night and highest values during the day. The minimum value was 0 and the maximum 1921, as shown in figure 7.

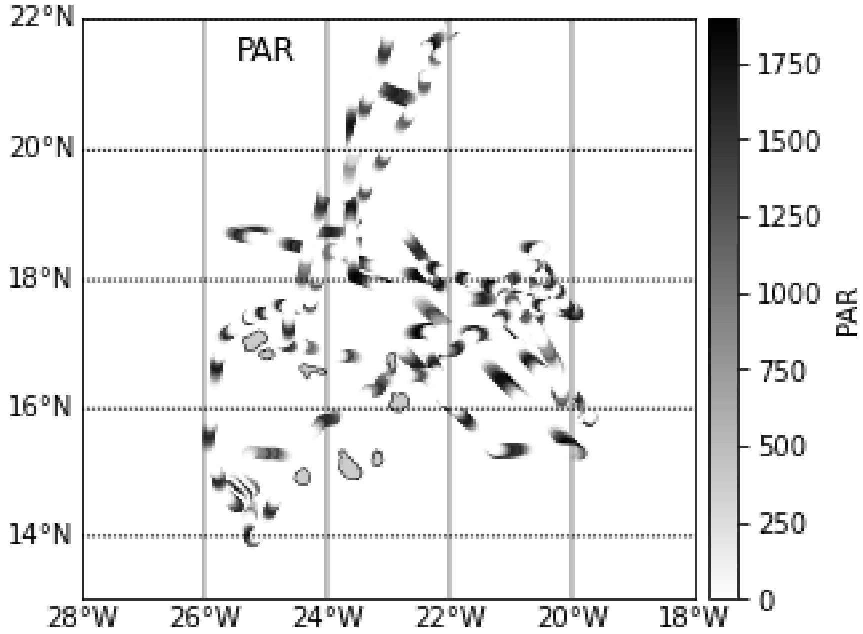

Figure 7. Along-track photosynthetically active radiation around Cabo Verde from October to December 2019.

4.2. Phytoplankton distribution

Chlorophyll a was analysed as a proxy for phytoplankton distribution. Chlorophyll ranged from 0.06 to 4.1 mg/m^3, with highest values within eddy 1, as shown in figure 8.

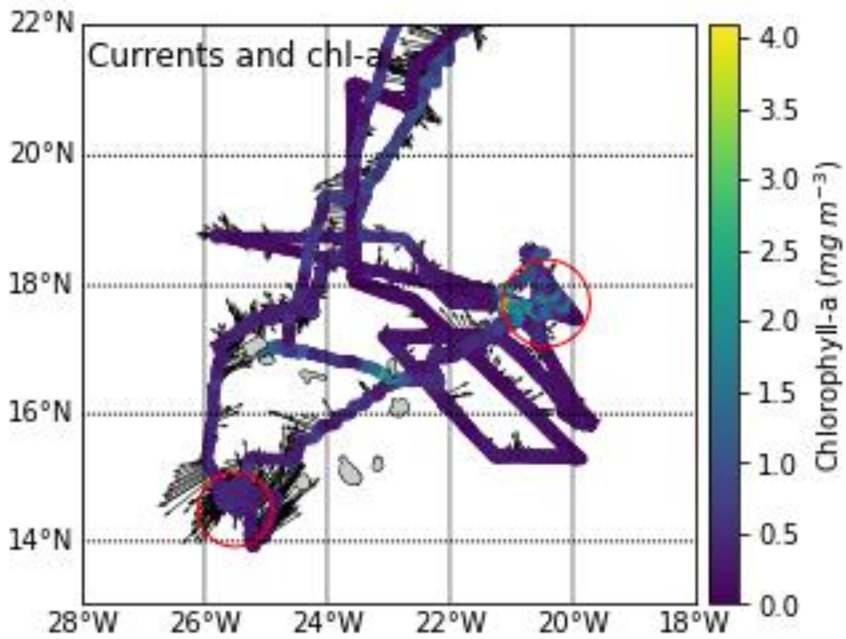

Figure 8. Along-track chlorophyll concentration around Cabo Verde from October to December 2019 in mg/m^3, measured with data from both saildrones. The two red circles indicate the two eddies studied. Black vectors indicate current direction and velocity as measured by the ADCP.

4.3. Hydroacoustic data

The focus of this research is to assess and quantify the plankton distribution in the Cabo Verde region and also determine how eddies do affect its productivity. We have post-processed and analysed the acoustic data using the post-processing and analysis software Echoview 12, defined an upper and lower limit, removed the background noise, and used a cleaned echogram for the analyses. We have also generated integration reports in Echoview, exported as csv files and conducted the analyses using Python, with volume backscattering strength Sv (in dB re 1m^2/m^3) and its integral, the nautical area scattering coefficient NASC (in m^2 n mi^{-2}) being the main metrics used.

The spatial distribution of integrated backscatter at 200 kHz (Figures 9 and 10) revealed two patterns: in general, NASC was approximately two-fold higher in the Cabo Verde region between 15° N and 18.5° N compared to the transit north of 19° N. Second, there were two productivity hotspots visible: One in the region impacted by eddy 1 (around 18° N, 21° W), the other close to the southern tip of Sal. In these two regions, NASC was raised by a factor of approximately 3 to 4 during the night compared to the mean values in the Cabo Verde region.

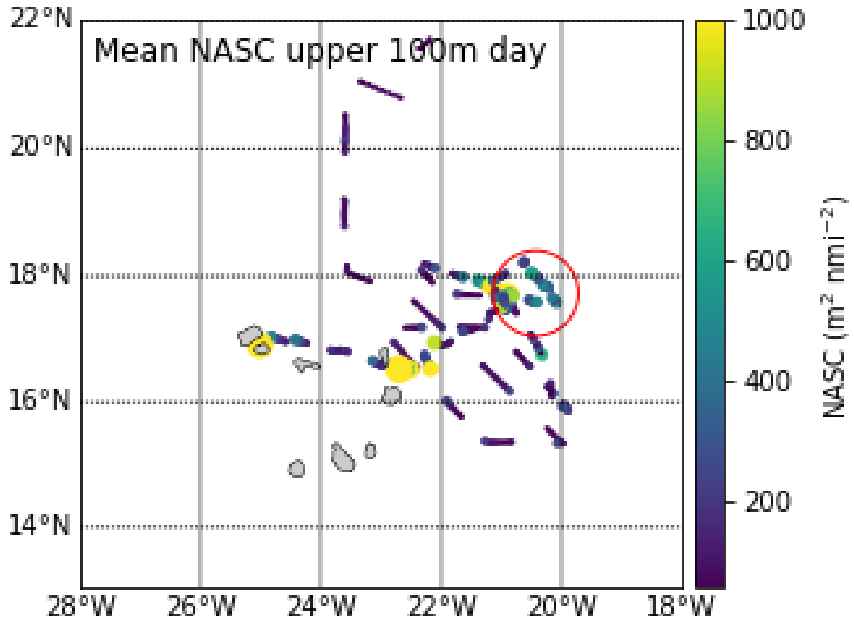

Figure 9. Nautical area scattering coefficient (NASC in m^2 nmi^{-2}) at 200 kHz (SD1053) integrated over the upper 100 m during the day. Data are hourly averaged.

