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MARCOS VINÍCIUS BARROS DA SILVA

A MORFOLOGIA DE CÂNIONS SUBMARINOS E SUA POSSÍVEL INFLUÊNCIA NA DINÂMICA DE SUBMESOESCALA AO LONGO DA COSTA NORDESTE DO BRASIL

Recife
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Tese apresentada ao Programa de Pós-Graduação em Oceanografia da Universidade Federal de Pernambuco, Centro de Tecnologia e Geociências, como requisito parcial para a obtenção do título de doutor em Oceanografia.

Área de concentração: Oceanografia Abiótica.

Orientadora: Profa. Dra. Tereza Cristina Medeiros de Araújo

Coorientador: Prof. Dr. Marcus André Silva

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RESUMO

Cânions submarinos são importantes feições no contexto morfológico e oceanográfico. Assim, o objetivo dessa tese é analisar o comportamento de massas de água fria sobre a plataforma e sua borda ao longo da costa nordeste do Brasil pela presença de cânions submarinos. Além disso, estudos de cânions vêm ganhando destaque junto com iniciativas para promover o desenvolvimento sustentável na Década Oceânica. O capítulo I mostra que os cânions são responsáveis pela variabilidade de temperatura e salinidade, transporte de sedimentos, nutrientes e poluentes, sendo considerados ainda *hotspots* de biodiversidade. O capítulo II apresenta um panorama dos estudos de cânions e sua ligação com a Década Oceânica para a América do Sul, com o resgate de 160 estudos para análise espaço-temporal, construindo uma linha temporal com os avanços, lacunas e previsões para o futuro dos estudos de cânions de acordo com os resultados da Década. Nesse contexto, a mudança de conhecimento sobre estudos de cânions reforça a capacidade da ciência oceânica de fornecer dados e informações necessárias, conhecimento e compreensão abrangentes do oceano, incluindo as interações humanas, e desenvolvimento de soluções homem-oceano. O capítulo III, aborda a interação fluxo-topografia entre a Subcorrente Norte do Brasil (NBUC) e os cânions cegos do Platô de Pernambuco localizados no Atlântico Tropical Sudoeste (SWTA), investigando o potencial de soerguimento de massas d’água durante a primavera e outono. Dados de CTD, reanálise do GLORYS12V1, batimetria e números adimensionais de Rossby e Burger foram usados para caracterizar o comportamento dinâmico. Foi observado uma variação sazonal da intrusão de massas d'água em dois vales de plataforma com uma diferença de temperatura de 2,5°C entre águas superficiais e profundas durante a primavera. Além de uma estrutura de temperatura escalonada em ambas as estações, indicando instabilidade abaixo da profundidade da camada de mistura e números adimensionais maiores durante o outono nos vales de plataforma. Nossa hipótese é que os vales da plataforma conduzem a água soerguida do talude em direção à costa. Para os cânions cegos, a reanálise revelou a presença de um redemoinho anticiclônico profundo e os números adimensionais indicam equilíbrio geostrófico fraco na borda do cânion e instabilidade da escala de comprimento horizontal da força do gradiente de pressão. Embora seja verdade que as águas costeiras e da plataforma do nordeste do Brasil sejam predominantemente oligotróficas na superfície, nossa observação de soerguimento subsuperficial raso (<60 m) deve ser considerada em trabalhos futuros no SWTA.

Palavras-chave: cânions submarinos; margem continental; Década Oceânica; interação fluxo-topografia.

ABSTRACT

Submarine canyons are important features in the morphological and oceanographic context. Thus, the thesis aim is to analyze the behavior of cold-water masses on the shelf and its edge along the northeast coast of Brazil by the presence of submarine canyons. In addition, canyon studies have been gaining prominence along with initiatives to promote sustainable development in the Ocean Decade. Chapter I shows that canyons are responsible for temperature and salinity variability, sediments transport, nutrients, and pollutants, being considered biodiversity hotspots. Chapter II presents an overview of canyon studies and its connection with the Oceanic Decade for South America, with the rescue of 160 studies for space-time analysis, building a timeline highlighting the advances, gaps, and forecasting for the future of canyon studies according to the Decade outcomes. In this context, changing of knowledge about canyon studies confirm the ability of ocean science to provide necessary data and information, comprehensive knowledge and understanding of the ocean, including human interactions, and development of human-ocean solutions. Chapter III discusses the flow-topography interaction between the Northern Undercurrent of Brazil (NBUC) and the blind canyons of the Pernambuco Plateau located in the Southwest Tropical Atlantic (SWTA), investigating the potential for uplift of water masses during spring and fall. CTD data, GLORYS12V1 reanalysis, bathymetry and Rossby and Burger dimensionless numbers were used to characterize the dynamic behavior. A seasonal variation of water mass intrusion was observed in two shelf valleys with a temperature difference of 2.5°C between surface and deep-water during spring. In addition to a staggered temperature structure in both seasons, indicating instability below the mixing layer depth and higher dimensionless numbers during fall in the shelf valleys. Our hypothesis is that the shelf valleys lead the water uplifted from the slope towards the coast. For the blind canyons, reanalysis revealed the presence of a deep anti-cyclonic eddy, and the dimensionless numbers indicate a weak geostrophic equilibrium at the canyon edge and instability of the horizontal length scale of the pressure gradient force. While it is true that the coastal and shelf waters of northeastern Brazil are predominantly oligotrophic at the surface, our observation of shallow subsurface uplift (<60 m) should be considered in future studies in SWTA.

Keywords: submarine canyons; continental margin; Ocean Decade; flow-topography interaction.

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1 INTRODUÇÃO

Os cânions submarinos são considerados importantes feições no contexto geológico (FILDANI, 2017), oceanográfico (FANELLI; BIANCHELLI; DANOVARO, 2018; JORDI et al., 2005; PALANQUES et al., 2005) e vêm alcançando espaço no contexto social também, principalmente como fontes de indução de poluentes (TUBAU et al., 2015a). De acordo com a classificação geomorfológica, os cânions podem ser diferenciados em dois tipos: 1) cânions submarinos comuns – normalmente em formato triangular e entalhados desde a plataforma continental até, em alguns casos, a planície abissal; e 2) cânions submarinos cegos – também com características semelhantes aos cânions submarinos comuns, porém não são entalhados na plataforma continental (WARRATZ et al., 2019).

Eles fazem parte de complexos sistemas que modificam a circulação local induzindo o levantamento de massas de água nas regiões de quebra de plataforma (KÄMPF, 2007; LE SOUËF; ALLEN, 2014; PAI et al., 2016), influenciando nas comunidades biológicas por alterar padrões de distribuição das propriedades da água do mar (ALLEN et al., 2001), transportando sedimentos, nutrientes e até poluentes de regiões mais rasas próximas a costa até zonas mais profundas (ALLEN; DURRIEU DE MADRON, 2009; MITCHELL, 2015). Os processos gerados pela presença de cânions submarinos e o grau de influência na linha de costa são variados, dependendo especialmente da sua localização no planeta. Vários autores destacam a heterogeneidade nos processos de circulação dos cânions variando de acordo com aspectos hidrográficos e meteorológicos (inundação ou tempestade) (PUIG et al., 2004; ROSS et al., 2009), oceanográficos (atividade de redemoinhos, correntes de maré ou ondas internas) (BRAVO et al., 2013; PANTOJA; MARINONE; FILONOV, 2017; VIANA et al., 1998) e morfológicos (declividade, transporte de sedimento) (BROTHERS et al., 2013; GRINYÓ et al., 2017).

A morfologia dos cânions atua como fator limitante vertical (profundidade), enquanto que as demais variáveis físicas agem como fatores limitantes horizontais para as comunidades habitantes das áreas de margem continental (DAWE; ALLEN, 2010; WALTER; PHELAN, 2016). A combinação entre as condições dinâmicas e a morfologia do terreno gera as características ambientais necessárias para a manutenção e desenvolvimento da biodiversidade na plataforma continental e talude, classificando as áreas de cânions submarinos como *hotspots* de biodiversidade (ROBERT et al., 2015; SANTORA et al., 2018). Próximo a regiões de cânions encontram-se alterações nos processos de transporte e levantamento de massa d’água ricas em nutrientes sobre a plataforma, que surgem pela interação do fluxo com a topografia, induzindo diferenças nas condições físicas do meio (salinidade, temperatura, gradiente de pressão, etc.) (KLINCK; FREELAND, 1996; KUNZE et al., 2002).

No Oceano Atlântico, a topografia de fundo nas margens continentais, é uma das principais responsáveis pelas maiores variações de fluxo próximo a linha de costa, sobretudo, aos processos advectivos originados pelas correntes de fronteira oeste. Os cânions submarinos, geralmente são formados perpendicularmente à linha de quebra das plataformas continentais, aumentando o transporte advectivo pelas correntes que se deslocam normalmente paralelas a linha de costa (LO; SULLI; AGATE, 2014; SHE; KLINCK, 2000). Efeitos de bombeamento de águas mais frias e salinas por advecção de correntes ocorrem devido a configuração topográfica encontrada em cânions submarinos, onde cada processo é relacionado a forma do cânion e as suas dimensões (JORDA et al., 2013; LOPEZ, 2001; RENNIE; PATTIARATCHI; MCCAULEY, 2009; TUBAU et al., 2015b).

Em regiões tropicais, por exemplo, as trocas de nutrientes da água através de cânions submarinos desempenham um papel importante no processo de fertilização na plataforma e quebra de plataforma, pois algumas regiões têm características oligotróficas e falta de renovação de nutrientes na coluna de água, especialmente em áreas de alta estratificação onde a troca é limitado (HOSEGOOD et al., 2017). Exatamente como acontece com o litoral do Nordeste brasileiro, onde as massas de água são oligotróficas em decorrência da alta estratificação da coluna d'água e da elevação da temperatura e salinidade no talude (ARAUJO et al., 2011; DOMINGUES et al., 2017; SCHETTINI et al., 2017).

Nesta região, tanto a plataforma continental quanto a área do talude demonstram uma complexa topografia de fundo, onde podemos destacar a presença de canais e estruturas semelhantes a cânions submarinos (BASTOS et al., 2015; GOMES et al., 2014; VITAL; FURTADO; GOMES, 2010). A morfologia é caracterizada por uma plataforma continental estreita e rasa, com média de 30 km de largura, 40 m de profundidade e profundidade de quebra de plataforma entre 50-60 metros de isóbatas (MARTINS; COUTINHO, 1981). A Plataforma Continental Sul de Pernambuco (PCSP) tem quase as mesmas características do litoral nordestino, exceto pela presença do Planalto de Pernambuco, que é responsável pelas principais mudanças nas condições oceanográficas e morfológicas do litoral nordestino (BUARQUE et al., 2016; CAMARGO et al., 2015), especialmente próximo à linha de quebra de plataforma, que possui conexão entre as regiões mais rasas e mais profundas através dos cânions cegos localizados no Platô de Pernambuco.

Vários trabalhos vêm sendo realizados sobre a interação do fluxo e sua resposta nas condições da plataforma continental (ALLEN, 2000; ALLEN; DURRIEU DE MADRON, 2009; JORDI et al., 2005; LE SOUËF; ALLEN, 2014; PORTER et al., 2016; WATERHOUSE; ALLEN; BOWIE, 2009). Contudo, a pesquisa de modelagem numérica aplicada às condições reais ainda está começando, pois, as tentativas de executar um modelo usando a topografia real gera um fluxo irreal que não representa a dinâmica e suas condições de contorno (CANALS et al., 2013; DENAMIEL; BUDGELL; TOUMI, 2013; PALANQUES et al., 2005; PANTOJA; MARINONE; FILONOV, 2017; WALTER; PHELAN, 2016).

Estudos recentes sugerem a interação de processos de declive e correntes ao longo da encosta como um processo importante (AMUNDSEN et al., 2015; VOIGT et al., 2013; WARRATZ et al., 2019). Apesar dos efeitos nas comunidades biológicas geradas pelos cânions, a hidrodinâmica é complexa e precisa ser mais discutida (ALLEN; DURRIEU DE MADRON, 2009; DE LEO; PUIG, 2018; HICKEY, 1997). Embora ainda exista um desafio operacional para obter dados sobre o cânion próximo à cabeça do cânion, principalmente devido à topografia íngreme e aos barcos de pesca muitas vezes intensos (HOWATT; ALLEN, 2013). A dificuldade de obtenção de dados para atualização dos modelos locais, somada à complexidade dos estudos de escoamento em cânions é o cenário ideal para a escassez de pesquisas com este tipo de abordagem.

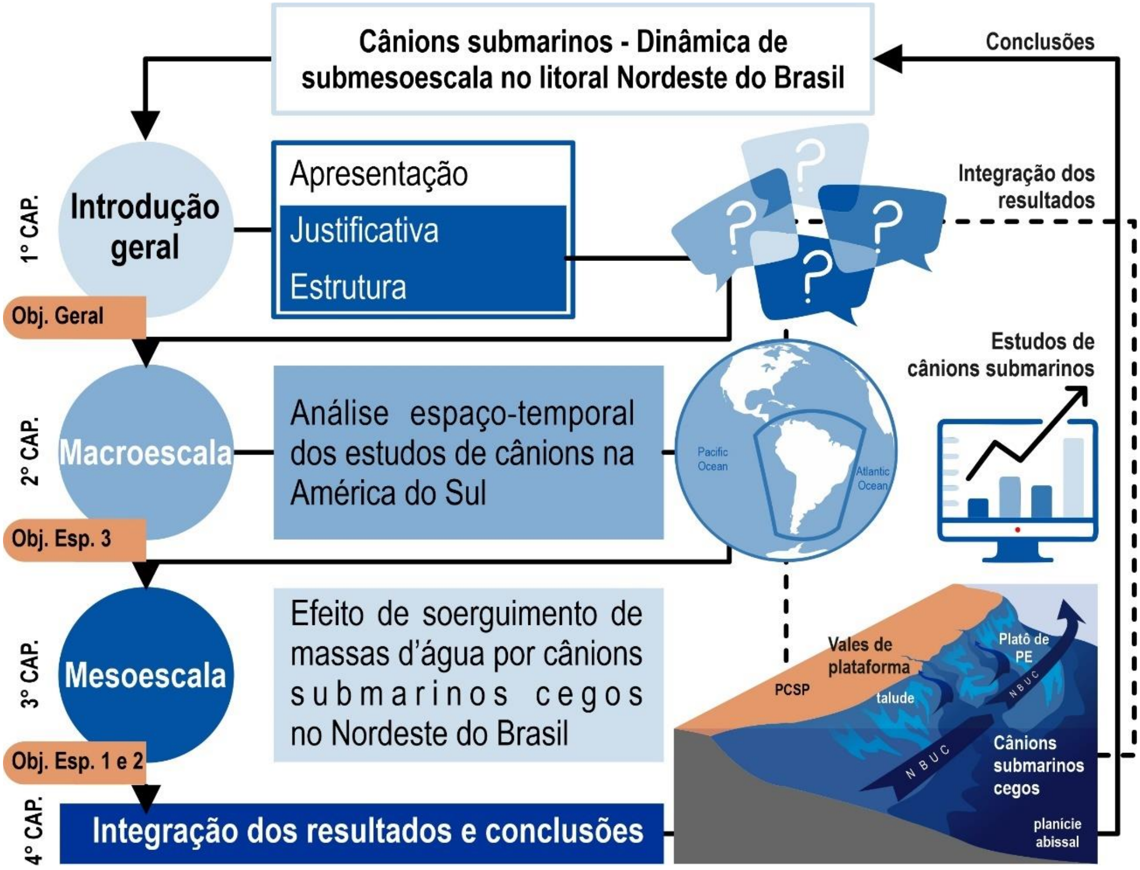
Um dos esforços para estimar o comportamento da dinâmica de fluxo em cânions submarinos está associado ao desenvolvimento de modelos que consideram o padrão de transporte advectivo, realizados através da caracterização de algumas propriedades e forçantes físicas como o parâmetro de Coriolis (f), frequências de variação de fluxo (ω) e de *Brunt Väisälä* (N), além das escalas características de comprimento (L), largura (W) e raio de curvatura da feição mais pronunciada antes da desembocadura do cânion (R) (ALLEN, 2004; DAWE; ALLEN, 2010). A partir disso, pode-se calcular o número de Rossby para categorizar a intensidade do fluxo e avaliar como em determinadas condições pode haver *input* de águas de regiões mais profundas para áreas sobre a plataforma, ou em outras palavras, indução do fenômeno de ressurgência.

Sabe-se que a maioria das pesquisas sobre dinâmica de fluxo em cânions submarinos deixa clara a influência da morfologia sobre dinâmica interna e que quase todas essas características e processos pertencem aos cânions de incisão da plataforma, ou seja, que discutem os maiores cânions que têm comumente incisão na plataforma continental ou podem até mesmo ter uma conexão direta com sistemas fluviais terrestres modernos. No entanto, na região da PCSP, os cânions do platô terminam na encosta, definidos como os chamados cânions "cegos" (HARRIS; WHITEWAY, 2011). A motivação para esta tese é demonstrar, por meio de análise de escala, que os cânions submarinos cegos do Platô de Pernambuco influenciam não somente na PCSP, como também ao longo do litoral Nordeste brasileiro. Principalmente, pelo aumentando o potencial de bombeamento de águas frias de zonas mais profundas para áreas mais rasas, o que se pode destacar como picos de ressurgência locais, contribuindo com a quebra do paradigma de que as águas adjacentes à costa do Nordeste brasileiro apresentam características unicamente oligotróficas.

1.1 ESTRUTURA DA TESE

A tese está organizada em 4 capítulos: 1) um capítulo introdutório de apresentação, justificativa e estrutura da tese; 2) um capítulo em formato de artigo (macroescala) de referencial teórico e discussão dos avanços dos estudos com cânions submarinos na América do Sul; 3) um capítulo em formato de artigo (mesoescala) para a discussão do efeito de soerguimento de massas d'água na região Nordeste do Brasil; e 4) um capítulo de integração dos resultados e conclusões (Figura 1).

Figura 1 - Fluxograma geral com as diretrizes e desenvolvimento da Tese.



O primeiro capítulo é de introdução e faz uma abordagem sobre a importância dos estudos com cânions submarinos em contextos gerais, destacando a sua morfologia como um dos principais aspectos responsáveis pelas trocas que ocorre entre as áreas mais rasas e as mais profundas no ambiente marinho. Este capítulo é baseado no objetivo geral da tese, a qual busca estimar o potencial de soerguimento e transporte de massas de água fria sobre a plataforma e borda da plataforma continental devido a presença de cânions submarinos ao longo da costa do Nordeste brasileiro.

O segundo capítulo faz uma retrospectiva por meio de uma revisão dos estudos com cânions submarinos na América do Sul e demonstra através de uma análise espaço-temporal uma linha do tempo com avanço desses estudos a sua relação com a Década Oceânica. Este capítulo serviu como referencial teórico, pois aborda o desenvolvimento de estudos com cânions submarinos no continente sul-americano desde o início dos anos 70 até os dias atuais. Este capítulo faz referência ao objetivo específico três (3), o qual busca classificar e comparar, a partir da literatura, quanto ao tipo de processo característico e o potencial de transporte associado, com outros canais e cânions já mapeados e classificados.

O terceiro capítulo é focado no efeito de bombeamento de massas d’água através de cânions cegos submarinos localizados no Platô de Pernambuco e sua influência na dinâmica de submesoescala no litoral Nordeste brasileiro. Este capítulo é relacionado aos objetivos específico um (1) e dois (2), onde respectivamente busca a identificação das regiões onde as condições morfodinâmicas apresentem indícios para o soerguimento de massas d’água, principalmente na Plataforma Continental Sul de Pernambuco.

2 OBJETIVOS E HIPÓTESE

Neste item encontram-se descritos os principais objetivos e hipótese que norteiam a presente pesquisa, evidenciando as características chave para o seu desenvolvimento e conclusão.

2.1 OBJETIVO GERAL

Estimar o potencial de levantamento e transporte de massas de água fria sobre a plataforma e borda da plataforma continental devido a presença de cânions submarinos ao longo da costa do Nordeste brasileiro.

2.2 OBJETIVOS ESPECÍFICOS

- Identificar regiões onde as condições dinâmicas apresentem indícios para o soerguimento de massas de água próximo a cânions submarinos, na Plataforma Continental Sul de Pernambuco.
- Relacionar, através de levantamento bibliográfico, a evolução das características dos estudos de cânions submarinos na América do Sul dentro do panorama global.
- Classificar, através da análise de escala, o comportamento dinâmico de massas de água e sua interação com a topografia de fundo próximo a região da quebra da plataforma continental, na costa Nordeste do Brasil.

2.3 HIPÓTESE

A hipótese que foi testada é a de que a presença de estruturas de canais e cânions submarinos alteram a dinâmica de fluxo local, influenciando nas condições físicas do meio na região do Nordeste brasileiro, onde a resposta dinâmica de mesoescala está relacionada pela interação entre a morfologia do fundo marinho e o sistema de correntes de borda oeste.

3 THE SOUTH AMERICAN ADVANCES OF SUBMARINE CANYONS STUDIES AND THEIR LINK TO THE OCEAN DECADE

Abstract

Submarine canyons have a relevant role in marine ecosystems. They are responsible for oceanographic conditions such as variability of temperature and salinity, sediment transport, nutrients, and even pollutants amongst marine areas. Submarine canyon studies have been growing and reaching prominence due to their importance in the Blue Economy. Initiatives to promote sustainable development for the ocean have been discussed in the Ocean Decade. Although canyons studies are increasing, how can we integrate these with the Ocean Decade outcomes? Thus, we aim to demonstrate an overview of the advances of submarine canyons studies and their link to the Ocean Decade for South America. We analyzed 160 studies divided into spatiotemporal analysis and study approaches according to the Ocean Decade outcomes. We discuss these articles, building a timeline and argumentative topics considering the advances, and discuss gaps to predict the future of submarine canyons studies in the Ocean Decade and Blue Economy context.

Keywords: Ocean Decade, continental margin, seabed, marine events, review, spatiotemporal analysis.

1. Introduction

Submarine canyons are relevant marine features that make up continental margins around the world. They are biodiversity hotspots responsible for marine environment health (ROBERTSON et al., 2020; SANTORA et al., 2018). Currently, several studies have been published about submarine canyons and their influence on the ocean and how a seabed feature is essential to provide a complex system amongst the geological (FILDANI, 2017), physical (AGUIAR et al., 2018), biological (BERNARDINO et al., 2019), and social (UDDIN et al., 2021) processes. Submarine canyons studies aim to understand the association of each process that belongs to their system, increasing the overview on different study subjects as well as the specific locals present on continental margins, shelf-break, slope, or close to the rise areas in the ocean (CALLOW et al., 2014; LAVAGNINO et al., 2020; LEYNAUD; SULTAN, 2010).

Several studies have been published and involve different approaches on submarine canyons. For instance, some studies have aimed to assess the impacts of pollution (CAU et al., 2017; KANE; CLARE, 2019). Other approaches are understudied and need to be developed, i.e. marine geohazards (MELEDDU et al., 2016) and geohabitats (TERNES; DE MACEDO

DIAS; DIAS, 2020). These studies are even understudied in developed countries, including countries in South America (SA). So, the need to improve the knowledge about submarine canyons in these areas is clear, especially about their oceanographic processes and impacts.

The lack of funding to scientific studies in SA has negative impacts in all spheres of a country, mainly in their economy. The Blue Economy concept is a popular term in ocean governance, which seeks to associate ocean-based development opportunities with environmental stewardship and protection (VOYER et al., 2018). Although its concept is complex and broad, we must highlight its importance following its objectives and feasibility in a balanced and coherent way amongst the countries (SMITH-GODFREY, 2016). However, it is a challenge due to concept variations and ways of applying the Blue Economy, and their association with the gaps in distribution of the spatiotemporal database of canyons studies in SA, especially in EEZs boundary. Canyon studies examine how countries explore their EEZs, and management of marine space is a matter of national and international importance due to conventions for oceanic areas established by the United Nations Convention on the Law of the Sea (UNCLOS) (POLEJACK, 2021).

Marine spatial planning (MSP) has developed as a mechanism to cope with the challenges that come along with the allocation of human activities and ecological functions to marine space (STEENBEEK et al., 2020). The main purpose of MSP is to promote sustainable development, to identify the use of maritime space, and to manage spatial uses and conflicts in marine areas (EUROPEAN UNION, 2014). The MSP concept has been designed to help with decision makers and stakeholders, the disclosure of knowledge, and management of the maritime Blue Economy and marine environment. However, management of marine space is a hard task and needs to be prepared in a systematic and organized way (MAYER et al., 2013). According to the authors, marine ecosystems have been affected by human activities such as fisheries, shipping, wind farms, recreation, and tourism. Thus, it is becoming crucial to regulate and plan marine spatial claims.

Therefore, we understand how canyon studies are important for management MSP and marine ecosystems as fundamentals to society. However, there are several questions to consider. What direction have submarine canyons studies taken over the years? How are they included in marine research? What are the next steps in canyon submarine studies? These are some questions about the future in this research area, and they can drive future studies to contribute to MSP and Ocean Decade Outcomes. The United Nations Decade of Ocean Science for Sustainable Development or Ocean Decade (2021-2030) emerged as an initiative to catalyze transformative ocean science solutions for sustainable development, connecting people, science, and technology to the ocean. The Ocean Decade is a great opportunity to change and support a sustainable development and galvanize ocean sciences for the future (IOC-UNESCO, 2021; RYABININ et al., 2019).

The Ocean Decade aims to promote the generation of data, information, and knowledge to move from the 'ocean we have' to the 'ocean we want' through seven outcomes which describe the 'ocean we want' at the end of the Ocean Decade Challenges: (1) A clean ocean where sources of pollution are identified and reduced or removed; (2) A healthy and resilient ocean where marine ecosystems are understood, protected, restored, and managed; (3) A predicted ocean where society understands and can respond to changing ocean conditions; (4) A safe ocean where life and livelihoods are protected from ocean-related hazards; (5) A sustainably harvested and productive ocean supporting sustainable food supply and a sustainable ocean economy; 6) A transparent and accessible ocean with open and equitable access to data, information and technology, and innovation; and 7) An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development (IOC-UNESCO, 2021).

Thus, this study aims to demonstrate an overview for the future of the role of SA submarine canyons studies and their link to the Ocean Decade, highlighting the advances, gaps, and forecasting of them into the marine science development. It also aims to approach their evolution for timeline building and its influence on the world scenario through spatiotemporal analysis.

2. Methods

2.1 Database formation

The Web of Science and Scopus were chosen to collect papers peer-reviewed in May 2020, which used the same set of keywords, and unlike most reviews, a filter for searching keywords was applied in the whole document to classify the canyons studies in a timeline even if it occurred as just a citation in all of them. Boolean operators were also chosen by the criterium of increase on the searching range. From that: ALL = ("submarine canyon*" OR canyon*) AND (Argentina OR Bolivia OR Brazil OR Chile OR Colombia OR Ecuador OR Guyana OR Paraguay OR Peru OR Suriname OR Uruguay OR Venezuela). In total, 468 studies were retrieved and analyzed for description of main results, but 308 papers were eliminated as they did not match the adopted criteria, such as paleocanyons or continental canyons (LIMA;

DIAS, 2008; MANSURBEG et al., 2012). Finally, 160 studies were selected to compose the database divided into spatiotemporal analysis and types of studies (Supplementary Data Sheet 1).

2.2 Timeline building

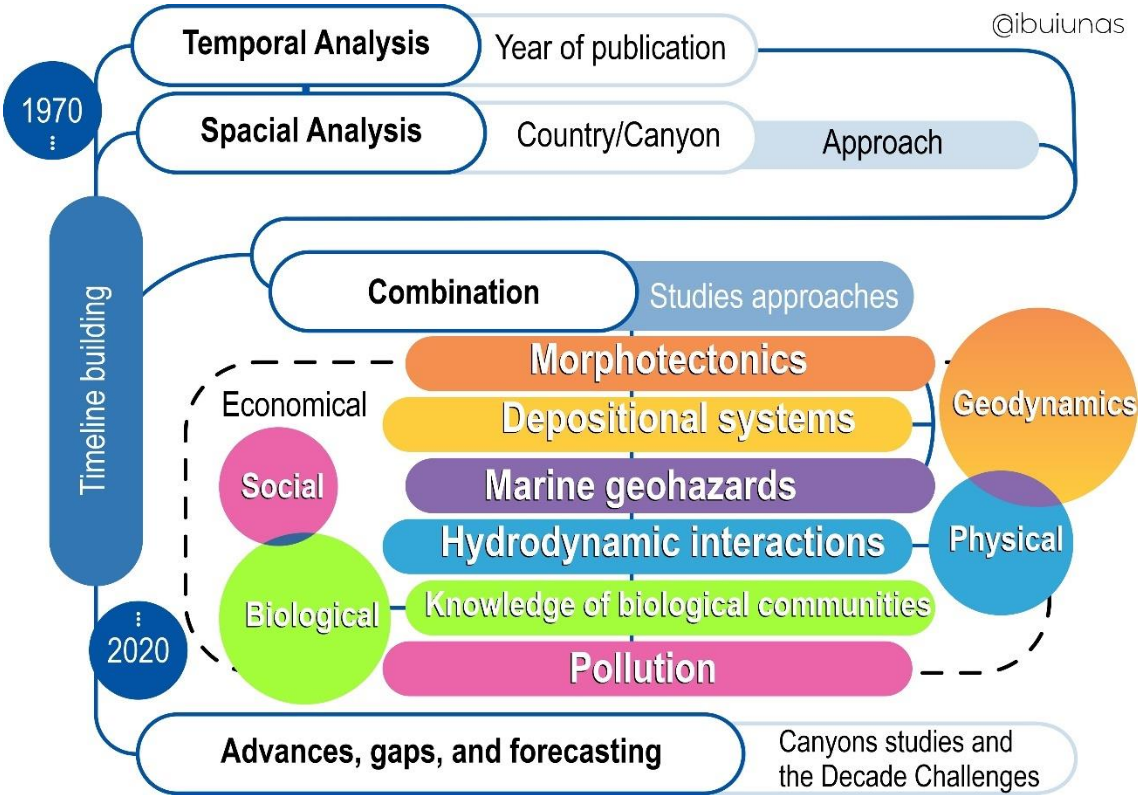
Three layers of analysis were assumed for timeline building, established by the results of the main aspects (temporal, spatial, and combination) and one layer related to the advances, gaps, and forecasts of canyons studies and their link with the Ocean Decade (Figure 1).

To check the chronology of studies, the temporal analysis was chosen. Thus, a Productivity Coefficient (P_c) was created, which is equal to the Analyzed Period (A_p) divided by the Number of Publications per Year ($NUPPY$). From this, we were able to estimate the percentage yield obtained by the difference of the P_c values concerning the previous year.

$$\boldsymbol{P_c = \frac{A_p}{NUPPY}}$$

On the other hand, the spatial analysis considers the distribution of studies among countries, identifying which agents are involved and what approach the studies have. Thus, we decided to rank the countries that publish the most in SA in ascending order, classifying them into three different approaches according to the development stages involving canyons studies, classified in identify (ID), qualify (QL), or quali-quantify (QLQT). The ID occurs when there is a citation of the submarine canyon feature "not directly" related to the study, i.e., when there is a reference to it in the text body without necessarily contributing to the development of the study, ignoring the submarine canyons in a discursive context. The QL occurs when the submarine canyons "characteristics" have contributed to the study development, complemented by a set of arguments observed in the main results, discussion, and conclusions, qualifying the importance of the canyon. At last, QLQT happens when the "characteristics" and "number" of canyons have also corroborated for its development, i.e., besides QL, the cataloging of them is indispensable for the discussion and complement in general.

Figure 1 - Methodological flowchart with the development steps and visualization of the results map.



In combination, we establish the connection with the studies approach, which is defined by their main characteristics. In total, six different study approaches have been identified, divided into four general groups, namely geodynamics (morphotectonics, depositional systems, and marine geohazards), physical (hydrodynamic interactions), biological (knowledge of biological communities), and social appeal (pollution), although each of them has a social character.

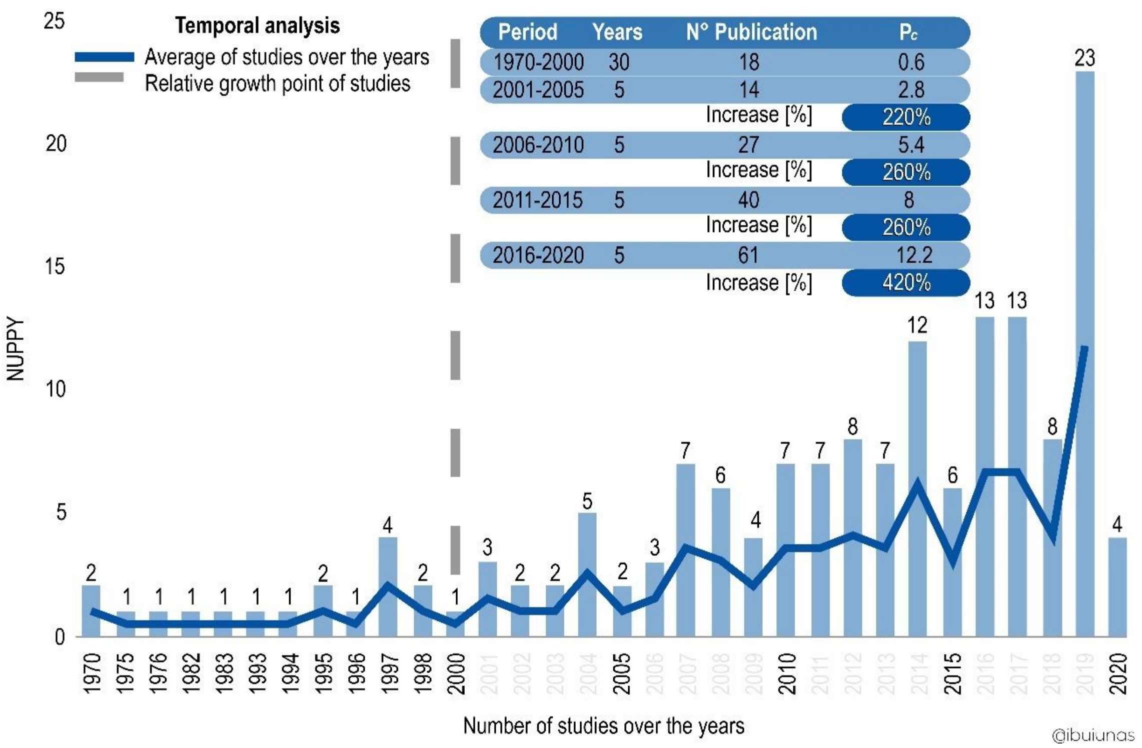
Finally, we have discussed the advances, gaps, and forecasting of knowledge of the evolution process involving submarine canyons studies in SA, highlighting the similarities with the Ocean Decade social outcomes.

3. Chronological progress in South America

Initially, 160 studies were verified for temporal analysis which presents two periods with different characteristics (Figure 2). The first is from 1970 to 2000 and it was verified that its publications did not have a successive periodicity (as an exception in 1994 to 1995) but has ten years between publication intervals (seen in 1983 to 1993). The second period is from 2001 to the present, with a gradual increase in the $NUPPY$, in addition to maintaining the periodicity over the years. Here, we also observe the relative growth point of studies that separate both periods if we consider the average of the $NUPPY$.

The individual analysis shows for the first period that the $NUPPY$ has a minimum of one publication per year (for most years until the year 2000) and a maximum of four in 1997. The average of studies over the years began with two studies in 1970, remained relatively stable with one publication per year (except in 1995 by two publications) in the following years until 1997, where four publications were verified, falling again to two and one studies, respectively in 1998 and 2000.

Figure 2 - Temporal analysis of submarine canyons studies from 1970 until April 2020 (unfinished), with an average of studies over the years (dark blue line), and relative growth point of studies (dash gray line). The highlight for the increase of productivity coefficient (P_c) which is equal to the period analyzed divided by the $NUPPY$.

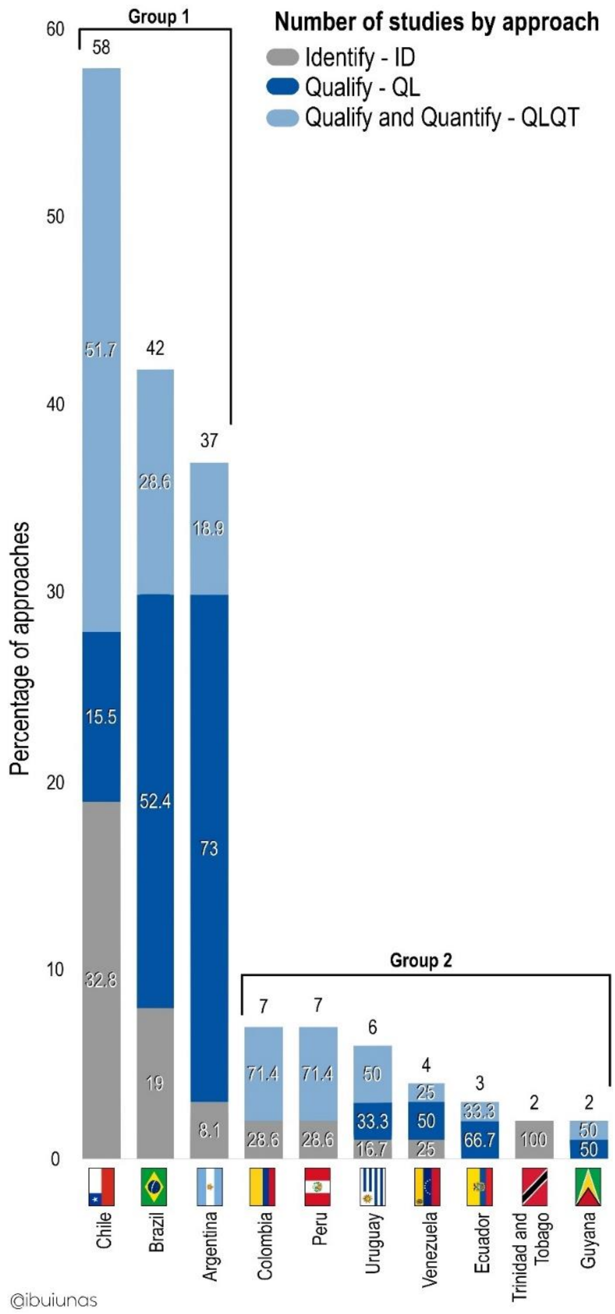


After the 2000s, a gradual and significant increase in the $NUPPY$ was identified. From 2001 to 2005, 14 studies were published with a P_c equal to 2.8. As a comparison, when analyzing the period from 1970 to 2000, we 18 studies re published in 30 years with a P_c of 0.6. This shows a 220% increase in P_c in comparison to the first period. Also, from 2006 to 2010 and 2011 to 2015, productivity increased and remained relatively constant, because even with the respective increase in the P_c of 5.4 and 8.0, the values in yield remained at 260.0%.

Comparing the period 2016-2020 (61 studies) with the previous (40 studies), we have an increase in both P_c of 12.2 and in the yield, reaching 420.0%.

In spatial analysis, the studies number among SA countries shows a difference between the two groups, separated by the criterion of extremes concerning the amount of publication by country. Also, the numbers point to diversity in the type of approach associated with submarine canyons studies for each country as ID, QL, or QLQT (Figure 3).

Figure 3 - Spatial analysis of submarine canyons studies with emphasis on the percentage of approach types concerning the ranking of publication by country and their division by groups.



Moreover, Figure 3 has two groups that stand out concerning the $NUPPY$. The type of approach is important for maintaining these numbers, especially when analyzing within Group 1 the studies that only mentioned canyons using the ID approach, reaching 32.8% in Chile with almost 20 studies published and in Group 2 Trinidad and Tobago with a 100% ID approach for only two published studies. It seems low in comparison QL and QLQT, but we must consider that the composition of each approach is fundamental when analyzing the spatial profiles of studies. Thus, making a relationship between Figure 3 and Figure 4, Brazil, Venezuela, and Guyana are three of the five countries mostly with a QL approach, at the beginning phase, while Argentina and Chile have a QLQT approach in the current phase. The largest numbers of publications with an ID approach are interspersed throughout the interval phase.