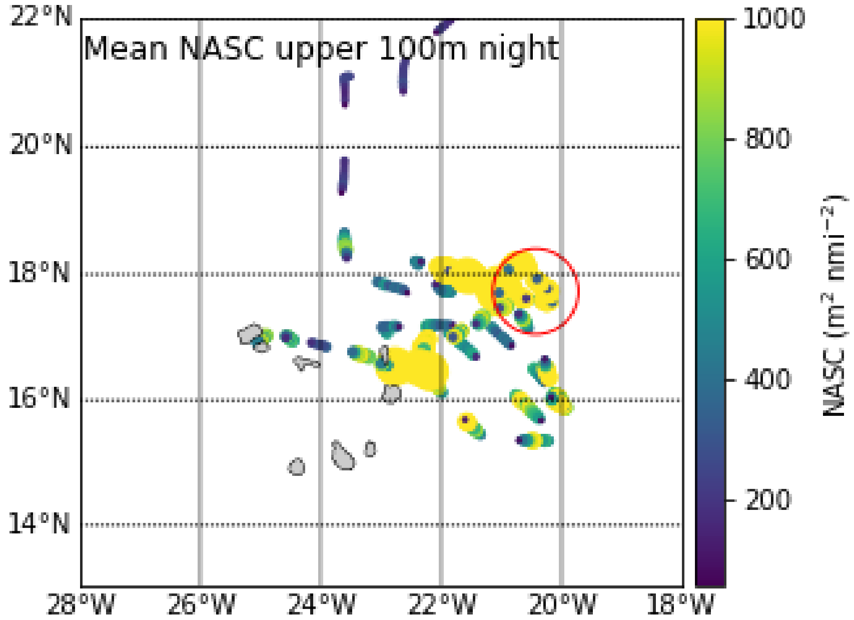

Figure 10. Nautical area scattering coefficient (NASC in m^2 nmi^{-2}) at 200 kHz (SD1053) integrated over the upper 100 m during the night. Data are hourly averaged.

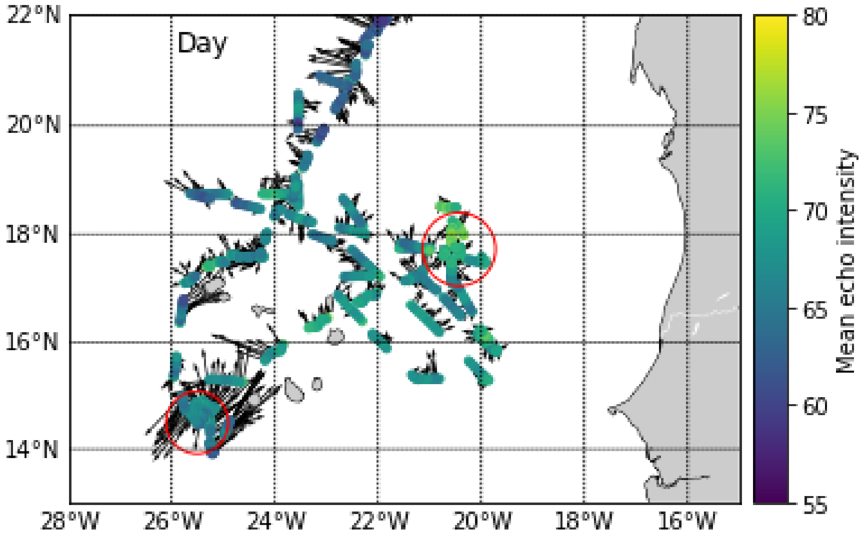

Figure 11. Mean echo intensity as well as current direction and velocity from the ADCP on SD1030 during the day.

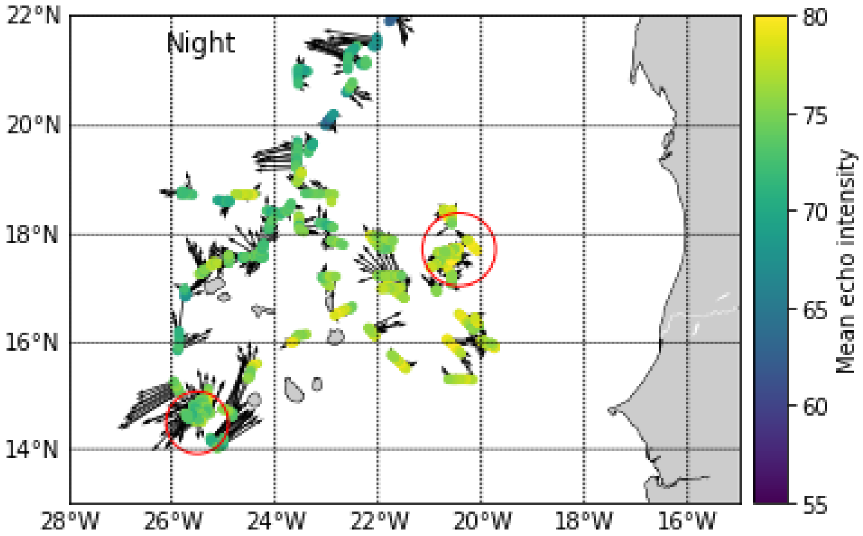

Figure 12. Mean echo intensity as well as current direction and velocity from the ADCP on SD1030 during the night.

To explore changes in the vertical distribution in the eddy compared to outside, data were classified according to distance from the eddy centre (located in the first half of December at approximately 17.7° N and 20.5° W, pers. comm. Tim Fischer). Since its radius during this time period was approximately 75 km, we defined observations that were within 75 km from this location as “in” and those that were 75-300 km from this location as “out” (see Figure 13).

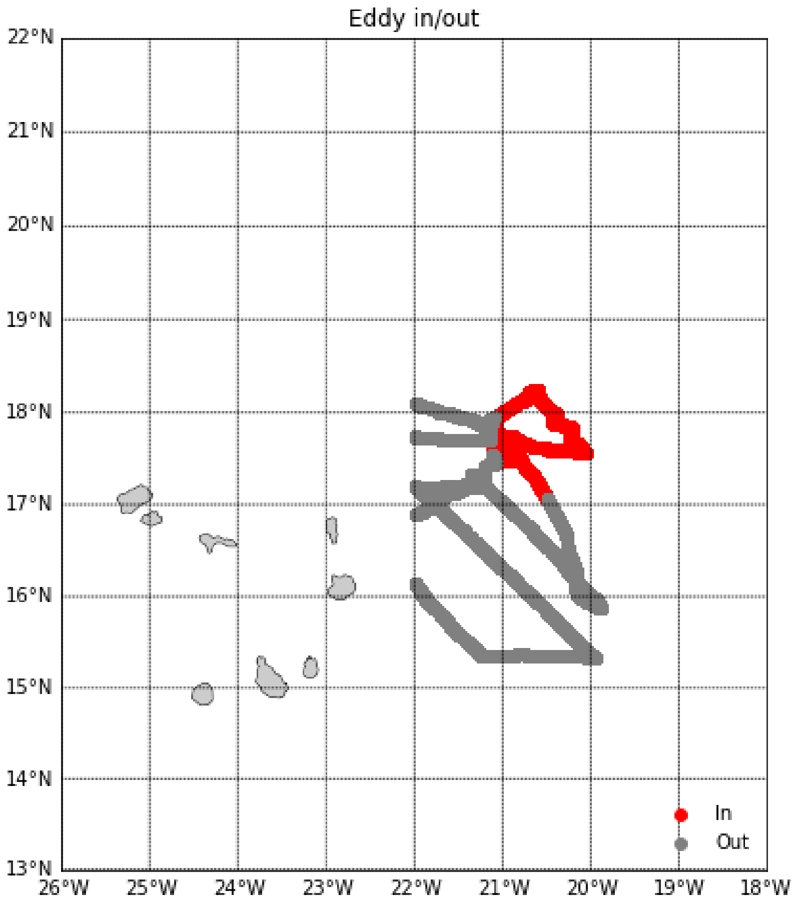

Figure 13. Map of the SD1053 track, indicating data defined as "eddy in" (red) and "out" (grey).

Within the eddy, the mixed layer depth was shallower compared to outside the eddy (see Figure 14), the surface temperature was cooler, and oxygen and chlorophyll-a values were higher. In particular, the usual pattern of surface depletion and a deep chlorophyll-a maximum in the pycnocline (Figure 14 a) was not visible, instead chlorophyll-a values were around 1 mg m^{-3} in the entire upper 50 m inside the eddy.

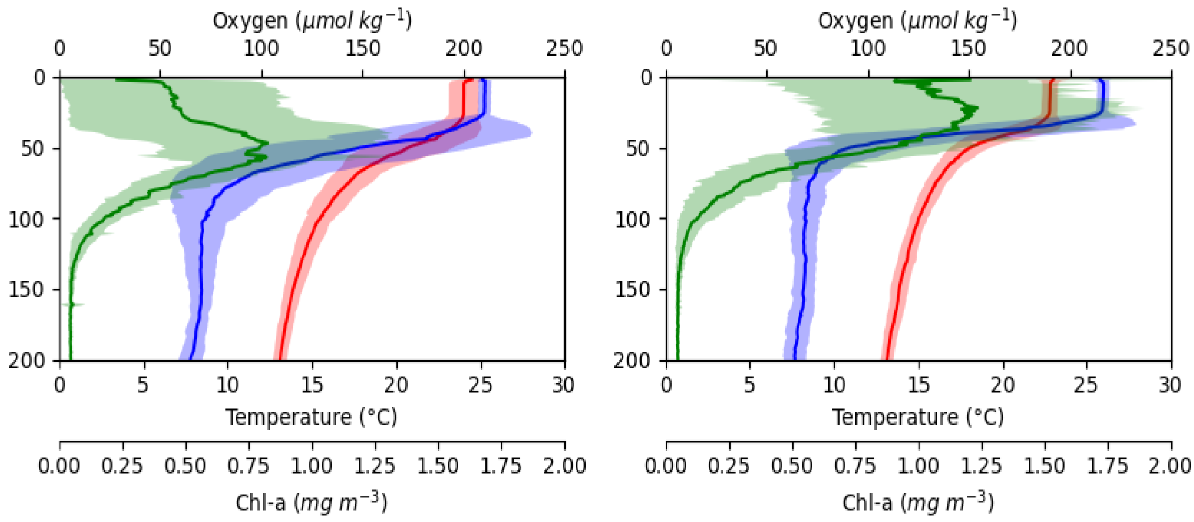

Figure 14. Mean (+-standard deviation) CTD profiles (Oxygen, Temperature, and Chlorophyll-a in blue, red and green, respectively) in the upper 200 m outside the eddy (75 - 300 km from core, left) and inside the eddy (<75 km from core, right). Data were obtained during RV Meteor cruise M160 during November/December 2019.

Both within and outside the eddy, NASC was highest in the upper 25 m and was three-fold higher during the night compared to the daytime hours. However, when comparing night time values from inside and outside, NASC inside the eddy was approximately two times higher than outside the eddy (Figure 15).

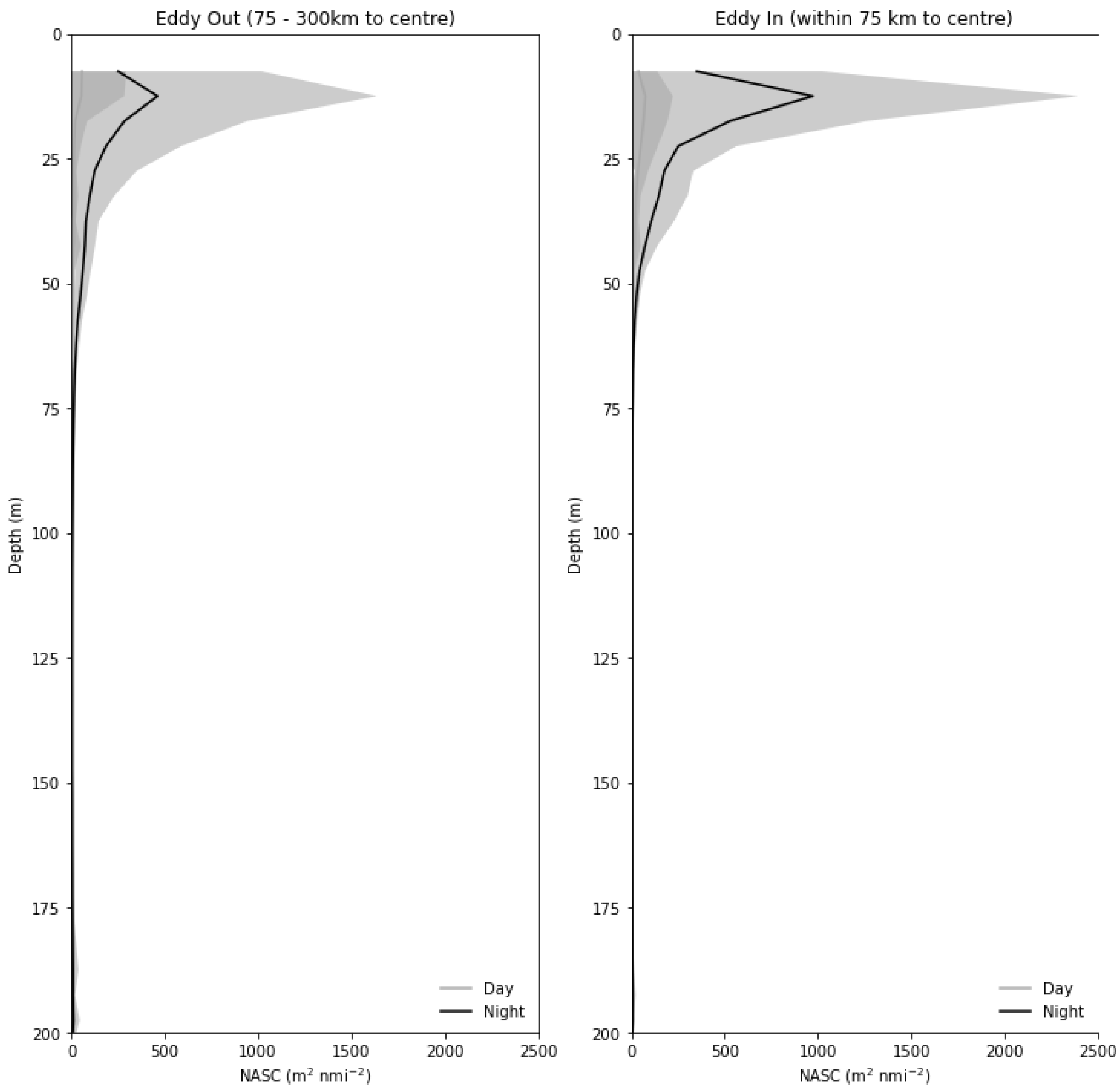

Figure 15. Nautical area scattering coefficient (NASC in $m^2 nmi^{-2}$) during the day and during the night from 75 to 300 km to the centre of the eddy (left) and within 75 km to the centre of the eddy (right) from October to December 2019.

For the zooplankton, the daytime backscatter seemed to be a more meaningful value for (meso)zooplankton than night time. During the night, all the micronekton (fish, euphausiids...) coming up was masking the signal. For that reason, we used the integrated backscatter upper 100 m during the day at 200 kHz as a zooplankton proxy.

To further explore the NASC patterns in and outside the eddy, it was plotted against distance to the eddy core. Closer to the eddy, the backscatter was higher than when moving away (Figure 16).

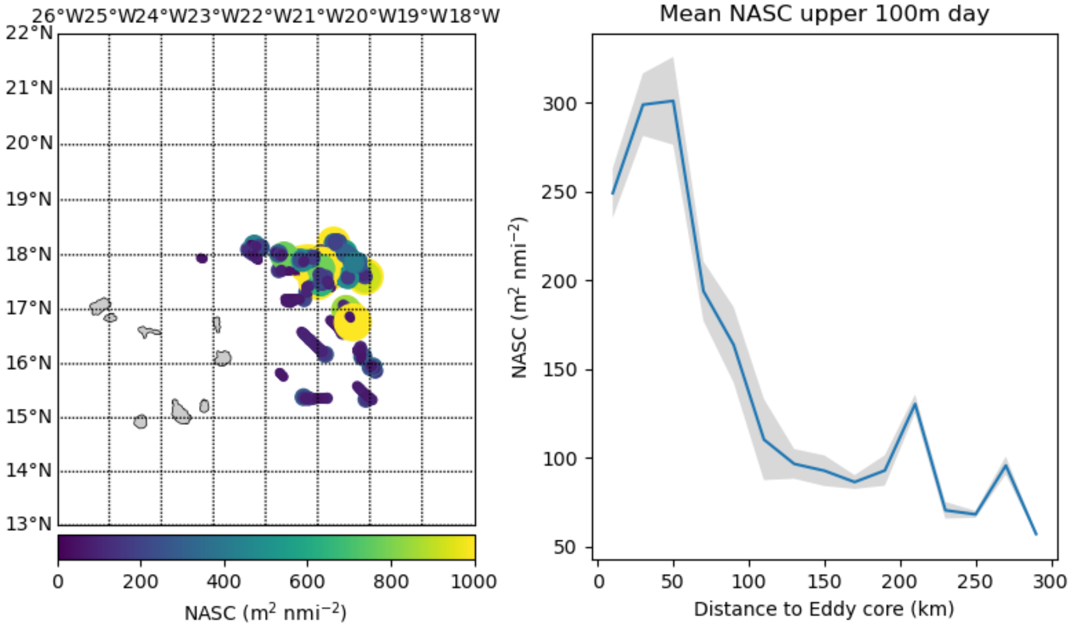

Figure 16. Map of NASC values (left) and the relationship between NASC and the distance to the eddy core in km (integrated over the upper 100 meters) during the day (right) around Cabo Verde from October to December 2019.