4. Type of studies and its spatial distribution

Submarine canyons studies were classified according to the main types: (1) morphotectonics, (2) depositional systems, (3) marine geohazards, (4) hydrodynamic interactions, (5) knowledge of biological communities, and (6) pollution. The spatial distribution model was used to find patterns and similarities in a systematic way and more effective responses to advance discussion on submarine canyons studies.

SA shows a spatial distribution pattern, especially when we assign the margin as an analysis parameter. There are differences between the studies carried out on the active margin as marine geohazards and those on the passive margin as coastal erosion (Figure 4) and the analysis topics with the biggest differences were realized in each study approach. The Supplementary Data Sheet 1 shows the quantity of studies that were chosen to represent the arise point of countries and their first specificities of studies over the timeline (as seen in Figure 5).

4.1 Morphotectonics

Morphotectonic studies have been made in the whole timeline relative to three different natures: geomorphological characterization, geomorphological evolution, and tectonic control. At first, the access for turbidites through seismic profiles investigation was performed to map the Demerara and Barracuda abyssal plain through the local bathymetry and morphological characteristics of submarine canyons (EMBLEY; EWING; EWING, 1970) (Figure 4B). Geophysical methods and sedimentary framework were used to recognize the geologic history of the southern Brazil-Uruguay continental margin (BUTLER, 1970). A high influx of sediment from Brazil was dispersed predominantly southeastward along the trend of the Fernando de Noronha Basin, to form the prominent lower Miocene acoustic reflector which occurs throughout the Equatorial Mid-Ocean Canyon (DAMUTH; GORINI, 1976) (Figure 4R).

Generally, morphotectonics studies are based on the identification of seabed features describing their morphological aspects. The acoustic intensity data (side-scan) to describe the morphology of the San Antonio submarine canyon was presented by Hagen et al., 1996, while Alfaro and Holz, 2014, have detailed characterization of the geomorphological architecture of gravity-driven deposits on the tectonically active Caribbean margin and its interpretation of the triggering mechanism of gravity-driven sedimentary processes (ALFARO; HOLZ, 2014). Almeida et al., 2015 (Figure 4S), have provided the first full data coverage of the seafloor between the upper and middle continental slopes (100m - 1300 m) adjacent to the Brazilian equatorial margin, using multibeam bathymetric data.

Geomorphological studies are used to classify the features as depressions, channels, pinnacles, and submerged reefs, and their association with seafloor sediment distribution and composition, as well as biological communities' interactions. Studies have discussed the influence of antecedent geology and distinct spatially and temporally driven processes in the formation of the shelf-upper slope depositional features in contrasting geomorphological and sedimentological shelf breaks (D'AGOSTINI et al., 2019) (Figure 4N). Also, these studies map the seafloor and geology in the near subsurface using 3-D seismic reflection data from four sedimentary basins, with specific interest in the identification of constructive and destructive surfaces that record the seafloor of these fore-arc basins (CALVÈS et al., 2017) (Figure 4H).

Seabed features like submarine canyons are an important evolution approach that can report on the major tectonic studies in subduction zones, describing the origin of basins based on tectonic control (SCHUBERT, 1982) (Figure 4E). They can be used to observe the origin and structural evolution of the Valparaiso Basin, which is the only morphologically prominent and structurally significant deep water forearc basin (LAURSEN; SCHOLL; VON HUENE, 2002), or study the morphotectonics in the forearc region, and their tectonic effect over the subducting Nazca Plate structure on the continental margin (LI, 1995). Geomorphology and geological controls that led to the incision of the La Aguja submarine canyon are discussed by (RESTREPO-CORREA; OJEDA, 2010) (Figure 4F), providing strong geologic and geophysical evidence of the major processes that sculpted the canyon: faulting, submarine erosion and axial incision, structural uplift, tectonic subsidence, and mud diapirism.

Seismic investigations to understand the sediment distribution was increased simultaneously to the new methods used. Studies focused on the plate boundary subduction contact, and the tectonic-sedimentary evolution provides a powerful tool to reconstruct exhumation histories of the source areas (CONTARDO et al., 2008; CONTARDO; KUKOWSKI; CEMBRANO, 2011; JEGOU et al., 2008). In the South-Central Chilean margin, for example, the reconstruction of the relevant processes is applied to sediment pathways that can be reconstructed based on longitudinally variable topographic and orographic settings (HEBERER; BEHRMANN; RAHN, 2011) (Figure 4K).

Studies involving climate changes were also developed concerning the variability of temperature and their impacts on the sea. Armijo et al., 2015, hypothesize that a global plate tectonic reorganization involving long-lasting viscous mantle flow has probably forced both Andean orogeny and global climate cooling since ~50 Ma. Michaud et al., 2015, (Figure 4G) evaluate the spatial and temporal contribution of tectonic and climate changes on the structural development and stratigraphic evolution of the Ecuador continental margin. Quaternary studies have progressed in continental margin zones and have been associated with geomorphological evolution studies such as sea level rising and the last glacial lowstand (CAMARGO et al., 2015). Shelf-margin studies to reconstruct late quaternary sedimentary and advance new insights into the age as well the hydrocarbons deposits under the seafloor are being developed (ERCILLA et al., 2019; MASON et al., 2019).

Also, mass transport complexes (MTCs) studies emerge as important deposits transported by submarine canyons. The MTC in deep-water basins means that efficient oil and gas exploration and development in such settings hinge on an understanding of the nature, processes of formation, distribution, and relationship between them. Deposits share with surrounding deep-water environments, and also pursue a detailed geomorphological study of the last glacial lowstand shelf-margin system along eastern offshore Trinidad (MOSCARDELLI; WOOD, 2008; MOSCARDELLI; WOOD; DUNLAP, 2012) (Figure 4C). Besides, recent mass-transport deposits (MTDs) in the Ecuador trench are identified, and their volumes and sources are estimated, discussing their potential causes by comparing their frequency with the sea-level rise over the last 23 kyr, turbidites frequency over ∼5 kyr, and local earthquakes frequency during the last century (RATZOV et al., 2010) (Figure 4F).

The evolution of methods and ways to collect data as well as the objective (2) of Ocean Decade, morphotectonics studies are fundamental to survey research to generate comprehensive knowledge and understanding of the ocean floor. Several morphotectonics studies have used advanced survey mapping technology to investigate the seabed (JARA-MUÑOZ et al., 2017), substrate (GRUETZNER; UENZELMANN-NEBEN; FRANKE, 2016), sediment layers (ESTEBAN et al., 2017), bedforms (GOMES et al., 2016) (Figure 4T), and flow-topography interaction (WARRATZ et al., 2019), but almost all describe in detail the marine morphology and its depositional architecture (DO NASCIMENTO SILVA; GOMES; VITAL, 2018; IDÁRRAGA-GARCÍA; LEÓN, 2019; LAVAGNINO et al., 2020).

4.2 Depositional systems

Depositional systems studies were carried out to understand the sedimentary processes in the marine environment, reporting how seabed features are formed. Depositional systems studies are divided into four categories: sediment dynamics, stratigraphic architecture, hydrocarbons, and chronostratigraphic. From sediment dynamics, studies of seabed mapping were the first found to evaluate sedimentary processes as a link with the previous specificity (morphotectonics). Damuth, 1975 (Figure 4A), have demonstrated how echograms can be utilized in conjunction with sediment data (piston cores, etc.) to evaluate sedimentary processes to best describe the morphological features mapping. Several methods were used to map a huge extension of the seafloor over the EEZ’s of SA countries as side-scan sonar, single-channel seismic reflection, and bottom sampling survey across the Peru-Chile forearc mapped a large submarine canyon system offshore of southern Peru and northern Chile (HAGEN et al., 1994).

Depositional studies are generally focused on understanding sedimentary mass transport (GRUETZNER; UENZELMANN-NEBEN; FRANKE, 2012; LORENZONI et al., 2012) through submarine canyons between continental shelves and abyssal plains, and understanding the characteristics of the sandy turbidites deposited on an active margin, which reveals their characteristics and patterns of Quaternary sandy deposits distributed across the entire Venezuelan margin (FAUGÈRES et al., 1993) (Figure 4C). These studies describe the sedimentary processes that occur near canyons as features formation (BRUHN; WALKER, 1995), the sand bodies geometry (BRUHN; WALKER, 1997; HÜBSCHER et al., 2002), grain-size distribution (HEBERER et al., 2010), submarine canyon as a conductor of sediments and nutrients (BERNHARDT et al., 2015, 2016), and the characteristics of organic matter present in bulk surface sediments (ESCOBAR et al., 2019) (Figure 4Q).

On the other hand, depositional systems studies have already deeply explored the flow-topography interaction (FRANCO-FRAGUAS et al., 2014) to analyze the imprint over the modern sediments of the local oceanographic phenomena and the complex interplay between different geostrophic currents and hydrological processes from the outer shelf to offshore (VIANA et al., 1998) (Figure 4N). According to Lima et al., 2007, the objective is to develop a tool to simulate the interaction between bottom currents and the submarine physiography, and to depict the relative importance of any individual current-forcing mechanism as a sediment-reworking agent.

Depositional systems studies also are following new estimates of age using geochemistry data sets to improve sedimentary evolution knowledge (MUÑOZ et al., 2004, 2007; VIOLANTE et al., 2010) and using chronostratigraphic analysis to understand and reconstruct the previous coastal environment. These studies aim to understand how the events of long-term exposure and limited subsidence have controlled the characteristics of the Holocene sedimentation, the distribution of the seascapes and the human uses management, particularly for the fishery areas (DOMINGUEZ et al., 2013) (Figure 4P). They also aim to study the dominant sedimentary processes (outer-shelf hydrodynamic, effects, cross-shelf export mechanisms, bottom-current, transport) which are discussed based on seism-acoustic profiles, lithological texture, grain-size distribution, and terrigenous Neodymium isotopic data (HANEBUTH; BENDER; NAGAI, 2019) (Figure 4M). Chronological studies were developed to investigate the temporal evolution of geological structures (COLLOT et al., 2019; RIEDINGER et al., 2017).

Stratigraphic architectures studies appeared to characterize the architecture of substrate, highlighting their sedimentary and morphological processes (BERTON; VESELY, 2016; VERGARA, 1997). Volker et al., 2012 (Figure 4J), summarizes the geologic setting of southern Central Chile using recently published geophysical, seismological, sedimentological, and biogeochemical data and their outcome is an overview of the current knowledge about the geology. Stratigraphic studies provide a measure of sediment rates to match the volume distribution with the factors that are supposed to control the sediment input, and yields information about their effectiveness of latitudinal sediment transport within the trenches as identified in active continental margins (VÖLKER et al., 2013). Stratigraphic studies are important to introduce the knowledge of hydrocarbons basins in offshore environments. Recent hydrocarbon exploration in offshore basins has led to the availability of numerous high-quality industry seismic and well-log datasets to the academic community (GORINI et al., 2014).

Several hydrocarbons studies were developed to rescue marine resources or something relating to an economic benefit (BENJAMIN; HUUSE; HODGETTS, 2015; ISOLA et al., 2020). There has been an increase in the number of studies focused on hydrocarbon potential.

That is the case of the Regência canyon study, which was induced mostly by a longer term (>400 000 years) decrease in sediment supply, resulting in the investigation of the turbidites form oil reservoirs in the Lagoa Parda (LP) oil-field, located near the mouth of the Doce River (BRUHN; WALKER, 1997) (Figure 4O). Methods of reflection in continental margins by high-resolution seismic activity are developed in an attempt to find hydrocarbon reservoirs (LÓPEZ-RAMOS, 2016). Marine seismic reflection cruises on continental margins have revealed deposits of gas hydrates, which are ice-like solids, constructed mainly from water that also contain a large concentration of gas (RODRIGO; GONZÁLEZ-FERNÁNDEZ; VERA, 2009) (Figure 4K).

4.3 Marine geohazards

Marine geohazards studies are divided into four different categories: earthquake events, tsunami prediction, submarine landslide, and coastal erosion. Each of them is associated with a type of continental margin (active or passive). Active margin studies on earthquake events report a potential sediment mass movement caused by tectonic control as turbidites. To analyze the potential sediment mass movement, studies have used various limit equilibrium methods, with shear strength values obtained mainly from vane shear tests and less frequently from direct shear and triaxial compression tests (BUSCH; KELLER, 1983). Studies aim to date the estimation of volume and sources of sediment to discuss their potential causes by comparing the frequency with the sea-level rise over the last 23 kyr, turbidites frequency over ~5 kyr, and to measure earthquake events (RATZOV et al., 2010) (Figure 4F). Aguilar et al., 2016 (Figure 4D), have proposed by analysis of sediment cores that a large historical earthquake on the El Pilar fault had consequences on the sedimentation within the Gulf of Cariaco.

However, geohazards studies to understand the earthquake events have used other methodologies, for example based on a joint inversion of these events, obtained through the minimum P wave velocity model (STOW; BRACKENRIDGE; TOULMIN, 2012). The marine and terrestrial network, which work independently from each other, provided a broadly similar earthquake distribution at the Central Margin of Chile (THIERER et al., 2005) (Figure 4I). Earthquake events are more common than we think and their signatures can be easily recorded by sediment core through structural patterns identified by seismicity networks throughout the world. Tréhu et al., 2020, have investigated the responses after the 2010 Maule earthquake using seismic high-resolution signatures of S and P waves, which have identified, as an example, 34 earthquakes located within at least six phase picks.

Earthquake events serve as a trigger to other processes in sequence, but this rule is not definite. Submarine landslides can also trigger a series of events depending on their magnitude (CAMARGO et al., 2019; CLARE et al., 2016; GEIST; LYNETT, 2011). According to Völker et al., 2009 (Figure 4K), a large volumetric mass (~24 km3) of displaced continental slope material that maintained much of its cohesion during the slump and run out process from a steep and high headscarp, suggested that a localized but dimensionally large and high tsunami could have been generated that was only counteracted by a large water depth of 4500m of the source area. In active margins, submarine mass wasting is related to the tectonic control, where continuous uplift of the forearc across transgressive upper plate faults results in very steep slope gradients (GEERSEN et al., 2011).

Tsunami prediction studies provide their potential effects on the coast, when its magnitude can be increased by the seafloor topography as submarine canyons and coastal features behave as several resonators (ARANGUIZ et al., 2019; ARANGUIZ; SHIBAYAMA, 2013). As well as shelf promontories, which exhibit bathymetric features with regards to tsunamis, affecting their submerged cape morphology, a potential tsunami generated seawards of the promontory could cause a specific mode of propagation and coastal impact (IOUALALEN et al., 2011). However, there is a challenge involving the prediction of tsunami risks, as its warning systems are increasing and becoming more accurate. Further, scenarios for identifying risk assessment by numerical simulation have been applied. Martínez et al., 2012, have analyzed the tsunami risk for an extreme event that allows to generate risk management criteria, to reconstruct the process of a given region by three different scenarios of risk assessment.

On the other hand, in passive margin, coastal erosion studies were developed to describe the dynamics of the shoreline position with submarine canyons as conductors of coarse sediment to the deep sea, and trails of depressions and sediment waves eroding submarine channels (HEINIÖ; DAVIES, 2009; KOKOT, 2004). Bittencourt et al., 2001 (Figure 4P), have monitored the morphodynamical variations of the beaches associated with an estuary contiguous through superposition of aerial photographs to show the presence of distinctive erosive and constructive cycles of low and high frequencies. Submarine landslide studies are also present in passive margin and focus on the sediment transport from the coast to the deep sea (DALLA VALLE; GAMBERI, 2011). According to Krastel et al., 2011, the continental margin of Uruguay and the de la Plata River extending into northern Argentina is an excellent site to study submarine sedimentation processes, their imprint on seabed morphology, and associated geohazards.

4.4 Hydrodynamic interactions

Studies that focus on physical aspects are divided into three categories: upwelling, wind-driven, and paleoceanography. Almost all studies describe upwelling events relative to the more different contribution in advances of canyons as interacting with the systems of currents with seabed topographic features, that influence the mesoscale distribution and retention organisms (VALLE-LEVINSON; MORAGA-OPAZO, 2006). The interaction between coastal topography, winds, and seasons have intensified upwelling as a complex system, involving transport, retention, and larval aggregation within mesoscale features as eddies and fronts (VARGAS et al., 1997) (Figure 4J). Amorim et al., 2012 (Figure 4P), have established a first regional picture on the influence of large-scale circulation and transient processes, as well as local topographic features, on the seasonal eastern Brazilian shelf circulation.

Submarine canyons are regions of enhanced upwelling and cross-shelf exchange including nutrient flux onto the shelf (HICKEY, 1997). Leth and Middleton, 2004, have suggested a likely mechanism for the enhanced upwelling of the Gulf of Arauco region: wind-forced upwelling in conjunction with deep upwelling by a cyclonic eddy and shoreward advection by a headland eddy next to the Gulf. To upwelling mechanisms, the onshore cross-shore pressure gradient supports the alongshore geostrophic flow that breaks the geostrophic constraint as it interacts with the canyon topography, driving water into the canyon (AGUIAR et al., 2018). The study looked at the adjustment of geostrophic currents, for example, and quasi geostrophic motion like coastal-trapped waves due to their abrupt variations of the bottom topography, modifying the coastal-trapped waves and their low-frequency energy, which can be dispersed into higher modes (SOBARZO; FIGUEROA; DJURFELDT, 2001).

Generally, physical aspects such as geostrophic currents, pressure gradient, and vorticity are the foundation of hydrodynamic interactions studies (BRAVO et al., 2013), however, biological conditions of induction of productivity that arise from the upwelling circulation have been studied more frequently in association (YANNICELLI et al., 2012). Also, measurement of high-productivity have increased together with hydrodynamic interactions, highlighting the potential of top-down control of the shelf production and export of nutrients (TESTA; MASOTTI; FARÍAS, 2018; VERGARA et al., 2017). Hence, an increase in biological communities has already impacted on nearby upwelling zones, mainly in submarine canyons.

Landaeta et al., 2008, have described a series of processes acting at different spatial and temporal scales, as an interaction of the spawning behavior of marine fishes that inhabit the southern part of the Humboldt Current and the frequency of occurrence on mesoscale physical processes.

On the other hand, wind-driven studies are also carried out to describe the circulation models by topographic control nearby submarine canyons and upwelling processes. Sobarzo and Djurfeldt, 2004, have characterized the physical development of the coastal upwelling process near Biobio and Itata canyons and its relation to local wind-forcing and the topographic control of the subinertial flow. Wind-driven processes promote a stronger variability in the water mass exchange between the canyon and the deep ocean near the surface, although the Japaratuba canyon seems to behave most of the time as a water export to the deep ocean, with reversed flow depending on the winds (DEL-GIOVANNINO; DOTTORI; MARTINS, 2000) (Figure 4Q). Winds to act on transporting the sediment plume offshore, reducing the shelf stratification and increasing the chances of a full upwelling. In the Mar del Plata canyon, the occurrence of upwelling is interrupted by strong downwelling events, which tend to advect buoyant waters northward and back toward the shore, "capping" the upwelling center (PIMENTO; GARVINE; MIINCHOW, 2008) (Figure 4L).

Wind-driven studies have been developed using different approaches such as upwelling studies. Studies to explain the formation of vortices in bay beaches, the establishing of currents and their interaction with the tide and local wind (LEITE et al., 2011), and to analyze the barotropic tidal currents and vortices (AGUIRRE; PIZARRO; SOBARZO, 2010), have illustrated the potential of top-down control of the shelf production and export of organic matter (BAIRD; LETH; MIDDLETON, 2007). Sobarzo et al., 2010, have presented the first analysis of diurnal-period wind variability and their current response. Intensity and seasonal cycles of winds create a unique coastal shelf environment with several special features. As a result, thermal stratification of the upper water column in spring and summer is governed by solar radiation, and temperature in the deeper water column is controlled by upwelling favorable wind stress (SOBARZO et al., 2007).

Lastly, the paleoceanography studies emerge to study the climate archive for palaeoceanographic environmental reconstruction, to present different approaches about paleocurrent records for the Last Glacial Maximum (LGM), and offer palaeoecological insights documenting past changes for anticipating future impacts on the environment (GU et al., 2019; WARRATZ et al., 2017), all of them carried out in the Mar del Plata canyon (Figure 4L).