To explore the island mass effect on plankton biomass, NASC was plotted against distance to the coast of Sal Island and against distance to Senghor seamount. Near to Sal coast, NASC values were elevated, being higher around 50 km off the coast and lower when moving away (Figure 17).

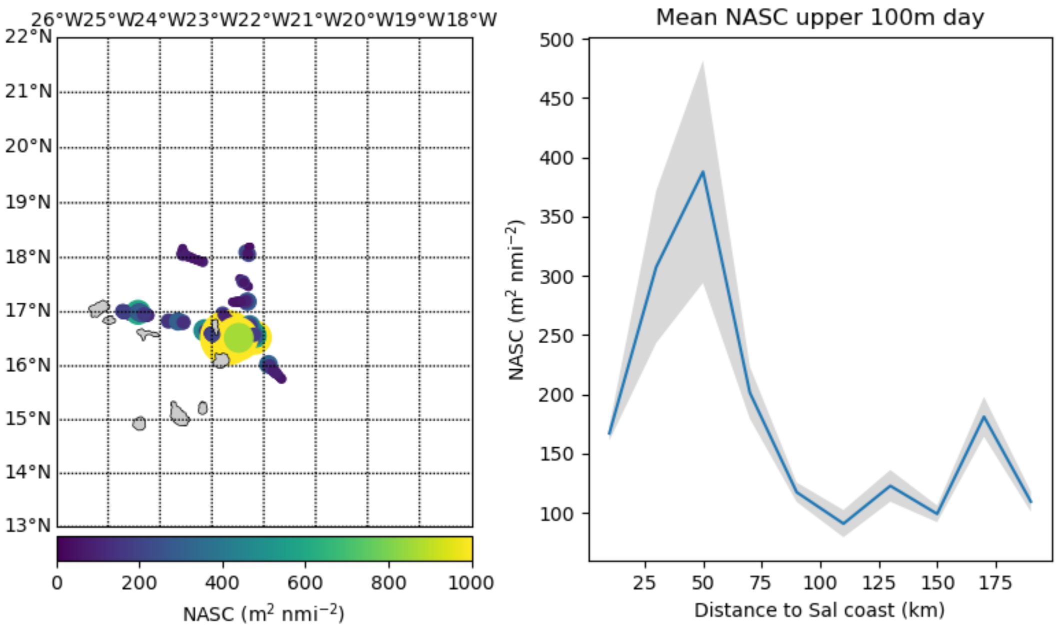

Figure 17. Map of NASC values (left) and the relationship between NASC and the distance to the coast of Sal Island in km (integrated over the upper 100 meters) during the day (right) around Cabo Verde from October to December 2019.

Very close to the Senghor summit, the backscatter was elevated, reaching values around 150 m^2 nmi^{-1}, decreasing when moving away, with values lower than 60 m^2 nmi^{-1} (Figure 18).

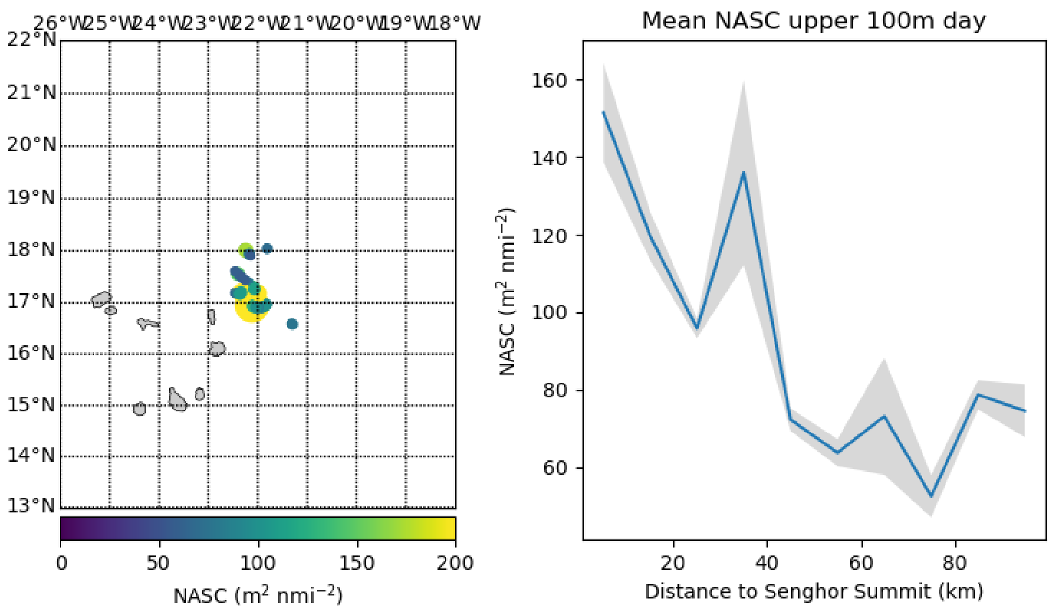

Figure 18. Map of NASC values (left) and the relationship between NASC and the distance to Senghor seamount in km (integrated over the upper 100 meters) during the day (right) around Cabo Verde from October to December 2019.

To further explore the effect of surface environmental conditions on plankton distribution, integrated NASC was plotted in relation to surface chlorophyll-a, temperature and salinity as measured by the saildrone (hourly mean values, Figure 19). NASC was positively related to chl-a, with a Pearson correlation coefficient of 0.55, negatively related to temperature, with a Pearson correlation coefficient of -0.38, and showed a weak negative correlation with salinity, in which the Pearson correlation coefficient was -0.16. All the correlations were statistically significant ($p<0.001$).

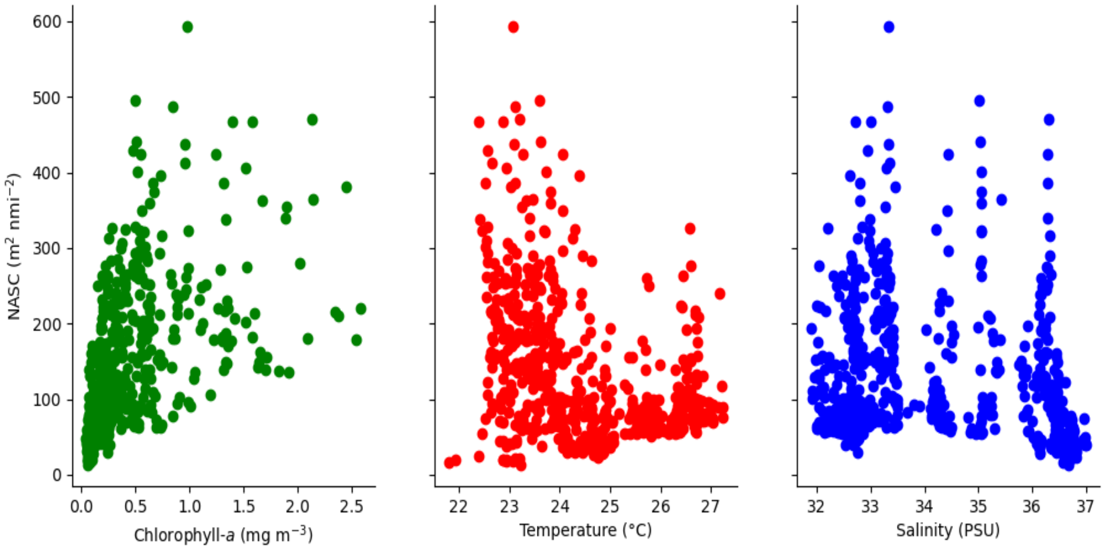

Figure 19. Relationship between NASC and environmental variables (Chlorophyll-a, Temperature and Salinity in green, red and blue, respectively) integrated over the upper 100 meters around Cabo Verde from October to December 2019. Values are hourly means during the day.