4.5 Knowledge of biological communities

Biological studies began in 2003 with five different natures of studies: vertical distribution, horizontal, taxonomy, ecology, and Marine Protected Areas (MPA). The vertical distribution is relative to nektonic and planktonic organisms that move in water columns, reaching the shallowest areas (BERNAL et al., 2019; LAURETTA; PENCHASZADEH, 2017). Valle-Levinson et al., 2003 (Figure 4J), have suggested two mechanisms that may cause the high primary productivity of the system of current and hydrographic variables in an equatorward facing bay adjacent to a coastal upwelling center. According to them, it is related to a persistent flow into the gulf through the deepest part nearby Biobio canyon and would be described with the diurnal variability in heat from ocean-atmosphere interactions and horizontal momentum from wind-driven stress, as mentioned previously. With the high frequency of semidiurnal tides, diurnal fluctuations superimposed onto others of lower frequency of wind-driven upwelling may contribute significantly to variations in the transport of individuals from bays in upwelling areas (YANNICELLI et al., 2006).

Transport and retention are physical processes responsible for moving early pelagic life stages from the spawning site toward an appropriate nursery ground, influencing the regulation of recruitment and year-class strength (LANDAETA et al., 2008). According to Castro, 1993, knowledge of the location of nursery areas of fishes has been considered as a research requirement for the management of fisheries (VAZQUEZ et al., 2016). On the other hand, the flow-topography interaction has also contributed to modify the vertical distribution and the intensity of its physical processes by upwelling zones which can impact the assemblage's variability. According to Rojas and Landaeta, 2014, the combined effects of coastline and bathymetry on the upwelling circulation may generate a spatially structured coastal habitat where three types of fish larval assemblages can coexist.

To better understand the environment characteristics, we decided to classify the horizontal distribution studies as associated with benthic organisms that have habitats and depend on the seafloor substrate to live. Benthic organisms are influenced by physical parameters such as temperature, salinity, and currents (ARAÚJO et al., 2018; BREMEC; SCHEJTER, 2019; TESO; URTEAGA; PASTORINO, 2019). However, chemical processes are mainly responsible for maintenance and variability of biological assemblages' distribution in submarine canyons where the nutrient exchanges are bigger than abyssal regions (YAMASHITA et al., 2018). Eichler et al., 2019 (Figure 4T), have shown habitat preferences associated with different foraminiferal species in newly-discovered environmental conditions and their potential to indicate palaeo-upwelling and other environmental conditions. Bernardino et al., 2019 (Figure 4N), have suggested that even with similar higher taxa composition, submarine canyons of E-SE Brazil host distinct assemblages individually and between canyon-slope habitats.

Ecology studies have compared benthic and fish communities to evaluate the relationship between their assemblages to study their eating habits and reproductive tactics (FLORES; BROGGER; PENCHASZADEH, 2019; SCHEJTER; LÓPEZ GAPPA; BREMEC, 2014). Penchaszadeh et al., 2016, have described the egg mass of a moon snail from deep waters, and the findings of all intracapsular stages of development in the same expedition, including early stages and hatchlings as enormous crawling juveniles, may suggest a long reproductive season. Penchaszadeh et al., 2017, have contributed to the understanding of the reproductive modalities of the family Volutidae in the Mar del Plata canyon. According to them, all the species studied until now experience direct development and hatch as crawling juveniles. Physical and abiotic factors associated with seabed features have structured shallow water communities even within small spatial scales due to differences in local conditions, such as topography and currents, through nutrient-rich currents reaching them through the canyons and aiding primary productivity, or by a combination among these factors (ROVIRA; GOMES; LONGO, 2019).

Generally, taxonomy studies were carried out to describe new species identified following the morphological characteristics (HASEGAWA et al., 2019), extending the known distribution range and a phylogenetic review of the genus (PEREIRA; ROCCATAGLIATA; DOTI, 2019; SIEGWALD et al., 2020), but also to investigate the reproductive habits (SÁNCHEZ; PASTORINO; PENCHASZADEH, 2018). Here, almost all taxonomy studies have approached the first report of a typical species related to submarine canyons environment as an effort to understand the biodiversity, spatial distribution, and habits of the biological communities and their relationship with these environments (LAURETTA; PENCHASZADEH, 2017; MARTINEZ; SOLÍS-MARÍN; PENCHASZADEH, 2019).

On the other hand, the MPA studies were carried out to understand the oceanographic characteristics that provide suitable foraging, reproductive, and spawn conditions and encourage conservation due to vulnerability and increasing economic interests at fishing areas. Schejter et al., 2016, have reported the most recent and complete checklist of benthic mega and macrofauna that summarized 240 taxa collected at three sites in the Namuncurá MPA. According to them, it will help detect indicator taxa vulnerable to trawling, recognize distribution patterns of the benthic organisms, and support management strategies. The MPA creation provides the identification of oceanographic processes that lead to prey availability which is fundamental for understanding the ecology of marine predators and developing conservation strategies for critical feeding ground habitats (BUCHAN; QUIÑONES, 2016). According to Almada and Bernardino, 2017, any scenario of deep seabed mining within its EEZ, conservation actions need to anticipate bidding auctions and exploration off those areas in a similar way suggested for the offshore oil and gas industry, since those areas lack proper biological assessment and likely host unique and vulnerable assemblages.

4.6 Pollution

Marine pollution by submarine canyons is becoming an issue that can affect the environment in many different aspects. A single pollution study carried out in the Fernando de Noronha Archipelago was identified concerning submarine canyons (IVAR DO SUL et al., 2013) (Figure 4R), which suggests the existence of an outward gradient of mean plastic-particle densities using biological assemblages.

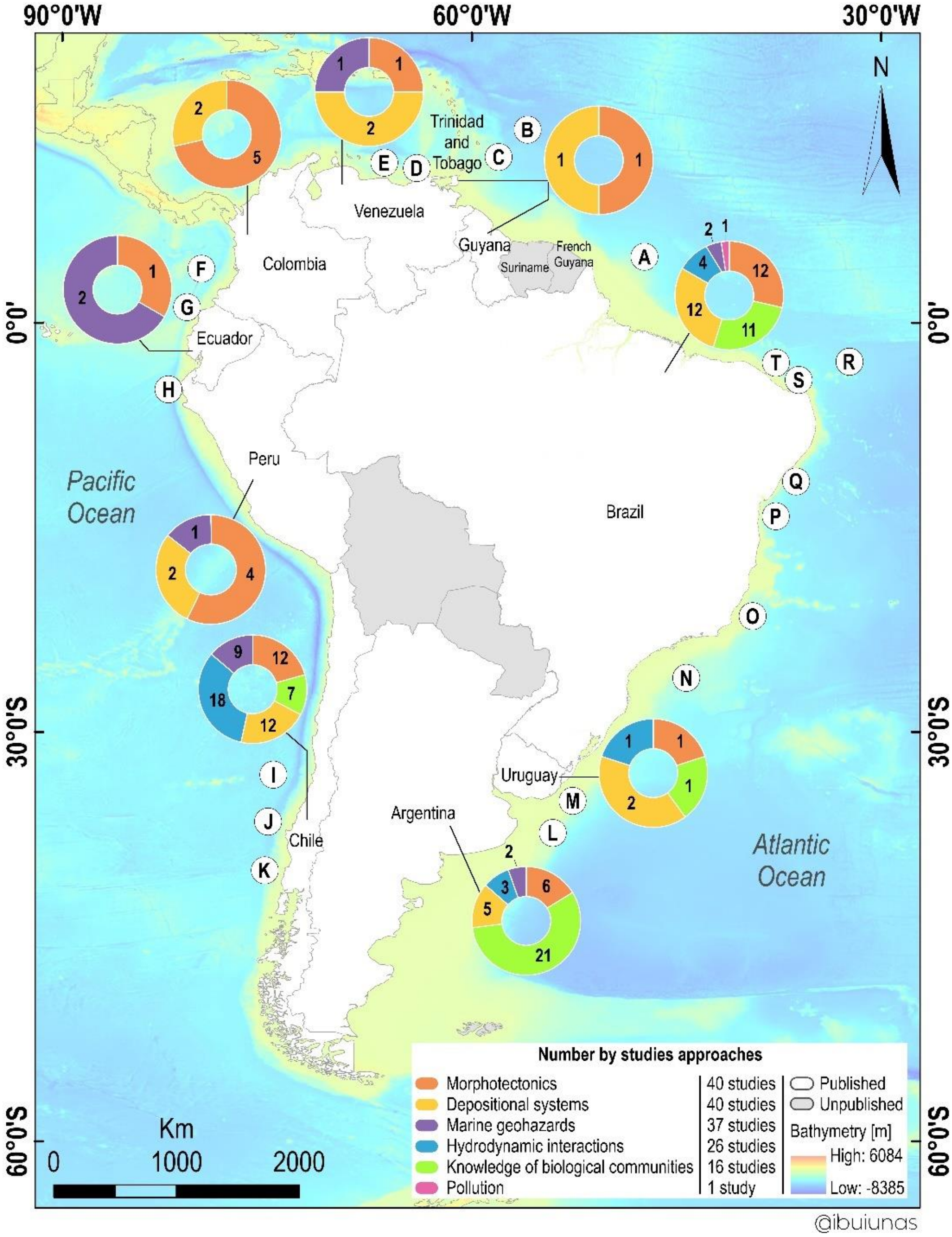
Here, the marine litter study summarized an overview about how the pollution through submarine canyons can transform the whole environment, changing the sediment accumulation rate even in small proportions, modifying the flow as physical barriers and generating impacts on biological communities (HARRIS, 2020; PIERDOMENICO; CASALBORE; CHIOCCI, 2019; UDDIN et al., 2021). The South Atlantic region is expected to present an upward trend in land-based pollution sources as a result of increasing urbanization and industrialization in the coastal zone and the lack of comprehensive regulation, appropriated enforcement, and abatement (HATJE et al., 2021). Some islands are uninhabited, while others are occupied by a few to thousands of people. In the Caribbean Sea, the permanent and/or temporary occupation associated with high costs for waste disposal result in potential land-based sources of plastics depositing in hundreds of insular environments and surrounding waters (MONTEIRO; DO SUL; COSTA, 2020; MONTEIRO; IVAR DO SUL; COSTA, 2018).

Technological advances have influenced all types of studies which can be observed in the methods used, as well as the different natures of each of them (Table 1).

Table 1 - Example of the general data set analysis table with the description of the main results of the bibliographic survey carried out for all research bases.

Authors	**Title**	**Methods**	**Margin**	**Type**
(EMBLEY; EWING; EWING, 1970)	The Vidal Deep-Sea Channel and its relationship to the Demerara and Barracuda Abyssal Plains	Seismic; Drill	Passive	Morphotectonics
(BUTLER, 1970)	Shallow Structure of the Continental Margin, Southern Brazil and Uruguay	Seismic; Bathymetry; Gravimetric; Magnetic	Passive	Morphotectonics
(DAMUTH, 1975)	Echo character of the western equatorial Atlantic floor and its relationship to the dispersal and distribution of terrigenous sediments	Seismic	Passive	Depositional systems
(SCHUBERT, 1982)	Origin of Cariaco Basin, southern Caribbean Sea	Seismic; Core; Gravimetric; Magnetic	Active	Morphotectonics
(BUSCH; KELLER, 1983)	Analysis of sediment stability on the Peru-Chile continental slope	Sediment; Core	Active	Geohazards
(VERGARA, 1997)	The Valparaiso Basin: a morphotectonic and sedimentological background	Seismic; Bathymetry; Sediment; Core; Side-scan	Active	Depositional systems
(VALLE-LEVINSON et al., 2003)	Flow-induced by upwelling winds in an equatorward facing bay: Gulf of Arauco, Chile	Hydrographic; Biological variables	Active	Knowledge of biological communities
(KOKOT, 2004)	Erosión en la costa patagónica por cambio climático	Fluvial discharge	Passive	Geohazards
(MOSCARDELLI; WOOD, 2008)	New classification system for mass transport complexes in offshore Trinidad	Seismic	Active	Depositional systems
(PIMENTO; GARVINE; MIINCHOW, 2008)	Observations of coastal upwelling off Uruguay downshelf of the Plata estuary, South America	Hydrographic	Passive	Hydrodynamic interaction
(RESTREPO-CORREA; OJEDA, 2010)	Geologic controls on the morphology of La Aguja submarine canyon	Seismic; Bathymetry	Active	Morphotectonics
(IOUALALEN et al., 2011)	The tsunami signature on a submerged promontory: the case study of the Atacames Promontory, Ecuador	Bathymetry; Satellite images; Modelling; Experiments	Active	Geohazards
(KRASTEL et al., 2011)	Sediment dynamics and geohazards off Uruguay and the de la Plata River region (northern Argentina and Uruguay)	Seismic; Sediment; Core	Passive	Geohazards
(IVAR DO SUL et al., 2013)	Pelagic microplastics around an archipelago of the Equatorial Atlantic	Biological assemblages	Passive	Pollution
(PENCHASZADEH et al., 2016)	Giant egg capsules and hatchlings in a deep-sea moon snail (Naticidae) from a southwestern Atlantic Canyon	Planktonic net	Passive	Knowledge of biological communities
(CALVÈS et al., 2017)	Fore-arc seafloor unconformities and geology: Insight from 3-D seismic geomorphology analysis, Peru	Seismic; Bathymetry; Hydrographic	Active	Morphotectonics
(ISOLA et al., 2020)	Tectonic and structural controls on Neogene fluid release in the Patagonian Continental Margin	Seismic; Bathymetry	Passive	Depositional systems
(LAVAGNINO et al., 2020)	Geomorphometric Seabed Classification and Potential Megahabitat Distribution in the Amazon Continental Margin	Bathymetry	Passive	Morphotectonics
(TRÉHU et al., 2020)	Post-seismic response of the outer accretionary prism after the 2010 Maule earthquake, Chile	Bathymetry; Seismicity	Active	Geohazards
(SIEGWALD et al., 2020)	A new species of the deep-sea genus Scaphander (Gastropoda, Cephalaspidea) from the Mar del Plata submarine canyon off Argentina	Trawl	Passive	Knowledge of biological communities

Figure 4 - Spatial distribution map of studies on submarine canyons areas (letters) in South America with emphasis on the number of publications by different specificities data with countries in white that have published and in gray that did not publish. (A) - Amazon. (B) - Vidal Deep-Sea. (C) -Darien Ridge. (D) - Manzanares. (E) - Los Roques. (F) - Patia/ Mira/ Esmeraldas/ La Aguja. (G) - Santa Helena/ Guayaquil. (H) – Paita/ La Bocana. (I) - San Antonio/ Rapel/ Mataquito/ Maule/ Itata. (J) - Biobio/ Lleulleu/ Imperial/ Toltén/ Lingue. (K) - Callecalle/ Chaihuin/ Chacao/ Cucao. (L) - Mar Del Plata/ Ameghino. (M) - Ignacio. (N) - Almirante Câmara/ Grussai/ Rio Doce/ Watu Norte/ São Tomé. (O) - Regencia. (P) - Salvador/ Itacaré/ Almada/ Uma/ Canavieiras. (Q) - São Francisco/ Japaratuba. (R) - Equatorial Mid-Ocean/ Fernanado de Noronha Arquipélago. (S) - Grossos/ Areia Branca/ Mossoró/ Apodi/ Ponta do Mel. (T) - Ponta do Mangue/ Macau/ Assu.



5. Change of knowledge and the evolution of canyon studies

Four groups of studies are observed in timeline: geodynamics (morphotectonics, depositional systems, and geohazards), physical (hydrodynamic interactions), biological (knowledge of biological communities) and social (pollution) studies. As a result, a sequence of arguments was followed for identifying some important aspects from submarine canyons studies in SA to analyze each of them and their link to the Ocean Decade.

Geodynamic studies are based on morphotectonic and depositional systems, since in the mid-1970s new methodologies triggered seabed mapping driven by technological advancements post World War II (JOHNSTONE; MCLEISH, 2020). Seabed mapping is becoming faster due to the investigation of oil reservoirs, and also the emergence of studies carried out in offshore areas (SOLHEIM; FORSBERG; YANG, 2007). The high $NUPPY$ is also related to the financial support of the main oil exploration companies which is observed nowadays (ROLIN; BOMPAIS; LE GUEN, 2013). Partnership between academy and industry is a trend that helps to map the EEZs regions considered of high potential for exploiting resources (KERRY; GARY; ROBERT, 2008). Depending on the location and investment sources, each EEZ may be partially or integrally linked to these resources (VOYER et al., 2018). Morphotectonic studies based on seabed mapping are observed practically along the whole timeline, even if they have emphasized only on technological development.

The climate change associated with sea level rise has increased the $NUPPY$ related to transport areas and sediment accumulation concentrated at mouths of rivers (LAVAGNINO et al., 2020). Studies on continental margins appear, where the methodologies are modified according to the purpose of each of them (IDÁRRAGA-GARCÍA et al., 2019). As a result, sediment dynamics studies have investigated below the seabed to identify how oil reservoirs have changed to determine eustatic cycles (GOMES et al., 2016). Geomorphological changes promoted by the sea level rising have become the focus for increasing investments in technologies that anticipate the occurrence of extreme events in coastal zones (RATZOV et al., 2012). Studies included exploring the smallest to the largest sources of impact on coastal erosion (KOKOT, 2004), classifying earthquakes with epicenters at sea (IOUALALEN et al., 2011), and prediction of submarine landslides and tsunami risks (ARANGUIZ; SHIBAYAMA, 2013; KRASTEL et al., 2011).

Marine geohazards emerge to represent coastal erosion, earthquakes, submarine landslides, and tsunamis (CAMARGO et al., 2019). Most geohazard studies are associated with the active margin on the subduction zone (NUNN; PASTORIZO, 2007), although they are also present on the passive margin (KRASTEL et al., 2011) (Figure 4). In active margin, studies have investigated features of the seabed as pockmarks as an indication of possible areas of gas hydrate leaks and indicative of energy sources (DE MAHIQUES et al., 2017), for mapping potential areas for the occurrence of extreme events as submarine landslides areas (ALBERTÃO et al., 2015). They have also aimed to introduce new techniques to predict extreme events and mitigate impacts (ARANGUIZ et al., 2019; MICHAUD et al., 2015).

Nevertheless, environmental social movements emerged to discuss the type of method used in marine surveys, leading to its reassessment and concern for the affected organisms (LEE et al., 2011). Studies based on the relationship of marine communities and their behavior appear in submarine canyon areas as bedforms (LASTRAS et al., 2011), type of substrate (HAGEN et al., 1994), degree of inclination (IDÁRRAGA-GARCÍA; LEÓN, 2019), depth changes (BERNAL et al., 2019), and marine relief (ROJAS; LANDAETA, 2014). Currently, the race for oil exploration gives space to the advancement to so-called benthic geohabitats, being used as a trigger for the investment of public and private initiatives to develop new projects focusing on the knowledge of marine biological assemblages and their association with different oceanographic processes (HERNÁNDEZ-MOLINA et al., 2011; TERNES; DE MACEDO DIAS; DIAS, 2020).

Physical studies are being carried out in active margins related with upwelling effect and its local biota association, mainly on the coast of Peru and Chile (SOBARZO et al., 2016). Although, the dimension of physical processes is not limited to upwelling zones and their influence on fishing areas (MONTERO et al., 2007; YANNICELLI et al., 2012), but also by processes such as wind driven (DEL-GIOVANNINO; DOTTORI; MARTINS, 2000; SOBARZO; BRAVO; MOFFAT, 2010) and paleoceanography (GU et al., 2019; VOIGT et al., 2013). Instead, we have a complexity of elements inserted to better understand the oceanographic relationships of each margin.

The environmental characteristics are determined by their interactions with sediment input, rainfall regime, intensity and direction of winds and currents, water masses, and biological assemblages, affecting a high complexity region such as the Amazon River mouth (Figure 4A) (JEGOU et al., 2008; LAVAGNINO et al., 2020). The sediment distribution, as well as the flow dynamic in submarine canyons, are examples of how the flow-topography interaction is fundamental for the maintenance of these processes (LORENZONI et al., 2012). Methodological advances, such as internal waves analysis (AGUIRRE; PIZARRO; SOBARZO, 2010), interaction of vorticity (LETH; MIDDLETON, 2004), or even water masses intrusion at shelf-break (BRAVO et al., 2013) have been a great influence in studies' evolution over the knowledge of physical processes that occur near coastal zones. The increase of $NUPPY$ and development of hydrodynamic models suggest the flow-topography interactions were carried out to better understand the role of submarine canyons in the edge effects, and transport of water masses from deeper to shallower areas (AGUIAR et al., 2018; AMORIM et al., 2012).