5. Discussion

Based on the backscattering characteristics of “fluid like” organisms such as zooplankton, they yield a stronger echo at higher frequencies than at lower frequencies. For swim bladder-bearing fish (and other organisms with gas-filled compartments like marine mammals or siphonophores), the opposite is the case. Without multifrequency observations and/or net-based ground truthing it is difficult to determine the composition of the signal. Comparing the mean volume backscatter at the two frequencies, the night time distribution seems to be strongly structured (see Figure 20). Due to the fact that during the night all the micronekton coming up was masking the signal, we used the integrated backscatter upper 100 m during the day at 200 kHz as a zooplankton proxy, assuming that this would include all nonmigratory mesozooplankton, which is the largest part of the mesozooplankton in this region (Kiko *et al*., 2020; Hauss *et al*., 2016).

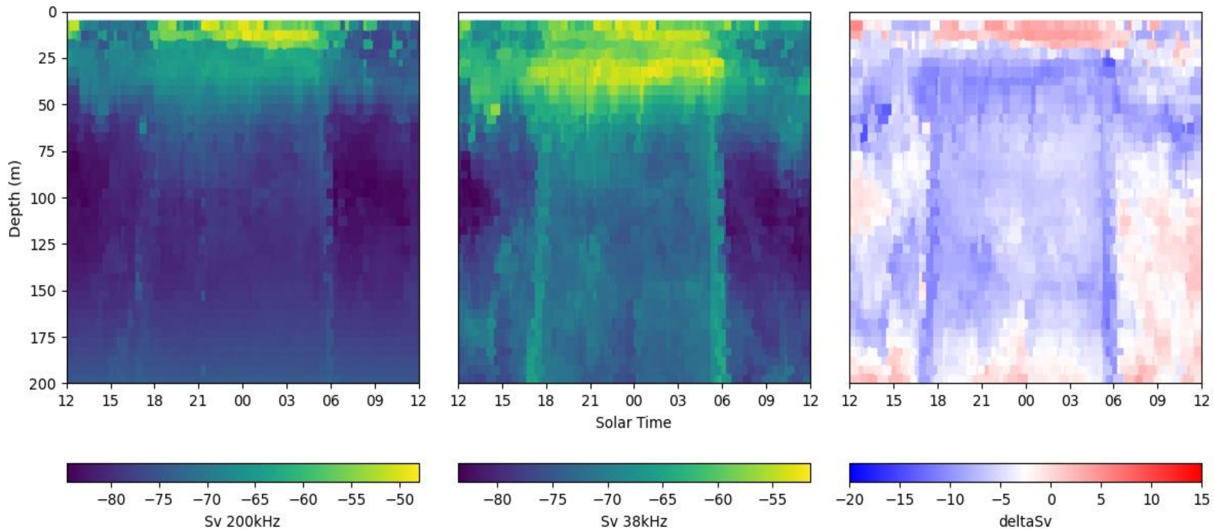

Figure 20. Example of a diel cycle of mean volume backscatter (SV) at 200 kHz (left), 38 kHz (middle) and the difference between the two (right) in the upper 200m on Nov 26, 2019 from noon to noon.

5.1. Phyto- and zooplankton distribution

The tropical Atlantic east of Cape Verde is one of the most productive ocean regions, as can be seen in the global distribution of Net Primary Productivity (see Figure 3A). These remote sensing estimates are based upon the surface chlorophyll (Behrenfeld & Falkowski, 1997), which is the most important photosynthetic pigment of phytoplankton. It absorbs mostly blue light and reflects green, resulting in a ratio that can be used as a proxy for determining Chl-a concentrations at the ocean surface.

On the mean monthly satellite data (Figure 3B), we can also see the phytoplankton patchy distribution, with a patch southwest of Fogo in eddy 2, a patch south of Sal, and another one in the eddy1 northeast of Sal. As zooplankton is the heterotrophic constituent of plankton and feed on phytoplankton, being the main link between phytoplankton and higher trophic levels, more food availability will lead to an increase on zooplankton/micronekton biomass, being, thus, channelled up the food web, as they serve as food for higher trophic levels organisms. But there are differences: e.g., eddy2 does not seem to be as productive in the higher trophic levels.

The enhancement of primary production is largely associated with the supply of nutrients into the euphotic zone (Arístegui *et al.,* 1997; Basterretxea *et al.,* 2002). According to past studies, nutrient availability in the region of Cabo Verde is predominantly regulated by the following four mechanisms: (i) the seasonal coastal upwelling on the western African coast that stimulates phytoplankton growth (Demarcq & Somoue, 2015), which sometimes reaches the Cabo Verde archipelago through ocean current or filament advection (Fernandes *et al.,* 2005); (ii) atmospheric deposition of iron-rich Saharan dust that can intensify phytoplankton growth, although with less pronounced implications (Fischer *et al.,*2016; Marañén *et al.,* 2016), (iii)nutrient injection induced by cyclonic and anticyclonic coastal generated eddies that can sustain enhanced surface levels of Chl-a at their core, transporting these unique environments (Karstensen *et al.,* 2015; Löscher *et al.,* 2015; Fischer *et al.,* 2016, Romero *et al.,* 2016) and (iv) current-topography interactions that lead to turbulent mixing at the slopes of the islands and seamounts (Andrade *et al.,* 2014; Doty & Oguri, 1956). Some of these processes are also interacting with each other, e.g., eddies also often carry an upwelling signature from the African coast into the open ocean, and eddy-associated currents may result in turbulence when the eddy path intercepts steep topography. In this study, a productive eddy northeast of the island of Sal (eddy 1) and another, smaller one southwest of the islands Brava and Fogo (eddy 2) were specifically targeted. Both are clearly visible in the satellite imagery of November 2019 (see Figure 3B) and featured elevated surface chl-a (and, thus, NPP), but eddy 1 clearly exceeded eddy 2. In the on-board chlorophyll data of the saildrones, chlorophyll was only slightly elevated in eddy 2, but in eddy 1 the highest values of the entire region were reached (Figure 8). Near the islands (southern tip of Sal and north shore of São Vicente), values were also elevated, somewhat confirming the island mass effect (Doty & Oguri, 1956). As expected, the results showed increased pelagic productivity at Senghor seamount (Figure 18B).

While there are some observations regarding the impact of eddies in the Cabo Verde region on hydrography (Karstensen *et al.,* 2015, 2017; Schütte *et al.,* 2016a, 2016b), biogeochemistry (Fiedler *et al.,* 2016; Grundle *et al.,* 2017), and primary productivity (Löscher *et al.,* 2015), there are only very few observations on zooplankton in relation to eddies in this region (Hauss *et al.,* 2016; Christiansen *et al.,* 2018). So, it remains somewhat unclear how primary productivity is channelled up through the pelagic food web, and there are no quantitative estimates of the "oasis" effect in such productive eddies, which could also make them important to commercial fisheries.

Karstensen *et al.,* (2015) documented severe hypoxic conditions (dissolved oxygen (DO) < 2 mol kg^{-1}) at 42 m depth when an anticyclonic eddy intersected the Cabo Verde Ocean Observatory mooring, north of São Vicente. Such DO depleted eddies are now thought to be recurrent in the region, and are directly related to the high primary productivity at the surface and subsequent oxygen consumption induced by the sinking of organic matter. In combination with the isolation of the upper layers against exchanges with surrounding waters, this creates "dead zones" in the open ocean (Karstensen *et al.*, 2015). Nevertheless, the surface primary productivity (Löscher *et al.*, 2015) as well as the surface zooplankton biomass (Hauss *et al.,* 2016) is increased in productive cyclonic and anticyclonic modewater eddies, although the subsurface "dead zone" is a barrier for vertically migrating zooplankton.

5.2. Effect of Environmental conditions on Plankton distribution

Salinity varied from 35.6 to 37.2, with an average of 36.4 (Figure 5), temperature ranged from 20.5 to 27.3 °C, with an average of 24.1 °C (Figure 6), the minimum value of PAR was 0 and the maximum 1921 (Figure 7), and chlorophyll ranged from 0.06 to 4.1 mg/m^3, with highest values within eddy 1 (Figure 8).

Within the eddy, the mixed layer depth was shallower compared to outside the eddy, the surface temperature was cooler, and oxygen and chlorophyll-a values were higher (Figure 14), showing that plankton is mostly distributed in the areas close to the eddy.

The eddy1 productivity is not continuously "high in core – low at the margin", but there is some spatial heterogeneity. In fact, the core does not feature the highest values, but the western margin.

NASC was positively related to chl-a, negatively related to temperature, and weakly negatively related to salinity (Figure 19), showing that chl-a do affect the distribution of phytoplankton in the region, and can, thus be used to predict plankton biomass in the Cabo Verde region, whereas temperature and salinity did not show a significant impact on plankton distribution.

5.3. Can environmental conditions be used to predict plankton biomass in the Cabo Verde region?

For acoustic backscatter we need to use some ground truthing methods (plankton nets and pelagic trawling, gillnets, seining, etc; Draštík *et al.*, 2009) that were not obtained within the scope of this study to really convert to biomass, since one of the limitations of hydroacoustic surveys is the taxonomic ambiguity that requires biological data to verify species composition.

The results showed a strong positive correlation between NASC and chl-a, a weaker negative (and likely nonlinear) one between NASC and temperature and weakly negative between NASC and salinity (Figure 19). As chl-a is used as a proxy for phytoplankton distribution and NASC is interpreted as a proxy for zooplankton/micronekton biomass, we can say that chl-a can be used to predict zooplankton/micronekton distribution in the Cabo Verde region, since the last one feeds on the first one. Temperature and salinity were weaker predictors of NASC. Since upwelling of nutrient-rich surface waters results in a lower sea surface temperature signature, it is logical that temperature and productivity (within a given tropical region) are inversely correlated. However, the link between temperature and higher trophic levels (as indicated by acoustic backscatter) is not as tight as to primary producers (as indicated by chl-a).

6. Conclusions

One of the goals of this mission was to track and sample a low-oxygen ACME. This goal was not reached, but two cyclonic eddies (different in their age and generation history) were sampled and interesting observations made. Two productivity hotspots were found, one in the cyclonic eddy northeast of Sal and the other close to the southern coast of Sal, where NASC was raised by a factor of approximately 3 to 4 during the night compared to the mean values in the Cabo Verde region. Within the eddy, the mixed layer depth was shallower compared to outside the eddy, the surface temperature was cooler, and oxygen and chlorophyll-a values were higher, showing that plankton is mostly distributed in the areas close to the eddy, indicating that the eddies do have an impact on its distribution. Both within and outside the eddy, NASC was higher during the night compared to the daytime hours, and closer to the eddy, the backscatter was higher than when moving away. Near to Sal coast and very close to the Senghor summit, NASC values were elevated, being higher around 50 km off the coast of Sal and reaching values around 150 m^2 nmi^{-1} close to the Senghor summit, and decreasing when moving away. NASC was positively related to chl-a, negatively related to temperature, and weakly negatively related to salinity, showing that chl-a do affect the distribution of phytoplankton in the region, and can, thus be used to predict plankton biomass in the Cabo Verde region, whereas temperature and salinity did not show a significant impact on plankton distribution. Further studies are needed, in order to better understand the impact of eddies in the Cabo Verde region on the pelagic food web. This could be done also looking at large single targets (predatory fishes) in eddies.

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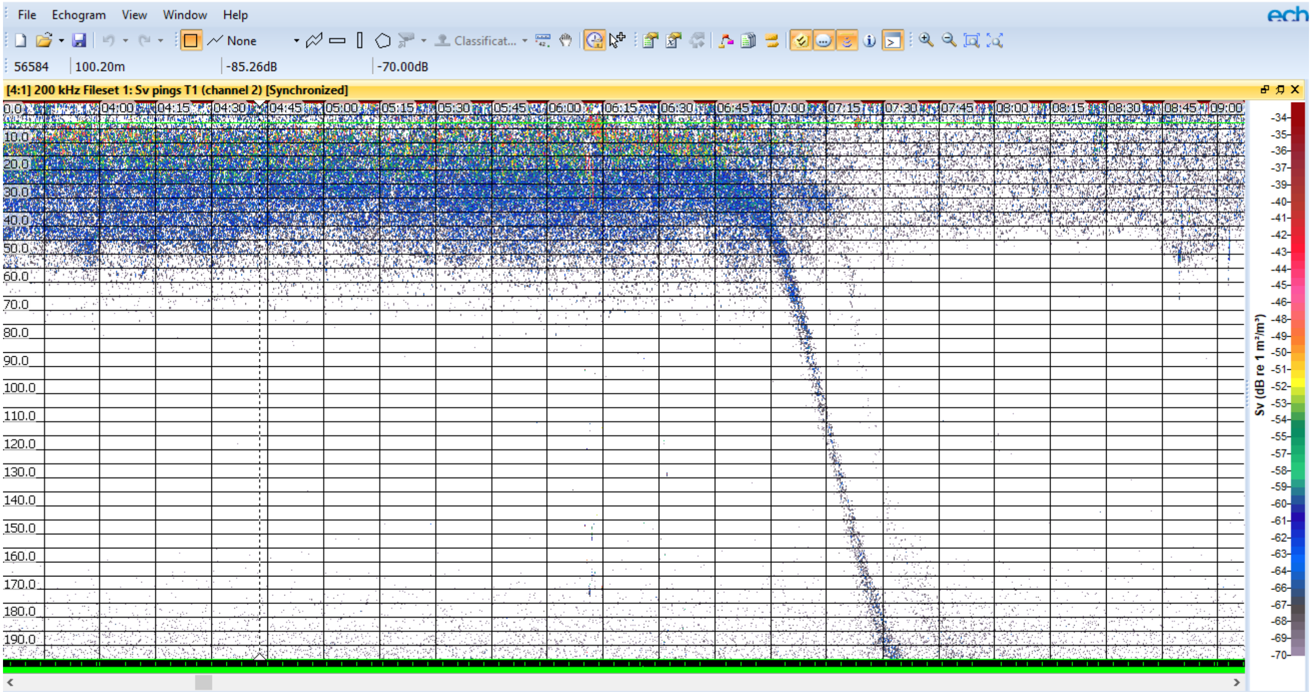
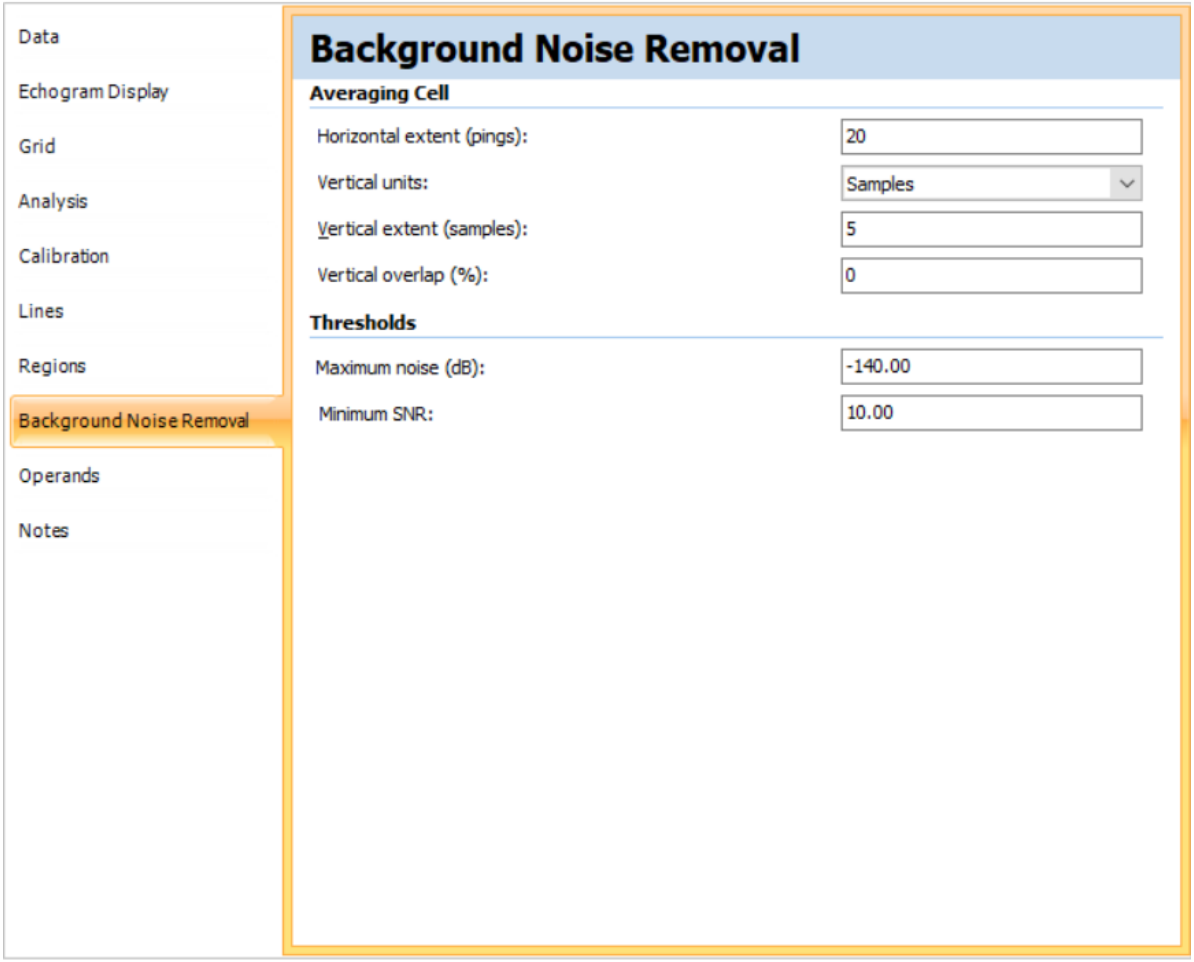
Appendix