The water column proprieties have changed the local ecosystems due to entry of more saline and cooler and nutrient-rich waters from deeper regions. Variation in the trophic chain, depending on the intensity of their changes, transform from an initially oligotrophic to mesotrophic or even eutrophic environment (MEDINA; CASTRO; PANTOJA, 2014). Submarine canyons areas have become the target of studies in the last decades, due to their fishing dynamic being of great importance to the economy with studies exploring fishing areas (CAMARGO et al., 2015; KATSANEVAKIS et al., 2011), and social aspect impacting publications for the creation of MPA, responsible for maintenance and conservation of marine life (ALMADA; BERNARDINO, 2017).

Biological studies approach two perspectives, (1) biodiversity of benthic organisms and their reproductive tactics, and (2) processes of the derivation of fish larvae and other organisms that belong to the water column (LANDAETA et al., 2008; YANNICELLI et al., 2006). Studies have demarcated the distribution areas, being horizontal for benthic communities (MOLINA et al., 2004) or vertical for nektonic organisms (ROVIRA; GOMES; LONGO, 2019). Studies which emphasize the creation of MPA's have become more frequent as a result of surveys of biodiversity and delimitation of organisms' distribution (SCHEJTER et al., 2016; YAMASHITA et al., 2018). As a result, an increase of knowledge of biological communities studies have discovered new species and biodiversity hotspots nearby submarine canyons, such as the research developed on the Argentine coastline (LAURETTA; MARTINEZ, 2019; TESO; URTEAGA; PASTORINO, 2019).

To the social group, Brazil has an unprecedented publication in the timeline with a focus on pollution that is related to microplastics in the Fernando de Noronha archipelago which have mentioned submarine canyons and their association with marine litter (IVAR DO SUL et al., 2013). Although this study does not show results related to canyons as vectors of dispersion of pollutants in the oceans, it demonstrates a trend established nowadays, due to the spread of the impacts caused by the uncontrolled use of plastic (CAU et al., 2017; MONTEIRO; IVAR DO SUL; COSTA, 2018).

6. Advances, gaps, and forecasting from submarine canyons and their link to the Ocean Decade

Submarine canyons studies are being developed due to the increase of interest for new perspectives about the land-ocean system (FERNANDEZ-ARCAYA et al., 2017; TUBAU et al., 2015a). Investments and politics that support creating more beneficial conditions for practical applications of new knowledge and technology are more present in the world framework in association with organized actions to achieve transformational ocean science (IOC-UNESCO, 2021; RYABININ et al., 2019). To provide solutions that will deliver optimal benefits to ocean science which is co-designed by a diverse range of stakeholders needs to be nothing short of a revolution in the way we generate and use ocean science (IOC-UNESCO, 2021), and promote sustainable development, to manage spatial uses and conflicts in marine areas (STEENBEEK et al., 2020).

Systematically, initiatives around submarine canyons studies are following scientific discussions focused on the ocean's future i.e., to develop an efficient politic of actions for building the ocean that we want and its perspectives for future generations. The Ocean Decade emerges as a revolution with the mission to catalyze transformative ocean science solutions for sustainable development, connecting people and our ocean. Submarine canyons studies have been presented as a Decade contribution that supports the Decade through provision of a necessary resource or implementation of a Decade Actions or even the coordination function of the Decade. The influence of the Ocean Decade as change in the trend of study's types with submarine canyons in SA can contribute to the advancement of knowledge and development of new approaches into the Decade overview.

A series of scientific marine content should be integrated to accomplish the Decade development. According to the IOC-UNESCO, 2021, among the Decade Objectives, objective 1 summarizes the urgent need for knowledge for regular integrated assessments of the state of the ocean and of ocean science capacity, promotion of new technology and increased access to technology, enhancement and expansion of observations infrastructure, and development of mechanisms to optimize citizen science initiatives. Objective 2 involves the mapping and understanding of ocean components, understanding of thresholds, and tipping points for the ocean system, increased use of historical ocean knowledge, improved ocean models and prediction services, and increased efforts in education, training, and transfer of marine technology. Objective 3 involves understanding of the role of ocean science in the development of interoperable and open-access data platforms and services, facilitation of co-designed and co-delivered ocean solutions including planning, management, and other tools and services, and the promotion of formal and informal education.

The evolution of SA canyons studies is included in the third objective. According to the timeline, we can observe two well-marked divisions, one from 1970 to 2000 and the other from 2001 onwards. At first, studies with submarine canyons were not well structured and present several gaps between periods of publication. Although we have known the importance of these environments, the focus of studies with submarine canyons in the 70s, 80s, and 90s were not heavily publicized among the academic community (Figure 2), except for those that intended to map the seafloor as a framework for knowledge advancement. The Nippon Foundation-GEBCO Seabed 2030 Project in partnership with Scripps Institution of Oceanography at the University of California San Diego is an example of it. They have strengthened their collaboration with a newly established Memorandum of Understanding (MOU) which has as its main purpose to pursue the attainment of worldwide bathymetric data, and to increase human understanding of the oceans. Also, GEBCO is a joint project of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC). The Nippon Foundation-GEBCO Seabed 2030 Project. (2021). https://seabed2030.org/news/nippon-foundation-gebco-seabed-2030-project-announces-new-collaboration-scripps-institution [Accessed August 24, 2021].

In canyon areas, the technology and time of survey are still limit the advance of studies in such vast, hostile, and difficult to access environments (HE et al., 2014). The constancy of events close to the coastal zone makes the region of continental margins one of the most dynamic places, whether due to the presence of natural or extreme events (GAO; COLLINS, 2014). From the 2000s, we can see a slight increase in the $NUPPY$ concerning submarine canyons, maintaining diversity, and exploration of content to the present day (Figure 2). It is important to search for better comprehensive knowledge of the continental margins, with advancement of the Ocean Decade insights in the last years and the association of new technologies for detailed mapping of the oceans provided an increment in the $NUPPY$ relate to scientific ocean research, including submarine canyons studies. The difference in study number is associated with the infrastructure availability and research incentives given for each country (FERNANDEZ-ARCAYA et al., 2017).

However, gaps are not only temporal but also spatial, which we can observe in the studies approach which is inserted in a period of the timeline. The information crossing shows that submarine canyons studies in SA follow a complex development trend, with a predominantly QL approach at the beginning, QLQT at the end, and isolated points of ID studies throughout the timeline (Figure 3). Several factors could be associated, such as the lack of investments and specialized training seen in some regions, due to specific interest and method of publication of each country, or due to technological limitations added to geographical barriers in areas of difficult access (KELLEY; DELANEY; JUNIPER, 2014). Although it is not appropriate to attribute its behavior and generalize only to these arguments, we must highlight technology as one of the main reasons and add an important aspect within the issue of the gaps: Ocean Science Diplomacy.

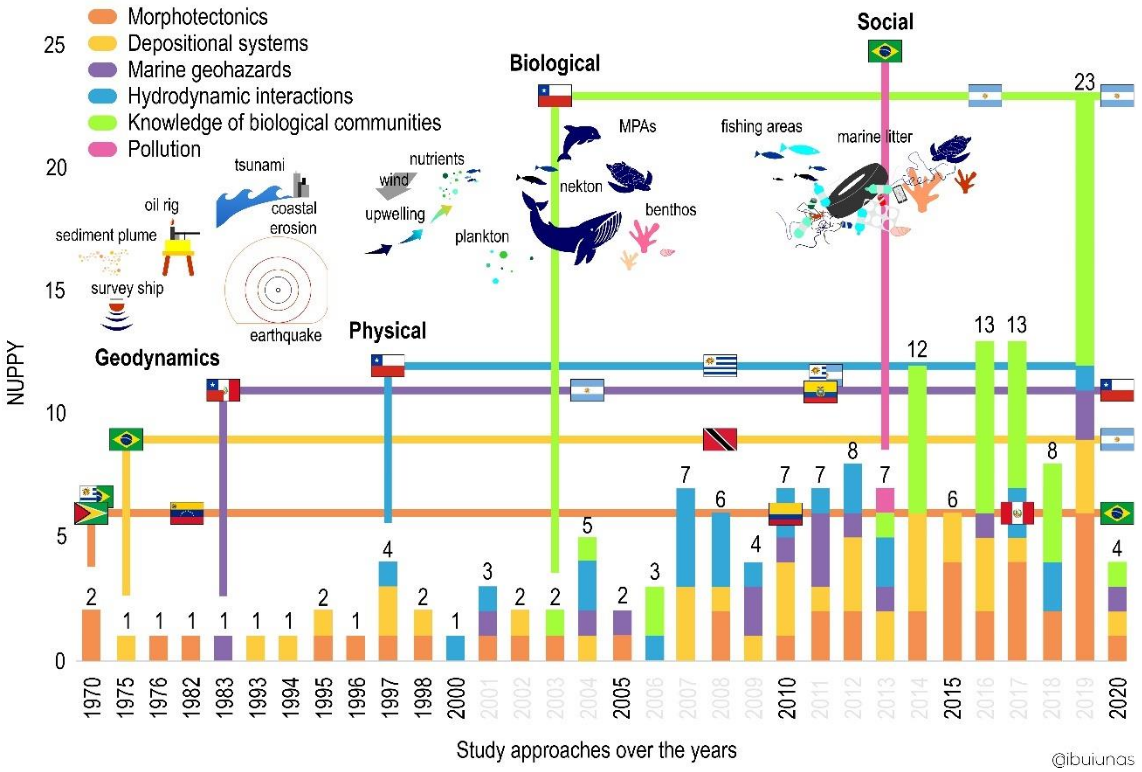
According to Polejack and Coelho, 2021, the lack of investments is hampering studies in Latin America and the Caribbean from accessing and using marine technologies to develop the science needed to inform decisions and international negotiation processes on an equitable basis. They also emphasize that researchers from developed countries often access funding and infrastructure to conduct research in Latin America and the Caribbean waters. However, researchers usually apply only a small portion of the funding in the foreign field, leaving local contributors with limited access to research equipment. Most marine research in the southern hemisphere has a limited research budget with highly fluctuating exchange rates, that is spent in keeping up with international standards which determine data accuracy, thus allowing replicability and comparison (POLEJACK; COELHO, 2021). As a gap, the lack of investments can be observed in almost all submarine canyons studies in SA, influencing the smallest $NUPPY$ of Group 2 seen in Group 1 (Figure 3) and diversity of studies per country (Figure 4).

Nevertheless, we must also consider the Blue Economy as an important approach within the gaps. However, the Blue Economy's approach is complex and needs to comply with several aspects to be applied coherently. The activity scale includes aspects such as the type of activity, the service the activity is providing, established and emerging industries, growth drivers for sustainable industrialization, and technological development of important countries to marine science. For Golden et al., 2017, the increased industrialization challenges the traditional paradigm of jurisdictional control of waters and seabed features within national exclusive economic zones (EEZs). According to the authors, this strain is currently becoming apparent in three different spheres: (1) nations’ capacities to govern the waters within their EEZs, (2) the international community’s capacity to regulate international waters, and (3) the ability of industrial and financial institutions to reach consensus on forms of self-governance.

Smith-Godfrey, 2016, and Golden et al., 2017, have identified activities relating to the oceans which both have similar proposals for the activity’s development like the Ocean Decade

Challenges. Although, it is necessary to realize that they will not be the same for all countries since the management of marine spatial planning processes is not equal. As a result, a contrast in the evolution of submarine canyons studies have been observed in SA with concentrations on different types and natures of studies, identifying a specific country as a major focus of publication with each subject (morphotectonics, depositional systems, marine geohazards, hydrodynamic interaction, knowledge of biological communities, or pollution) (Figure 5).

Figure 5 - Timeline evolution of submarine canyons studies in South America, highlighting the changes in the specificity of study trends (geodynamics, physical, biological, and social) and their main publication agents to represent the arise point of Number of Publication per Year (NUPPY) among the countries and their first specificities of studies over the timeline.



According to Golden et al., 2017, to change this scenario would be to reimagine the oceans as a shared space and a resource capable of providing social, environmental, and economic goods, but only if transparency, coordination, and the commitment to balance competing objectives are at the forefront of public policy and governance, finance, and management of global supply chains. As well as technological development and the entire management process for planning the use of marine space, all of this is included as an economic factor that can be represented in the $NUPPY$ variation for submarine canyons surveys for the SA. Economic activities within the Blue Economy are fundamental for the investment of new perspectives for canyons studies throughout the world. Although, Latin America and the Caribbean struggle to conduct marine scientific research and seize the opportunities of Blue Economy due to their limited access to state-of-the-art technology (POLEJACK; COELHO, 2021). The Blue Economy has contributed to the development of submarine canyons studies as well as the formation of the Ocean Decade Challenges based on seven most urgent social outcomes.

The Ocean Decade (2021-2030) appears as an aspect oscillating between gaps and forecasts because it is structured as the main vector that will lead the evolution of the relationship between humans and the sea, although it is still in the beginning development process (HEYMANS et al., 2020; POLEJACK, 2021; POLEJACK; COELHO, 2021; RYABININ et al., 2019). As a gap, the Decade Challenges as seven outcomes are still obstacles to be overcome, and probably the change will not occur only within the given period. We must highlight how those studies with submarine canyons in SA are framed in this scenario, even when they are ambiguous, behaving sometimes as a gap or as forecasts. Nevertheless, they play a strong role within environmental study, contributing to the understanding of the types of processes and actors involved in the horizontal transition zones, marked by the land-ocean limit, and vertically defined by the balance of oceanographic components present in the water column.

As a forecast, ignoring the fact that pro-ocean actions have been gaining strength due to the initiatives promoted by the Ocean Decade is a contradictory attitude, especially due to the impact generated in various geopolitical, economic, and social spheres (STEENBEEK et al., 2020). Generally, when we approach forecasts concerning marine science in any aspect, we find an immediate association with the Ocean Decade Challenges and their social outcomes. It is practically impossible to talk about the future of the oceans and not relate to any objectives mentioned for the decade.

6.1 The Decade Challenges as an overview for the future of submarine canyons studies

We saw here that each study approach related to submarine canyons had a relationship to one outcome mentioned in the Ocean Decade Challenges. This relationship was presented in the following chronological order according to the timeline of submarine canyons studies in SA relative to the decade outcomes, as discussed previously. The Ocean Decade Challenges summarizes the needs based on: (1) A clean ocean, through identifying and removing sources of pollution; (2) A healthy and resilient ocean, with mapped and protected marine ecosystems; (3) A predicted ocean, enabling society to understand current and future ocean conditions; (4)

A safe ocean, protecting people from ocean hazards; (5) A sustainably harvested and productive ocean, providing food and resources for the blue economy; (6) A transparent and accessible ocean, giving citizens equitable access to data, information, and technologies; and (7) An inspiring and engaging ocean, which here, serves as a cycle of marine events to outcomes where society understands and values the ocean in relation to human wellbeing and sustainable development (Figure 6).

Figure 6 - Cycle of marine events following chronological order according to the timeline of submarine canyons studies in South America relative to the Ocean Decade outcomes.

(6) **Morphotectonics & a transparent and accessible ocean**, giving citizens equitable access to data, information, and technologies. In morphotectonic studies, the evolution of technology has provided improvements in the collection method and, consequently, the increased interest in studies in areas of submarine canyons. Although the efforts of morphotectonics studies to map and study the seafloor is in order to produce a “transparent and accessible” ocean, the enormous need for more ocean information in the scientific, governmental, private, and public sectors demands a change in ocean education at all levels (RYABININ et al., 2019). Morphotectonic studies have presented a consistent proposal over marine research, evaluating new technologies, methods, and approaches for understanding submarine topography. Also, the challenges into the MSP have been designed to help decision

makers, stakeholders, and students understand and manage the maritime Blue Economy and marine environment.

As well as objective (1) posed by the Ocean Decade, which includes sub-objectives related to the provision of knowledge for regular integrated assessments of the state of the ocean and of ocean science capacity, the promotion of new technology and increased access to technology, enhancement and expansion of observations infrastructure, and development of mechanisms to optimize citizen science initiatives and the recognition and inclusion of local and indigenous knowledge is also crucial (IOC-UNESCO, 2021). Thus, we can associate morphotectonic studies with the Decade Challenge (6) “a transparent and accessible ocean”, that forecasts how advances of new technologies and the digital revolution are transforming the ocean sciences to deliver data and information to all stakeholders (RYABININ et al., 2019).

(5) **Depositional systems & a sustainably harvested and productive ocean**, providing food and resources for the Blue Economy. This concerns the exploitation of sea resources, spatially led by oil prospecting in offshore areas and later by fishing surveys in areas nearby canyons, considered biodiversity hotspots. Observing the development of depositional systems studies, we can include them in two goals that seek to strengthen global partnerships to achieve the targets of the 2030 Agenda for the Ocean Decade: 1) Knowledge and solutions for a sustainable ocean economy and 2) Knowledge and solutions for low-impact ocean energy. Hence the depositional systems should be included on Decade Challenge (5) “a sustainably harvested and productive ocean” which should create a better understanding of the interactions and interdependencies of the ocean ecosystem and environmental conditions and processes and the use of resources and the economy. According to Ryabinin et al., 2019, this is a major task in context of the development of the ocean economy that will document the potential impacts from environmental changes on the established and emerging maritime industries and their ability to generate growth, especially for least developed countries and Small Island Developing States (SIDS).

(4) **Marine geohazards & a safe ocean**, protecting people from ocean hazards. The objective is based on marine geohazard studies, giving visibility to the most common events, such as coastal erosion, to the most impactful, such as earthquakes, submarine landslides, and tsunamis, present on active continental margins, or coastal erosion in passive margins. Marine geohazards are one of the challenges established for the Ocean Decade to attempt to understand how they can impact the coastal zone in social, economic, and environmental ways. Therefore, it is important to enhance multi-hazard early warning services for all geophysical, ecological,

biological, weather, climate, and anthropogenic-related ocean and coastal hazards, and mainstream community preparedness and resilience (IOC-UNESCO, 2021). According to Ryabinin et al., 2019, the decade will promote research aimed at minimizing impacts of various changes and risk reduction through adaptation and mitigation, contributing to enhanced preparedness and awareness of society with regard to ocean risks. Thus, for the Ocean Decade, submarine geohazards are concerning the Decade Challenge (4) “a safe ocean”, whereby human communities are much better protected from ocean hazards and where the safety of operations at sea and on the coast is ensured (RYABININ et al., 2019).

(3) **Hydrodynamic interactions & a predicted ocean**, enabling society to understand current and future ocean conditions. This concerns hydrodynamic interactions studies, highlighting the upwelling effect, the dynamics of currents, water mass flows, and their interactions with other oceanographic processes in submarine canyons. Hydrodynamic interactions studies have discussed the gaps between ocean-atmosphere interactions and the effects of climate changes to ensure that physical aspects and their variability of proprieties, especially within the water column, are known more deeply. For the decade challenge, it is important to enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt, and build resilience to the effects of climate change across all geographies and at all scales to improve services including predictions for the ocean, climate, and weather (IOC-UNESCO, 2021).

Studies based on modelling and prediction of the seasonality of upwelling events and their impacts on the whole environment with transport of nutrients from deeper to shallowest areas are fundamental to the management of fishing areas. According to Ryabinin et al., 2019, knowledge of present and future conditions is a pre-requisite to the development of sustainable ocean economic policies and ecosystem-based management, and through systematic ocean observations under the Ocean Decade, it would be possible to map all ocean basins to initialize coupled models and facilitate improved ocean understanding. Hence, hydrodynamic interactions studies can be inserted on the Decade Challenge (3) “a predicted ocean” which has the capacity to understand current and predict future ocean conditions and their impact on human well-being and livelihoods (RYABININ et al., 2019).

(2) **Knowledge of biological communities & a healthy and resilient ocean**, with mapped and protected marine ecosystems. Biological communities’ studies in submarine canyons compose the framework for comparing social outcomes, focused on the creation of Marine Protection Areas because of surveys of biodiversity and the delimitation areas of the

distribution of organisms. Biological studies are a response to geodynamics (morphotectonics, depositional systems, and marine geohazards) and physical studies. Biological studies have a vertical distribution of planktonic and nektonic organisms in the water column influenced by physical proprieties, and horizontal distribution of benthic organisms on the seabed substrate based on sediment characteristics. Each group has an important ecological role for understanding the complexity of the marine biological assemblages and their interactions to provide a biodiverse environment. It leads to conservation of the MPA's nearby canyon areas i.e., biodiversity hotspots.

Knowledge of biological communities' studies are important for the knowledge of and solutions for management of ecosystems faced with multiple stressors (IOC-UNESCO, 2021), evaluating the economic and societal value of the ocean and its ecosystems to stimulate marine spatial planning, MPA, coastal zone management, and other ecosystem-based management approaches (RYABININ et al., 2019). Thus, the biological communities' studies can be inserted on Decade Challenge (2) "a healthy and resilient ocean" in which (RYABININ et al., 2019) marine ecosystems are protected, elucidating impacts of cumulative stressors on the ocean, its seas, ecosystems, and resources, hence providing required information to enable actions, which can reverse the ocean ecosystem degradation.

(1) **Pollution & a clean ocean**, through identifying and removing sources of pollution. Finally, we relate the Ocean Decade to the first pollution study in association with submarine canyons and the confirmation of a strong trend line regarding the advances in pollution research in the oceans. However, the reversal of the degradation cycle will evolve not only through research and development of innovative solutions in individual institutions but also through collaborations between national and international groups of stakeholders, including scientists, traditional communities, indigenous peoples, and the private sector who could contribute with their experience, time, and other resources (HATJE et al., 2021).

Thus, the Decade Challenge (1) "a clean ocean" should be related to pollution studies which assume integrated research will assess the human and environmental shorter-term and long-term risks from ongoing and future types of ocean pollution and generate new ideas on how to reduce ocean pressures by recycling, improved waste management, and strengthening the governance regimes that encourage more sustainable production and consumption (RYABININ et al., 2019). Ensuring that the most vulnerable environments are properly protected from pollution and its consequences requires the early establishment of agreements, protections, and policies that will minimize social inequality and secure a clean ocean (HATJE et al., 2021).

All of these are based on the unique opportunity to change the way we support sustainable development and galvanize ocean sciences for future generations (HATJE et al., 2021; IOC-UNESCO, 2021; RYABININ et al., 2019). Therefore, we can understand a little better how submarine canyons studies are being developed over the years in SA. Also, we observe the period with the highest $NUPPY$, the person responsible for the publication, the main approach, the importance of the location of the studies, and the type of studies identified in each study. Parallelly, we have the timeline to understand the evolution of studies and their role in the overview for the future, demonstrating how it is inevitable to dissociate the relationships among geological, physical, biological, and social (economical) conditions in spatiotemporal analysis and type of studies.

7. Conclusions

To advance submarine canyons studies, we have geodynamic studies at the base of evolutionary overview. Morphotectonic studies explore seafloor investigation and development of new technologies for data collection in areas of difficult access. The interest in understanding sedimentological processes is increasing, with the first studies on sea level rise, eustatic cycles, and seismic stratigraphy on the continental margins. Marine geohazards are presented as events impacting the coastal zone. Differences between the types of geohazards and their link to active and passive margins are observed. The physical studies of hydrodynamic interactions arise to further restrict this scenario. The upwelling zones have influenced the fishing areas, even the interactivity between the processes is important for building the environmental conditions leading to the nutrients' distribution and biodiversity close to the submarine canyons. The behavior of biological communities is a response to these events, which has a vertical distribution of planktonic and nektonic organisms in the water column and horizontal distribution of benthic organisms on the substrate. Each group has an important ecological role in understanding the complexity of the marine organisms and their interactions as biodiversity environments to establish the conservation of the MPA nearby canyon areas as biodiversity hotspots. In addition, we have pollution as a source of impact on all aspects mentioned above. Marine litter deposits on the seabed, in addition to polluting the environment causing impacts on biological communities, can also modify the sediment accumulation rate even in small proportions and alter the flow as they are considered physical barriers, especially close to submarine canyons.

In summary, we observed that the spatiotemporal distribution of submarine canyons studies is different in two types of margins (active and passive), as it interferes with the way that studies will be carried out. It is also evident that the main reasons for it are associated with geological, physical, biological, or social processes. Moreover, economic investments generated by Blue Economy and the evolution of new technologies are two aspects that occur simultaneously and, therefore, are fundamental to understanding the overview of submarine canyons studies in SA. As future steps, the development of new technologies to map the seafloor appear as a link of interaction between two geological aspects to an environmental approach with the emergence of a new trend in marine science, the so-called benthic geohabitats, to promote sustainable development, knowledge, and marine environments disclosure.

As well as the three main objectives proposed by the Ocean Decade (IOC-UNESCO, 2021), the change of knowledge on submarine canyons studies in SA play an important role in: 1) Increasing the capacity of ocean science to deliver needed ocean data and information; 2) Generating comprehensive knowledge and understanding of the ocean including human interactions, and their interactions with the atmosphere and the land sea interface; and 3) Increasing the use of ocean knowledge and understanding, and developing the capacity to contribute to development human-ocean solutions. To progress in several thematic areas of ocean science, it is necessary that most societal outcomes are awarded action by society, governments, or by key stakeholders. It is essential that ambitions of the private sector, governments, and involved managers grow along with the progress in research. Also, active, intensive, and efficient communication of advances on ocean sciences should be a key enabling factor (RYABININ et al., 2019). As a result, an overview about the spatiotemporal trends of submarine canyons studies in SA was developed to describe the timeline building and to know what its relationship is to the Ocean Decade outcomes.

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4 WATER MASSES PUMPING EFFECT THROUGH BLIND SUBMARINE CANYONS IN THE WESTERN TROPICAL ATLANTIC BOUNDARY

Abstract

Flow-Topography Interaction can be considered as a particular set of processes resulting of the currents interaction with a topographic gradient, specially associated with submarine canyon areas, which are important morphological features with potential to upwelling and cross-isobath transport on the continental margins. The South Pernambuco Continental Shelf (SPCS) and Pernambuco Plateau located on the Southwestern Tropical Atlantic (SWTA), present incised morphological features, highlighting the shelf valleys and blind canyons, which do not have a connection to the shelf or an onshore river system. They are likely features for interactions between the dominant along-shelf flow represented by the strong western boundary North Brazil Undercurrent. We investigated potential canyon induced upwelling and the respective mechanisms at the late spring/early fall context. CTD and reanalysis data from GLORYS12V1, and *in situ* bathymetric measurements were used to characterise the hydrodynamics and canyon morphology, respectively. Then, we combined both to obtain dimensionless numbers from dynamical scale analysis to infer possible imbalances of the acting forces. Reanalysis data evidenced uplift at the slope not related to the blind canyons. CTD data indicated a seasonal variation of the intrusion of water masses, especially at the shelf-break for the Middle shelf valley and Campas shelf valley. A temperature difference of 2.5°C (2.0°C) between surface and deep waters was observed during the late spring. A stepwise temperature structure was present in both seasons, indicating instability below the mixed layer depth, the uplifting of isotherms, and the corrosion of the lower portion of the surface mixed layer. The dimensionless parameters analysis reveals highest Rossby values during the fall, mainly in Zieta shelf valley (R_0=130.87) and Csv (R_0=111.71), and lower values for the canyons of the Pernambuco Plateau. Our hypothesis is that the shelf valleys might play a role in conducting the uplifted slope water coast-ward. For the blind canyons, although no related upwelling was observed, reanalysis revealed the presence of a deep anti-cyclonic eddy at one of the blind canyon's mouth. Rossby and Burger numbers indicate a weak geostrophic balance at the canyon rim, and instability of the horizontal length scale of the pressure gradient force, with tendency to vorticity control. While the paradigm that shelf and coastal waters off north-eastern Brazil are mostly oligotrophic in the surface is true, our observation of shallow (<60 m) subsurface uplift should be considered in future works in the SWTA.

Keywords: western boundary current; submarine canyons; dimensionless scaling analysis; shelf-break upwelling; North Brazil Undercurrent; western tropical Atlantic.

1. Introduction

Flow-Topography Interaction (FTI) can be considered as a particular set of processes resulting of the currents interaction with a topographic gradient. In the ocean, the currents can interact with many bottom features, such as submarine canyons, slope, islands, etc. Some of the FTI interactions can result in water column stratification destabilization, leading to orographic upwelling (ALLEN; DURRIEU DE MADRON, 2009; ALLEN; HICKEY, 2010; CASTELAO, 2011; HYUN; HE, 2010; NETO; DA SILVA, 2014; OKE; MIDDLETON, 2000; ROUGHAN; MIDDLETON, 2002; SCHAEFFER; ROUGHAN; MORRIS, 2013; WATERHOUSE; ALLEN; BOWIE, 2009).

Particularly, submarine canyons are important morphological features on the continental margins and represent a complex dynamic system that continuously affects the sedimentary, oceanographic, biological and ecological characteristics of the coastal zone around the world (AMARO et al., 2016; ROBERTSON et al., 2020). They are responsible for the transport of water masses (CANALS et al., 2013), sediments (CANALS et al., 2006; PUIG; PALANQUES; MARTÍN, 2014), nutrients (RAMOS-MUSALEM; ALLEN, 2019; RAMOS MUSALEM, 2020; SALDÍAS; RAMOS-MUSALEM; ALLEN, 2021), organic matter (BOSLEY et al., 2004) and pollutant exchanges between the continental shelves and the abyssal plain (TUBAU et al., 2015a). The maintenance of favourable conditions for nutrients transport in canyons makes the environment conducive to the development and enrichment of communities of organisms in the areas closest to them, making the submarine canyons biodiversity hotspots (BERNARDINO et al., 2019; FANELLI; BIANCHELLI; DANOVARO, 2018). Generally, the nutrient exchange takes place specifically in areas near its margins, due to changes in barotropic and baroclinic flow behaviour associated with sudden changes in topography and physical aspects of seawater (KÄMPF, 2012).

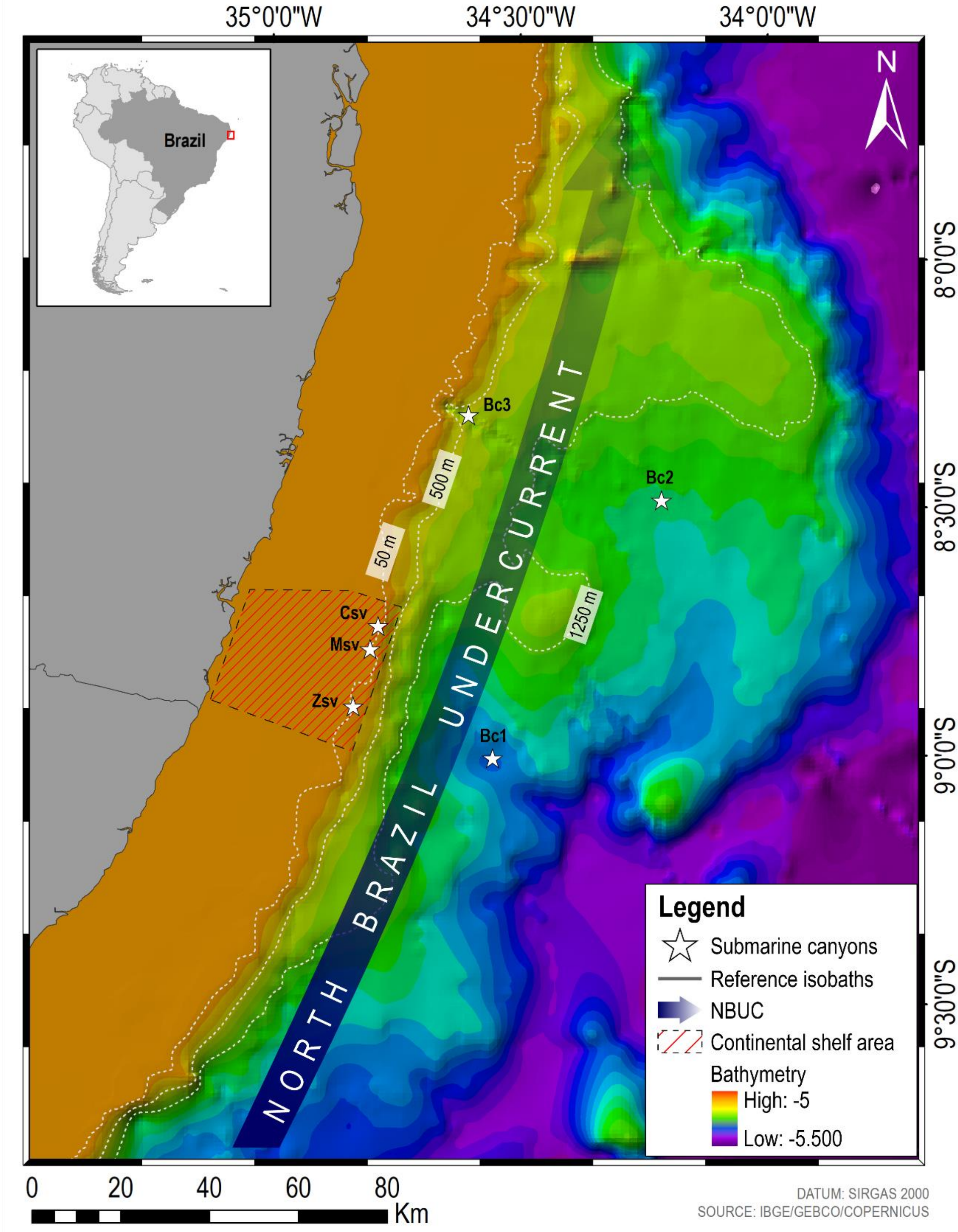
We can expect three main flows by advection- driven upwelling over the canyons at the shelf-break (1) Shelf flow, (2) Upwelling current, and (3) Deep flow. The canyon related upwelling at the shelf-break can be driven by the imbalance alongshore of cross-shore pressure gradient force in the canyon due to the topography blockage (FREELAND; DENMAN, 1982; HOWATT; ALLEN, 2013). Thus, the upwelling requires that the shelf flow tends in the opposite direction to the propagation of the Kelvin and shelf waves, being onshore as it crosses the canyon wall and offshore as the flow reaches the downstream rim of the canyon (near the canyon head) (ALLEN et al., 2001; HICKEY, 1997). Furthermore, the upwelling current flows along the canyon against the downstream canyon wall, under the shelf flow at the canyon head and along the downstream rim near the head. Thus, it is thick on the downstream side and pinched to nearly zero thickness on the upstream side. (DAWE; ALLEN, 2010; HOWATT; ALLEN, 2013; KÄMPF, 2012). Finally, the deep flow is located below the slope with flow in the canyon toward the canyon head on the downstream side and returns toward the ocean on the upstream side of the canyon leading to deep cyclonic vorticity. Moreover, field and laboratory experiments involving upwelling processes in steep and deep canyons have been suggested that the deepest flow is also raised to the continental shelf by deep vorticity the presence or in absence of a cyclonic eddy just above the canyon rim depth. (ALLEN, 2000; ALLEN; HICKEY, 2010; HICKEY, 1997; MIRSHAK; ALLEN, 2005).

Recent studies suggest the interplay of down-slope processes and along-slope currents as an important process for canyons (AMUNDSEN et al., 2015; VOIGT et al., 2013; WARRATZ et al., 2019). Despite the effects on biological communities generated by the canyons, the hydrodynamics are complex and need to be further discussed (Hickey, 1997; Allen and Durrieu De Madron, 2009; De Leo and Puig, 2018). Several authors highlight the heterogeneity in canyon circulation processes that may vary according to hydrographic and meteorological aspects (flood or storm) (PUIG et al., 2004; ROSS et al., 2009), oceanographic (eddy activity, tidal currents or internal waves) (VIANA et al., 1998) and morphological (slope, sediment) (BROTHERS et al., 2013; GRINYÓ et al., 2017). However, there is an operational challenge to obtain data over the canyon near the canyon head (close to the slope), mostly due to the steep topography and to the often intense fishing boats (HOWATT; ALLEN, 2013). Additionally, the difficulty of obtaining data to update local models, added to the complexity of canyon flow studies is the ideal scenario for the lack of research with this type of approach. Thus, there is a need for the development of new methodologies to investigate flow responses to blind canyons interaction. In this instance, some dimensionless numbers that relate flow and canyon morphology can be useful to have an estimative of dynamic balance in canyons empirically (HOWATT; ALLEN, 2013).

In tropical regions, water nutrient exchanges through submarine canyons play an important role on fertilization process in shelf and shelf-break, as some regions have oligotrophic characteristics and lack of nutrient renewal in the water column, especially in areas of high stratification where the exchange is limited (HOSEGOOD et al., 2017). This is the case of the Northeast Brazilian coast, where the water masses are oligotrophic as a result of the high stratification of the water column and the elevated temperature and salinity over the slope (ARAUJO et al., 2011; DOMINGUES et al., 2017; SCHETTINI et al., 2017). The Pernambuco Plateau and the South Pernambuco Continental Shelf (SPCS), located on the Southwestern Tropical Atlantic (SWTA), has almost the same bottom characteristics as the north-eastern coast, except for the presence of the Pernambuco Plateau, which might be responsible for the major changes in oceanographic conditions and morphology concerning the north-eastern coast (BUARQUE et al., 2016; CAMARGO et al., 2015), especially near the shelf-break, which marks the connection between the shallower and deeper regions through canyons. Generally, almost all these characteristics and processes can be observed related to submarine canyons (AHUMADA-SEMPOAL et al., 2013; PAI et al., 2016). However, instead of slope canyons, our study area present a system of shelf valleys (SVs) incised into the continental shelf that may have a direct connection to modern terrestrial fluvial systems (DA SILVEIRA et al., 2020). In addition, on the oceanic region adjacent to the SVs, deep canyons can be found incised on the Pernambuco Plateau, defined as so-called “blind” canyons (HARRIS; WHITEWAY, 2011), which are deeper and wider than the SV’s. The main flow acting in region is of the equatorward western boundary current. The North Brazil Undercurrent (NBUC), which together with the North Brazil Current (NBC), is an important component of the upper Atlantic Meridional Overturning Circulation (AMOC) (DOSSA et al., 2021; SCHOTT et al., 2002, 2005; STRAMMA et al., 2005; STRAMMA; FISCHER; REPPIN, 1995; VELEDA et al., 2012).

In this work we are interested in FTI related to the features incised on Pernambuco’s continental margin. Particularly, the SVs incised on the continental shelf and the blind canyons incised on the Pernambuco Plateau. We investigate potential interactions between the dominant along-shelf flow represented by the strong tropical Atlantic western boundary NBUC (SCHOTT et al., 2005), and those features off Northeast Brazil. Using an integrated approach comprising *in situ* measurements and reanalysis product in the late spring/early fall context; we characterised the hydrodynamics, canyon morphology and obtained flow-topography related dimensionless numbers (mostly, Rossby and Burger) to investigate potential canyon induced upwelling and the respective mechanisms. The observational data and modelling approach used to obtain the dimensionless numbers are presented in the next section.

Figure 1 – Location of the study area, bathymetry data (coloured pallet), limits of the continental shelf study area (closed polygon with a black line) encompassing the location of the shelf valleys and blind canyons (white stars). North Brazil Undercurrent – NBUC represented by a blue arrow.