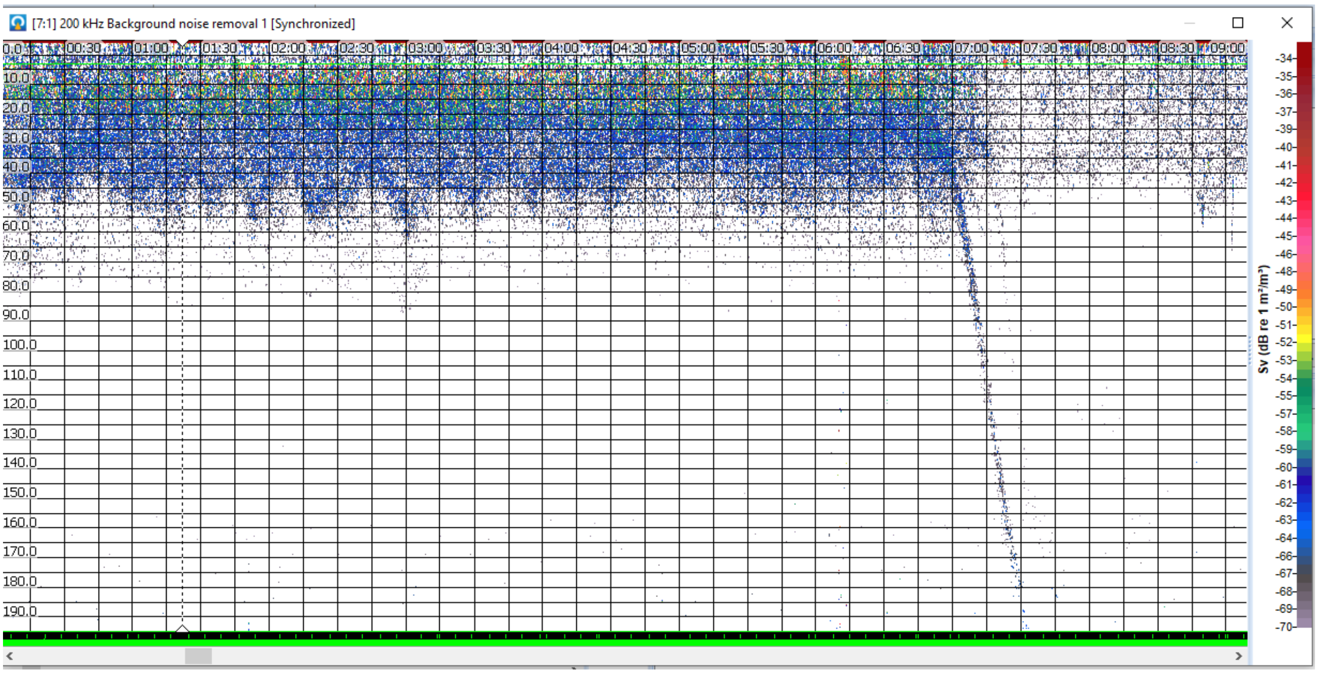
Appendix 1: Echogram for December 2019 at 200 kHz



Appendix 2: Settings used to remove background noise



Appendix 3: Cleaned echogram for December 2019 at 200 kHz



Appendix 4: Script used to draw the map of the way travelled by the saildrones

```python
import os
os.environ['PROJ_LIB'] = r'C:/Users/wascal-gsp/Anaconda3/pkgs/proj4-5.2.0-ha925a31_1/Library/share'

import numpy as np
import matplotlib.pyplot as plt
import psycopg2 as pgsql
import pandas.io.sql as sql
from mpl_toolkits.basemap import Basemap
import cartopy.crs as ccrs
import matplotlib.patches as mpatches

mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")

#plot cape verde integrated backscatter
latmin = 13
latmax = 45
lonmin = -28
lonmax = 20



#select hourly bins
df_sd1030 = sql.read_sql("""SELECT latitude as lat, longitude as lon
                            FROM sd1030_env
                            ORDER BY time
                            """, mydb)
#select hourly bins
df_sd1053 = sql.read_sql("""SELECT latitude as lat, longitude as lon
                            FROM sd1053_env
                            ORDER BY time
                            """, mydb)


fig = plt.figure(1, figsize=(8, 8))

proj = ccrs.Orthographic(central_longitude=-25.0, central_latitude=5.0)
ax = plt.subplot(1,2,1, projection=proj)
ax.set_title('A', y=1.0, pad=-14,  fontweight='bold')
dpp =1

ax.coastlines(resolution='110m')
ax.gridlines()
#add box for insert
ax.add_patch(mpatches.Rectangle(xy=[-28, 13], width=10, height=9,
                                    facecolor='none',edgecolor='red',
                                    transform=ccrs.Geodetic()))
```

Appendix 5: Script used to plot salinity distribution

```
#Importing the packages
import os
os.environ['PROJ_LIB'] = r'C:/Users/wascal-gsp/Anaconda3/pkgs/proj4-5.2.0-ha925a31_1/Library/share'

import numpy as np
import matplotlib.pyplot as plt
import psycopg2 as pgsql
import pandas.io.sql as sql
import math
from mpl_toolkits.basemap import Basemap

#Connecting to my database
mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")

#Plotting Cape Verde salinity distribution from both saildrones
latmin = 13
latmax = 22
lonmin = -28
lonmax = -18

#Reading the data
sd1030 = sql.read_sql(f"""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as lo
                            FROM sd1030_env
                            where latitude >= {latmin} and latitude <= {latmax} and longitude >= {lonmin} and
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)
sd1053 = sql.read_sql(f"""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as lo
                            FROM sd1053_env
                            where latitude >= {latmin} and latitude <= {latmax} and longitude >= {lonmin} and
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)


fig, ax1 = plt.subplots()

m = Basemap(projection='merc', lat_0 = 12, lon_0 = -20,
              resolution = 'i', llcrnrlon = lonmin,  urcrnrlon = lonmax, llcrnrlat = latmin, urcrnrlat = latm

#Defining generate_list
def in_cv_area_lon(lon):
    return lon >= lonmin and lon <= lonmax

def in_cv_area_lat(lat):
    return lat >= latmin and lat <= latmax
```