2. Materials and methods

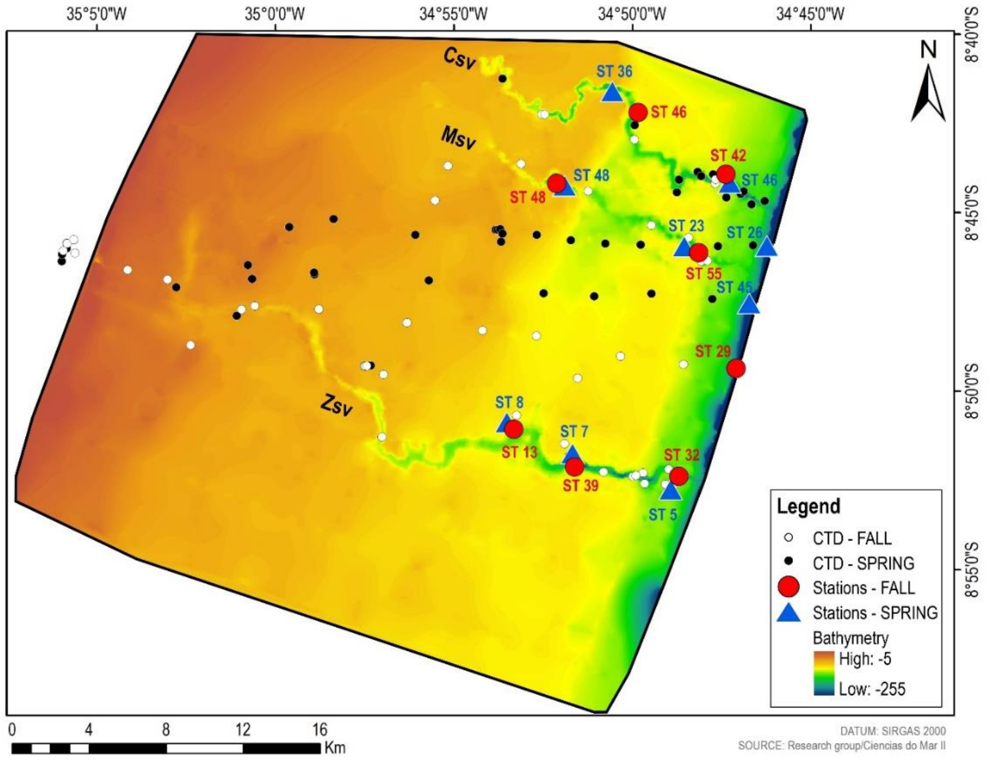
2.1 Data acquisition and processing

The dataset used in this work consist of *in situ* thermohaline and bathymetric measurements obtained in the study region, and supplementary local hydrographic and bathymetric information available from online databases. In total, six seafloor structures were analysed, three on the Pernambuco Plateau, referred as blind canyons or Bc1, Bc2, and Bc3. Also, three SVs located at the shelf-break called Zieta, Middle, and Campas shelf valleys (Zsv, Msv, and Csv, respectively) were examined (Figure 1). Bc1 is incised to the southern portion of the Plateau and nearby of the SVs, whilst Bc2 is on the northern and its canyon head is linked by the Bc3. Bc3 is the prolongation of Bc2 projected in the continental slope. Furthermore, the Zsv is the southernmost SVs, and therefore nearest from the Bc1 canyon head. The Msv is between Zieta and Campas shelf valleys. Finally, the Csv is adjacent to Bc1 canyon head (Figure 3a, b).

The observational data set consists of single beam bathymetry (collected between 2004 and 2017) and 105 vertical profiles of physical parameters collected from the surface to near bottom depth using a Seabird SBE911+ conductivity temperature depth (CTD) probe, as part of the Ciências do Mar II Project. 49 CTD stations were performed in December of 2018 (late austral spring) and 56 stations during April 2019 (early austral fall). While the whole CTD dataset was used to classify water masses in the spring and fall, 17 stations were selected to define water masses inside the Zsv, Msv and Csv at the shelf (<50 m isobaths) and shelf-break depth (±50 m isobaths) and at the adjacent slope (>50 m isobaths) in both seasons (Figure 2). The quality control methodology used to qualify the entire CTD dataset was adapted from INGLEBY and HUDDLESTON (2007), which consists in performing 8 reference tests on each hydrographic profile. The tests were applied using information included on metadata as well as salinity and temperature variables previously pre-processed.

In first instance, we verified if there was any indication of upwelling through CTD profiles and a selected oceanic model product. For this, we used the monthly averaged (January of 1993 to June of 2019) current, pressure, salinity, and temperature data from GLORYS12V1 reanalysis model from the Copernicus Marine Environment Monitoring Service (CMEMS) – MERCATOR database (https://marine.copernicus.eu/). The model was chosen due to its good representation of the hydrodynamical conditions in the region (DOSSA et al., 2021). It has a 1/12° horizontal resolution and 50 vertical levels and considers ETOPO1 (1 arc-min resolution) for the deep sea and GEBCO 08 (30 arc-sec) for the shelf bathymetry. The levels are set to obtain higher resolution for the surface circulation (22 layers from 0-100m compared with only 21 from 100 to ~2866 m). In addition, the model assimilates satellite data from surface such as sea surface temperature and salinity to reduce biases. The climatology for the variables were then calculated to remove any interannual biases so that the general pattern for late spring and early fall was representative.

Figure 2 – Location of CTD profiles at the continental shelf area with detailed bathymetry (coloured pallet, from 5 to 255 m depth) and selected CTD stations collected from Ciências do Mar II project (colour of the number of stations according to the season) for late spring (blue triangles) and early fall (red circles) water masses characterization within the Zieta (Zsv), Middle (Msv), and Campas (Csv) shelf valleys.



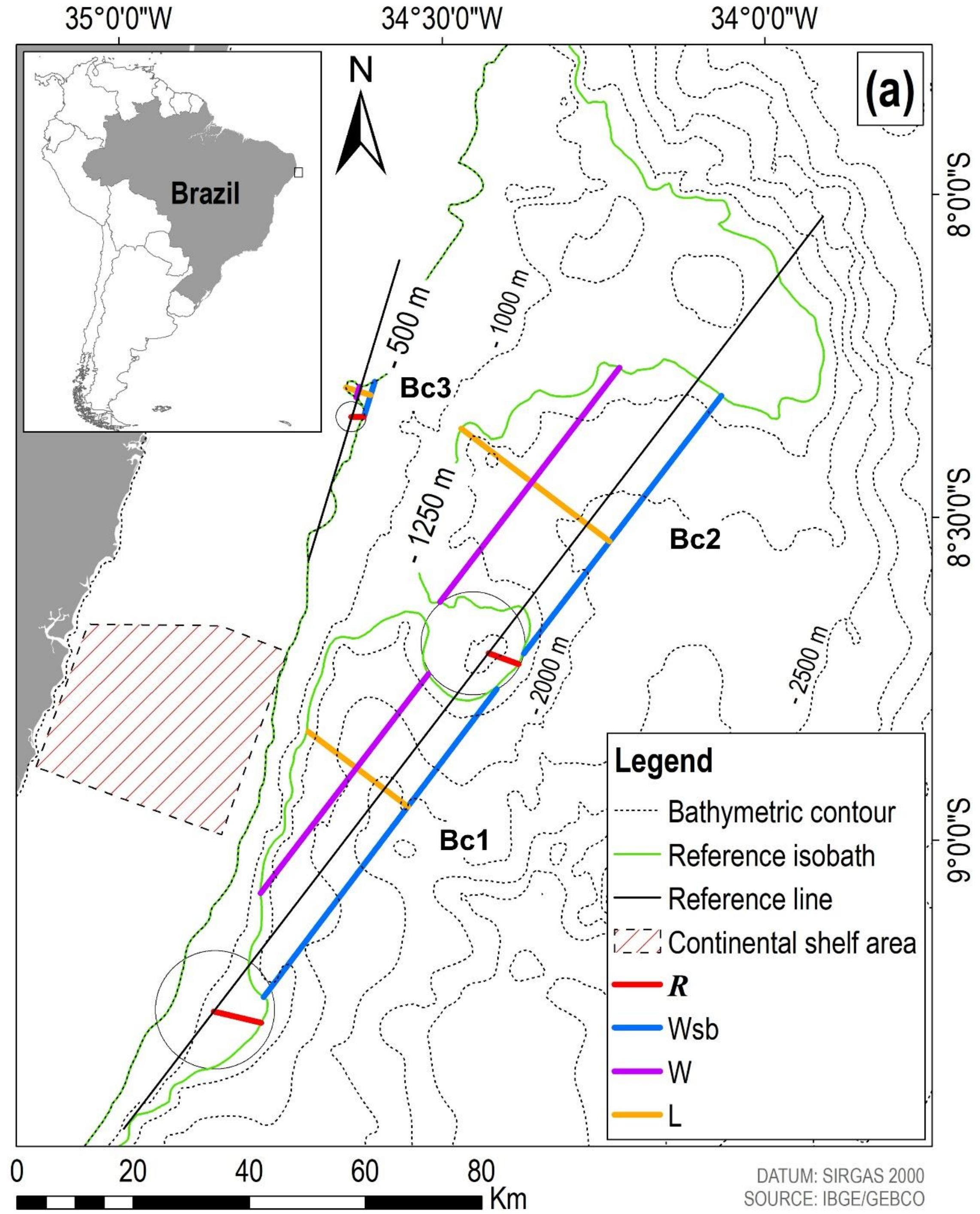
The bathymetric online database were obtained from the General Bathymetric Chart of the Oceans – GEBCO (bathymetric chart at 30 arc-sec resolution), available at https://www.gebco.net/data_and_products/gridded_bathymetry_data/, fully covering the Pernambuco Plateau area. The bathymetry provided by GEBCO was used for the blind canyons located in the Pernambuco Plateau. This methodology was adopted due to the small ratio between the resolution cell size dataset and the dimension of the largest features in the Pernambuco Plateau (Figure 3a), which allows the obtainment of characteristics lengths (Bc1, Bc2, and Bc3). However, to define characteristic lengths of the SVs located on the shelf (Zsv, Msv, Csv in Figure 3b), the *in situ* bathymetric data were used, due to the grid resolution limitations of GEBCO database.

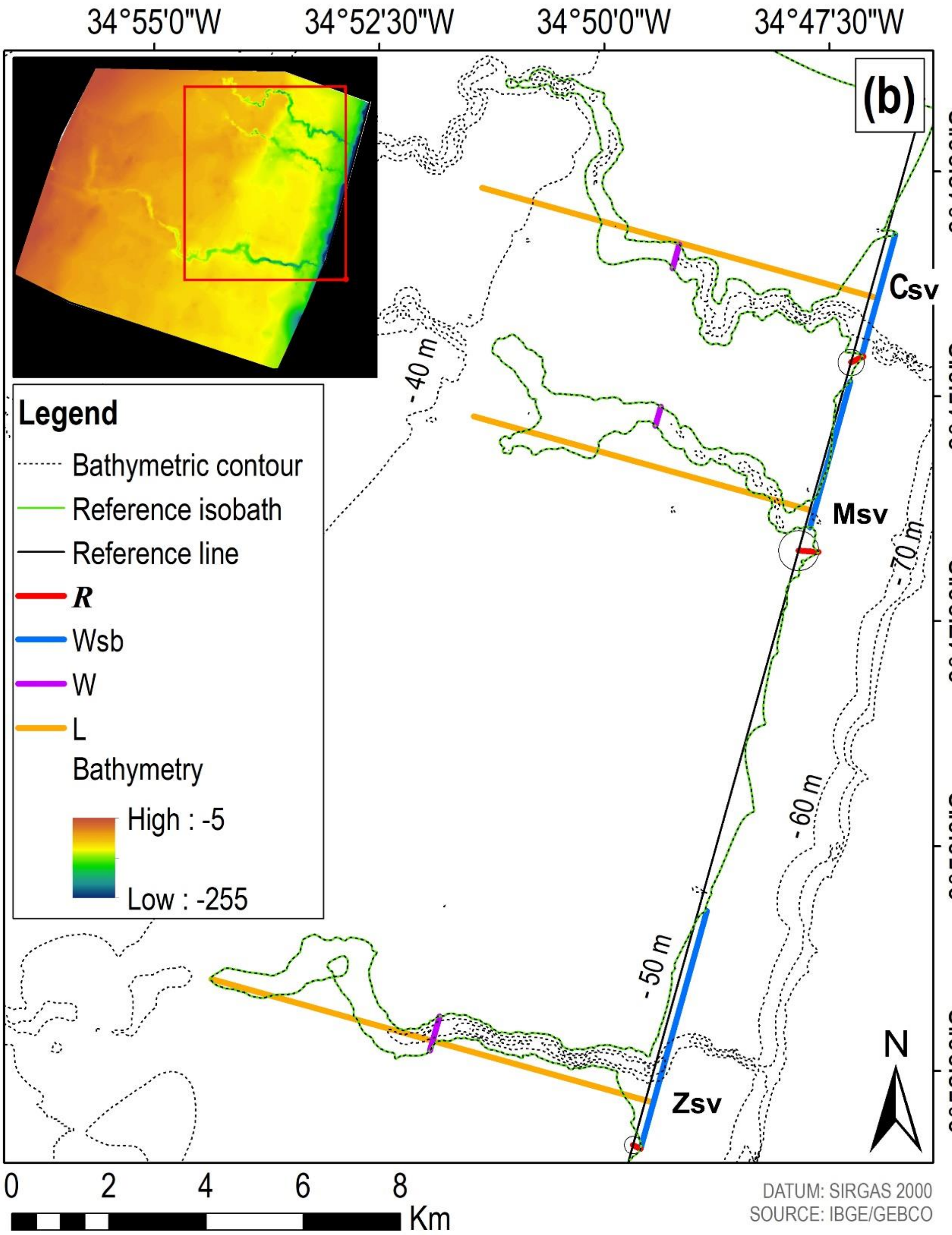
The characteristic lengths for each feature were extracted from the determination of reference isobaths, following ALLEN and HICKEY, (2010). The authors use the radius of curvature ($\mathcal{R}$) identification criterion to define reference isobaths, which is the limiting isobath in the upper upstream corner of the canyon for length extraction (Figure 3) (ALLEN; HICKEY, 2010). Thus, for the extraction of the characteristic lengths of three SVs, the reference isobaths 50 m (shelf-break average depth) were chosen. To extract lengths of the canyons in the located in the intermediate portion between the plateau and continental shelf area (Bc3), the 500 m depth isobath was used. Finally, the last isobath, 1250 m depth, was chosen to get the lengths characteristic of the canyons at the plateau (Bc1 and Bc2). The 50, 500m and 1250 isobaths represent the maximum depth at the mouth, used as reference to obtain the climatological absolute current velocity (U), temperature and pressure from GLORYS12V1 model product. The values for each canyon were obtained from profiles at the closest position of the maximum depth point at the mouths. Then, density (ρ) was calculated with the free available GSW Oceanographic Toolbox from temperature, salinity, and pressure. Brunt–Väisälä Frequency (BVF) represented by (N) was calculated from the model density and depth profiles following Eq. 1, Where $d\rho/dz$ is the vertical density gradient, ρ_0 the reference density and g the gravitational acceleration. We considered ρ_0 and g constants as 1026.95 kg.m^{-3} and 9.80665 m.s^{-2}, respectively.

Equation 1: $$\mathrm{N} = \sqrt{-\frac{g}{\rho_0}\frac{\partial\rho(z)}{\partial z}}$$

The data provided at the reference depth was combined with the length characteristics to obtain dimensionless numbers used in the dynamic scale analysis for both seasons, during the late spring and early fall.

Figure 3 – Plan view of the isobaths of Pernambuco Plateau blind canyons (a) (Bc1, Bc2, and Bc3), and the shelf valleys at the SCSP (b) (Zsv, Msv, and Csv), with the location of the reference line RL (black line - such as a shelf-break line), the canyons length L (orange line), the canyons width W (purple line), the width at the shelf-break W_{sb} (blue line), and the radius of curvature $\mathcal{R}$ (red line).





2.2 Dimensionless numbers

Dimensionless numbers as a function of flow properties and characteristic lengths were obtained for each shelf valley and blind canyon (Figure 3).

The collected variables were applied to understand flow balance on the canyons, such as the strength of velocity upstream of the canyon U, the Coriolis parameter ʄ, and the layer stratification generated by the BVF (N), where U and N were restricted to the same scale.

In parallel, the geometric parameters generated from the identification of the shelf-break line or reference line (RL), are useful to extract the characteristic lengths, all referring to the canyons. They are shelf-break depth (H_s), length of the canyon (L), depth at the head of the canyon (H_h), the width of the canyon at the reference line (W_{sb}), the width of the canyon at half-length (W), depth change across the canyon mouth (H_c) and the radius of curvature ($\mathcal{R}$) as seen previously (Table 1).

According to ALLEN and HICKEY (2010), in dynamical scaling analysis several dimensionless numbers are selected to represent the essential physical aspects. They are potential numbers using to develop theories involving the real and laboratory conditions into the dynamic scale.

We obtained three Rossby numbers (R_0, R_l, and R_w), in addition to the Burger number (B_u) and the aspect function of Rossby (Ꝼ) (Table 1). The Rossby number R_0 as a function of the radius of curvature represents the tendency of the flow to follow (low Rossby) or to break the geostrophy and cross the canyon isobaths (high Rossby) (ALLEN, 2004; WATERHOUSE; ALLEN; BOWIE, 2009). The R_l, as a function od the length of the canyon represents the ability of the flow to lift the isopycnals. Therefore, tendency for upwelling can be represented by the response of the dimensionless Rossby numbers. Whereas the Burger number, is the balance between stratification and rotation, and as a function of the canyon width, represents the tendency of eddy formation at the canyon rim.

Table 1 – Dimensionless numbers.

Number	Specification	Equation
$\boldsymbol{R_0}$	Rossby number	$U/\mathfrak{f}\mathcal{R}$
$\boldsymbol{R_l}$	Rossby number as length function	$U/\mathfrak{f}L$
$\boldsymbol{R_w}$	Rossby number as width function	$U/\mathfrak{f}W_{sb}$
$\boldsymbol{B_u}$	Burger number	$NH_s/\mathfrak{f}W$
$\boldsymbol{F}$	aspect function of Rossby	$F(R_0) = \frac{c_1 R_0}{c_2 + R_0}$

3. Results

3.1 Climatological Fall/Spring setting

To investigate if there is some indication of upwelling at the study region, we analysed the GLORYS12V1 product monthly climatology of temperature and salinity at the surface, 56 m (shelf-break) and 450m (above reference depth for the shelf canyons). The results are presented on Figure 4 and Figure 5 for, respectively, temperature and salinity during late spring and early fall.

For the period analysed the climatology shows high temperatures at the surface with no indication of strong horizontal temperature gradient indicative of upwelling (Figure 4a, b). Early fall presented higher sea surface temperature than the late spring, with average values 29°C (Figure 4a) and 27°C (Figure 4b), respectively. At the shelf-break, in both fall and spring, close to the slope, a decrease in temperature (around 25-26°C) was observed in relation to the adjacent oceanic water (Figure 4c, d). The slope/ocean temperature gradient was higher in the early fall than the late spring due to the already higher temperatures at the ocean for this period. At 450m (Figure 4 e, f) and below (not shown) no marked slope/ocean temperature gradient was perceived.

At the surface, salinity was high (>36.5) for both periods, however, slightly higher for the early fall than the late spring (Figure 5a, b). At 60m (Figure 5c, d), the salinity increased in relation to the surface, with values around 37 for almost all the region. Below 450m the values were lower than 35, representative of deeper water masses (Figure 5e, f).

The subsurface current acting against the slope is the equatorward NBUC, that dominates the dynamics in our study region (Figure 1). At the Pernambuco Plateau latitude (centred at 8.25°S) NBUC is stronger (>60 $m.s^{-1}$) between 70-700m and 100-650m for the early fall (Supplementary video S1) and late spring (Supplementary video S1), respectively. Maximum NBUC values, higher than 0.8 $m.s^{-1}$, are found between 200 and 250 m (Supplementary video S1 and S2). At the surface, during the fall (Figure 6a), the main flow is northward with an along coast band-like increase in velocity (~0.5 $m.s^{-1}$), reaching 0.6 $m.s^{-1}$ at the northern limit, representing NBUC expression in shallower depths. The shallower NBUC during the fall can also be observed in the same band as with stronger velocities (0.5-0.8 $m.s^{-1}$ from the southern to the northern limit; Figure 6c) at the shelf-break. In contrast, the current velocity at the surface in the late spring is weaker (<0.4 $m.s^{-1}$; Figure 6b) and southward south of 7.5°S above the shelf and slope. Still, at the shelf-break, we can observe the NBUC northward flow starting to show, with weaker velocities (<0.6 $m.s^{-1}$; Figure 6c) and the same intensification in the northern limit. At 450 m depth, the velocity values (>0.6 $m.s^{-1}$) and patterns are similar for both periods, revealing little seasonal change. For the deep ocean, although we did not observe any isotherm lifting related or close to Bc1 and Bc2 (not shown), an anti-cyclonic eddy was observed at both, fall and spring period above and close to Bc2 mouth depth (Figure 7a-d).