Appendix 6: Script used to plot temperature distribution

```python
#Importing the packages
import os
os.environ['PROJ_LIB'] = r'C:/Users/wascal-gsp/Anaconda3/pkgs/proj4-5.2.0-ha925a31_1/Library/share'

import numpy as np
import matplotlib.pyplot as plt
import psycopg2 as pgsql
import pandas.io.sql as sql
import math
from mpl_toolkits.basemap import Basemap

#Connecting to my database
mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")

#Plotting Cape Verde temperature distribution from both saildrones
latmin = 13
latmax = 22
lonmin = -28
lonmax = -18

#Reading the data
sd1030 = sql.read_sql(f"""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as lon
                            FROM sd1030_env
                            where latitude >= {latmin} and latitude <= {latmax} and longitude >= {lonmin} and
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)
sd1053 = sql.read_sql(f"""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as lon
                            FROM sd1053_env
                            where latitude >= {latmin} and latitude <= {latmax} and longitude >= {lonmin} and
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)


fig, ax1 = plt.subplots()

m = Basemap(projection='merc', lat_0 = 12, lon_0 = -20,
              resolution = 'i', llcrnrlon = lonmin,  urcrnrlon = lonmax, llcrnrlat = latmin, urcrnrlat = latma

#Defining generate_list
def in_cv_area_lon(lon):
    return lon >= lonmin and lon <= lonmax

def in_cv_area_lat(lat):
    return lat >= latmin and lat <= latmax
```

Appendix 7: Script used to plot currents and chlorophyll distribution

```
#Importing the packages
import os
os.environ['PROJ_LIB'] = r'C:/Users/wascal-gsp/Anaconda3/pkgs/proj4-5.2.0-ha925a31_1/Library/share'

import numpy as np
import matplotlib.pyplot as plt
import psycopg2 as pgsql
import pandas.io.sql as sql
import math
from mpl_toolkits.basemap import Basemap

#Connecting to my database
mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")

#Plotting Cape Verde currents from SD1030 and chlorophyll distribution from both saildrones
latmin = 13
latmax = 22
lonmin = -28
lonmax = -18

#Reading the data
sd1030 = sql.read_sql("""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as lon,
                            FROM sd1030_env
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)
sd1053 = sql.read_sql("""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as lon,
                            FROM sd1053_env
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)
#Selecting hourly bins
adcp_integ = sql.read_sql("""SELECT date_trunc('hour', time) as time, avg(latitude) as lat, avg(longitude) as
                            FROM saildrone_adcp_data
                            GROUP BY date_trunc('hour', time)
                            ORDER BY time
                            """, mydb)

#Defining generate_list():

print(sd1053)
chla_values = sd1053.chla.values
latitude_list = sd1053.lat.values
longitude_list = sd1053.lon.values

def in_cv_area(lat, lon):
```

Appendix 8: Script used to plot NASC in and out of the eddy

```
import psycopg2 as pgsql
import pandas.io.sql as sql
import matplotlib.pyplot as plt
import pandas as pd
import datetime
import os

os.environ['PROJ_LIB'] = 'C:/Users/wascal-gsp/Anaconda3/pkgs/proj4-5.2.0-ha925a31_1/Library/share'
from mpl_toolkits.basemap import Basemap
import numpy as np

##connect to the local_use database
mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")


latmin = 13
latmax = 22
lonmin = -26
lonmax = -18

df_in= sql.read_sql("""SELECT lat, lon
                            FROM saildrone_ek80_200khz
                            WHERE distance_to_eddy1 <75
                            AND lon>-22
                            """, mydb)

df_out= sql.read_sql("""SELECT lat, lon
                            FROM saildrone_ek80_200khz
                            WHERE distance_to_eddy1 BETWEEN 75 AND 300
                            AND lon>-22
                            """, mydb)


eddy_in_day = sql.read_sql("""SELECT layer, layer_depth_mid as depth, AVG(nasc) as nasc, STDDEV(nasc) as nas
                            FROM saildrone_ek80_200khz
                            WHERE distance_to_eddy1 <75
                            AND lon>-22
                            AND CAST(solar_time as time) between '08:00:00' AND '18:00:00'
                            GROUP BY layer, layer_depth_mid
                            ORDER BY layer_depth_mid
                            """, mydb)

#print(eddy_in_day)

eddy_in_night = sql.read_sql("""SELECT layer, layer_depth_mid as depth, AVG(nasc) as nasc, STDDEV(nasc) as na
                            FROM saildrone_ek80_200khz
```

Appendix 9: Script used to plot the relationship between NASC and distance to Sal

```
import os
os.environ['PROJ_LIB'] = r'C:/Users/wascal-gsp/Anaconda3/pkgs/proj4-5.2.0-ha925a31_1/Library/share'

import psycopg2 as pgsql
import pandas.io.sql as sql
import matplotlib.pyplot as plt
from mpl_toolkits.basemap import Basemap
import pandas as pd
import numpy as np


##connect to the local_use database
mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")


latmin = 13
latmax = 22
lonmin = -26
lonmax = -18


df = sql.read_sql("""SELECT ROUND(s.distance) as distance, AVG(s.lat) as lat, AVG(s.lon) as lon, AVG(s.nasc) a
                            FROM
                            (SELECT distinct distance_to_sal as distance, lat, lon, SUM(nasc) as nasc
                            FROM saildrone_ek80_200khz
                            WHERE distance_to_sal <200
                            AND distance_to_eddy1 >200
                            AND CAST(solar_time as time) between '08:00:00' AND '18:00:00'
                            AND layer_depth_mid BETWEEN 15 and 100
                            GROUP BY distance, lat, lon) AS s
                            GROUP BY distance, lat, lon
                            """, mydb)


#plot a map of integrated NASC over the area
fig = plt.figure(1, figsize=(10, 6))

ax1 = fig.add_subplot(1,2,1)

m = Basemap(projection='merc', lat_0 = 12, lon_0 = -20,
              resolution = 'i', llcrnrlon = lonmin,  urcrnrlon = lonmax, llcrnrlat = latmin, urcrnrlat = latma

lons = df.lon.values  # needs .values here
lats = df.lat.values   # same as above
x, y = m(lons, lats)

```

Appendix 10: Script used to plot the correlation between NASC and environmental variables

```
import psycopg2 as pgsql
import pandas.io.sql as sql
import matplotlib.pyplot as plt

##Connecting to the local_use database
mydb = pgsql.connect(database="local_use", user="postgres", password="xxxx")



####select hourly mean integrated backscatter (sum of binned backscatter down to 100m)
#### daytime only (08:00-18:00 solar time)
####join the hourly mean environmental data by time
df = sql.read_sql("""SELECT n.nasc, e.htime, e.chla, e.temperature, e.salinity
                            FROM
                            (SELECT distinct DATE_TRUNC('hour', s.datetime_utc) as time, AVG(s.nasc) as nasc
                            FROM
                            (SELECT DISTINCT datetime_utc, SUM(nasc) as nasc
                            FROM saildrone_ek80_200khz
                            WHERE CAST(solar_time as time) between '08:00:00' AND '18:00:00'
                            AND layer_depth_mid BETWEEN 15 and 100
                            AND nasc <200
                            GROUP BY datetime_utc
                            ORDER BY datetime_utc) as s
                            GROUP BY time) as n
                            FULL OUTER JOIN
                            (SELECT DISTINCT DATE_TRUNC('hour', time) as htime, AVG(temperature) as temperatu
                            FROM sd1053_env
                            GROUP BY htime) as e
                            ON n.time = e.htime
                            ORDER BY e.htime
                            """, mydb)

#filter out rows where no echosounder data exist; not necessary for plotting but to look at dataframe.

df = df[df.nasc.notnull()]

print(df)


fig = plt.figure(1, figsize=(12, 12))

ax1 = fig.add_subplot(1,3,1)

ax1.scatter(df.chla, df.nasc, c='green')
plt.xlabel('Chlorophyll-$a$ (mg m$^{-3}$)')
plt.ylabel('NASC (m$^{2}$ nmi$^{-2}$)')
```