Figure 4 – Horizontal section for climatological temperature at surface (a,b), 60 m (c,d), 450 m (e,f) depth for December (late spring) and April (early fall). Current direction and intensity are represented by the arrows.

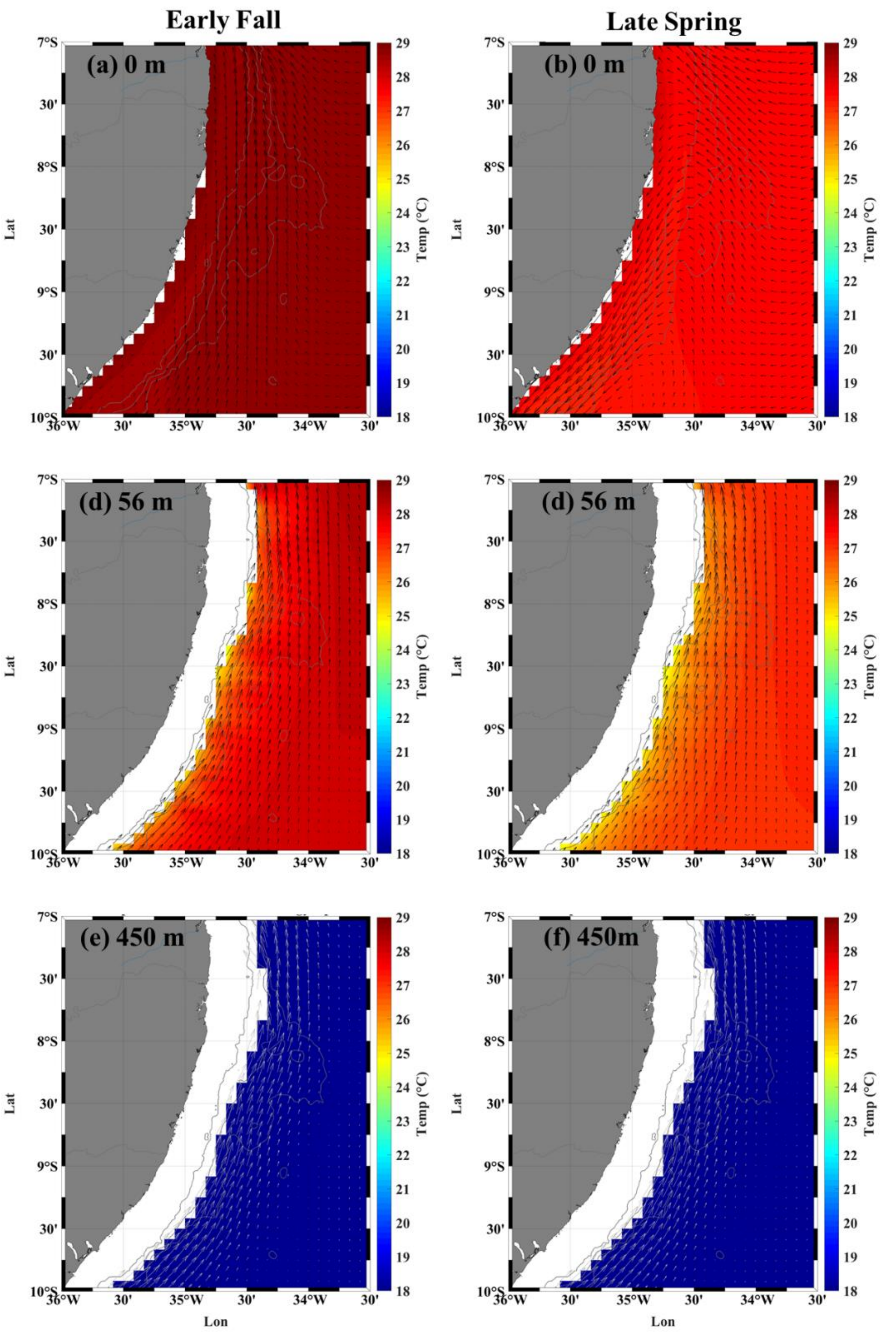


Figure 5 – Horizontal section for climatological salinity at surface (a,b), 60 m (c,d), 450 m (e,f) depth for December (late spring) and April (early fall). Current direction and intensity are represented by the arrows.

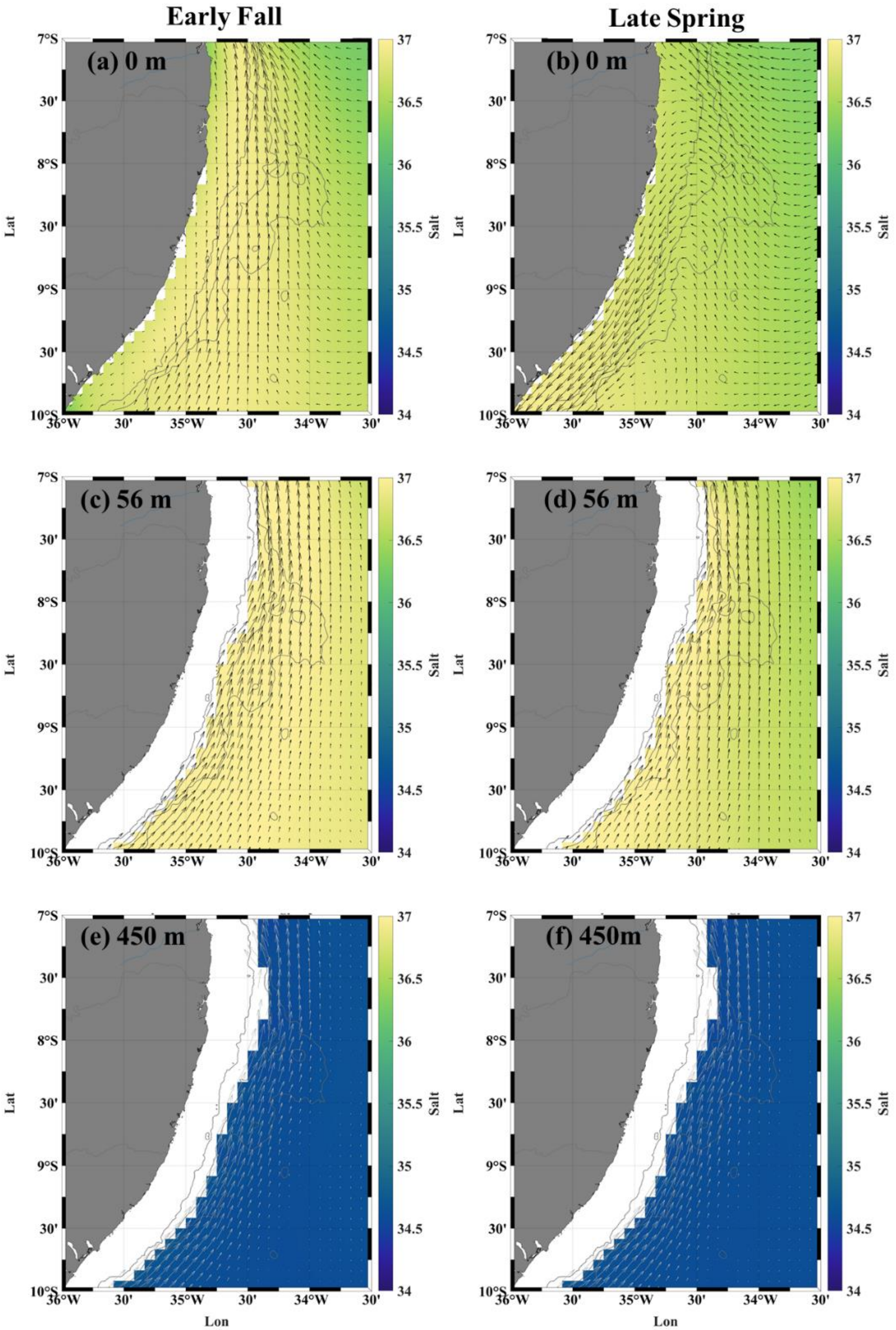


Figure 6 – Horizontal section for climatological velocity at surface (a,b), 60 m (c,d) and 450 m (e,f) depth for December (late spring) and April (early fall). Current direction and intensity are represented by the arrows.

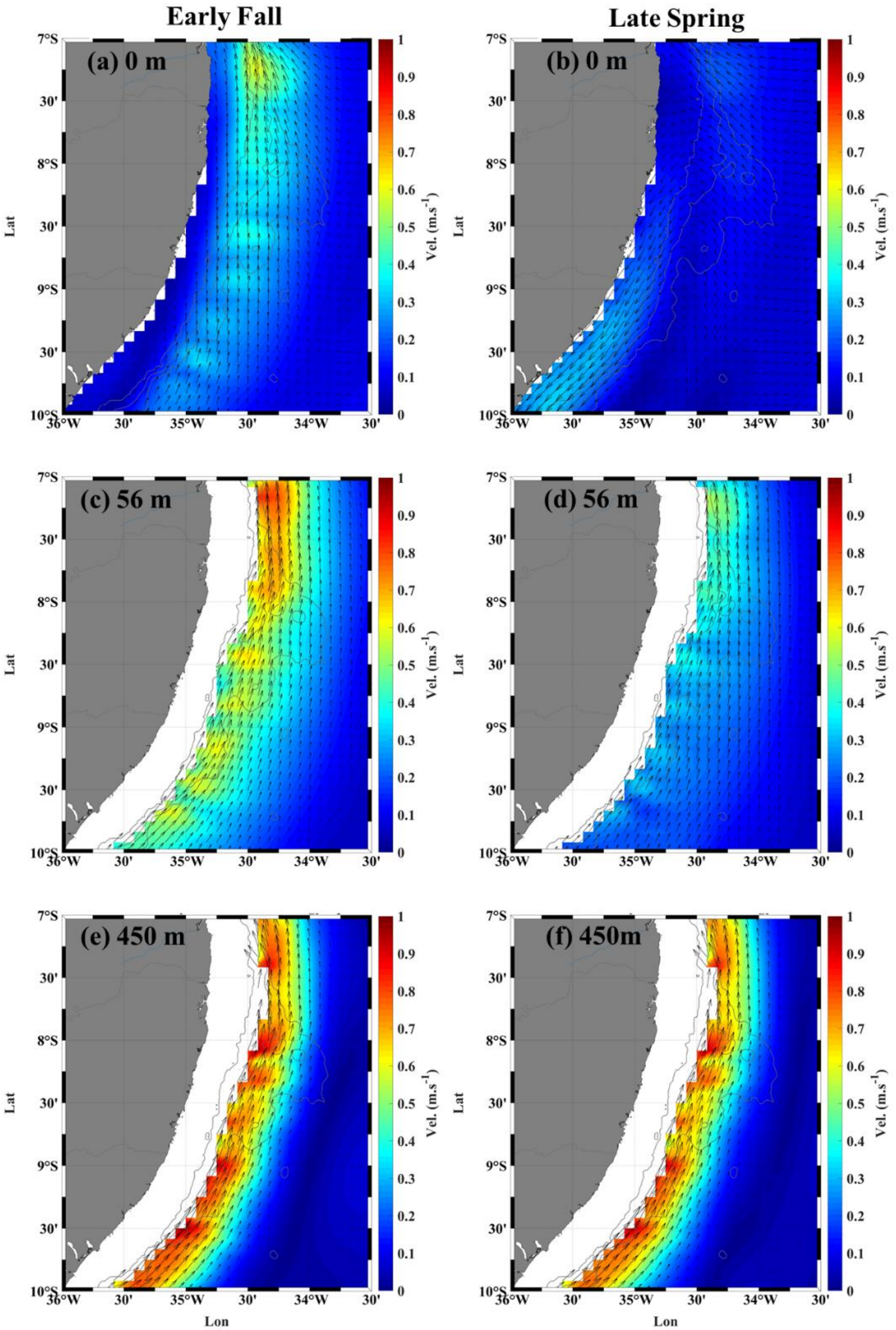
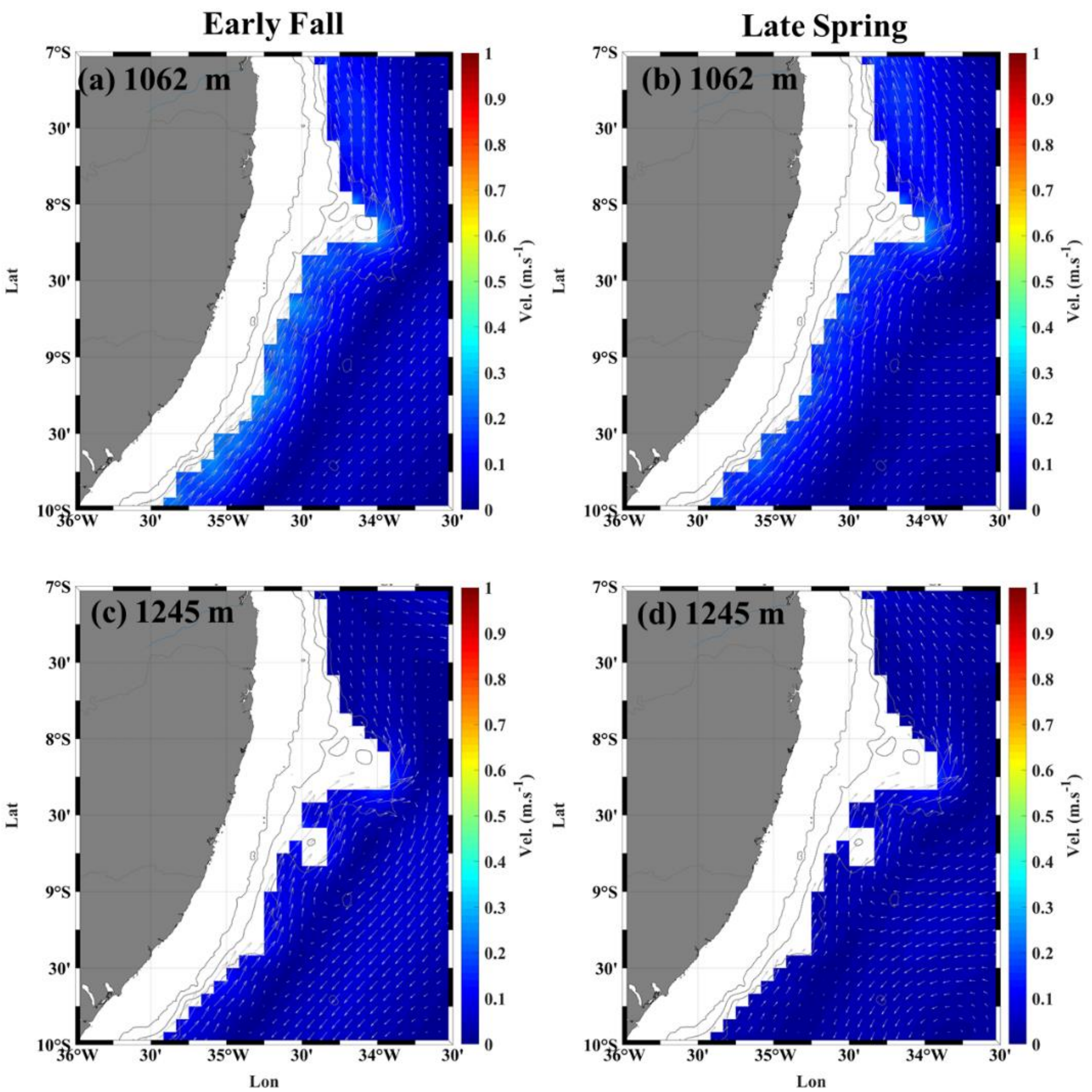
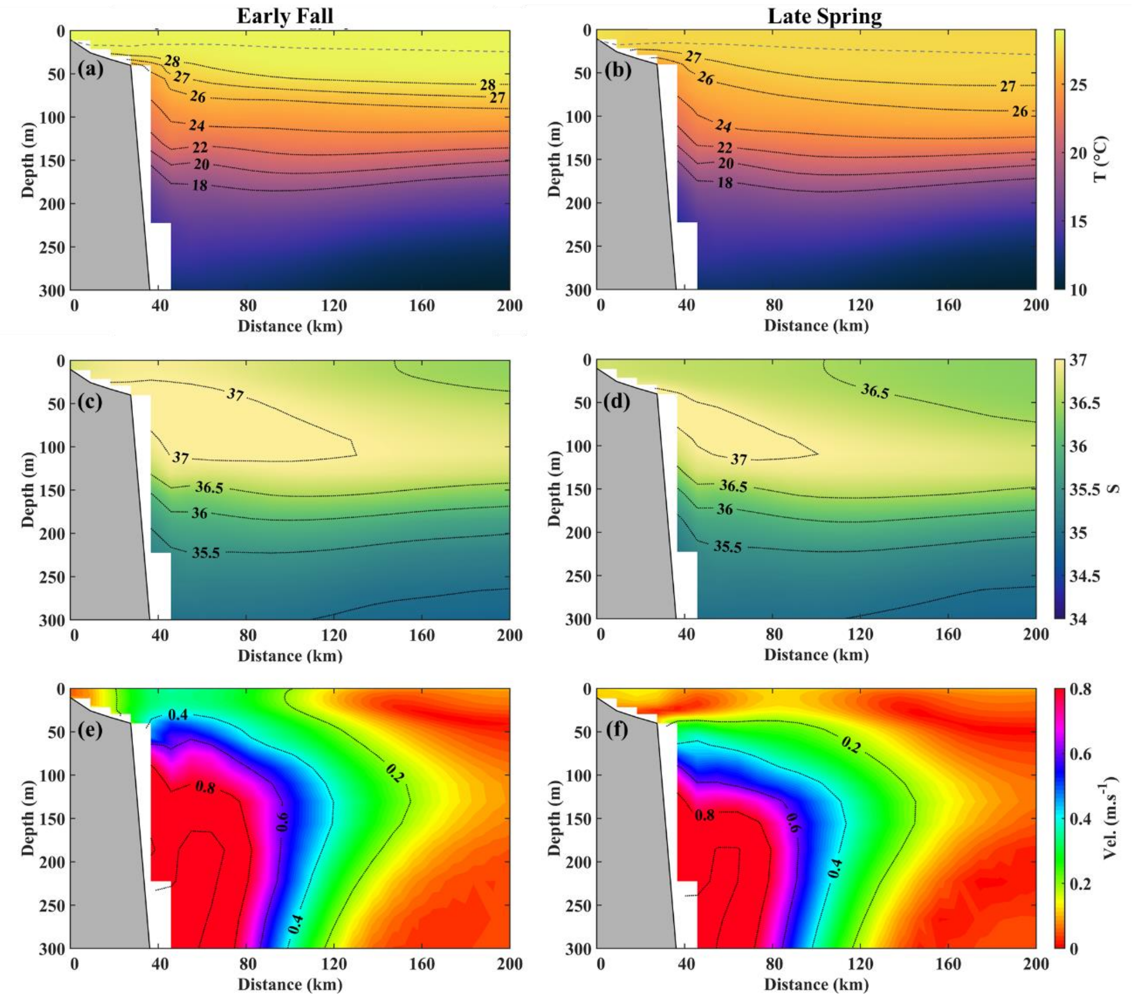


Figure 7 – Horizontal section for climatological velocity at 1062 m (c,d) and 1245 m (e,f) depth for December (late spring) and April (early fall). Current direction and intensity are represented by the arrows.



Back to shallow depths, we selected a zonal transect to represent temperature, salinity, and current velocity at 8.25°S from the surface down to 300 m and from the coast to 200 km offshore (Figure 8). We observed the lift of the isotherms close to the shelf break, however, below 250 m there seems to be a deepening of the isotherms (Figure 8a, b). The lifted waters seem to reach the outer shelf, close to the bottom, with colder isotherms close to the bottom at the late spring (25°C) when compared to the fall (26°C) (Figure 8b, c). Additionally, a maximum salinity core (S≥37) was observed between 25 and15m depth and extending from the outer shelf to 125 and 110 km offshore in early fall and late spring, respectively (Figure 8c, d). Besides the increase of the zonal extension, this maximum salinity seems to reach shallower depths at the slope at the early fall, when the current is shallower (Figure 8e), implicating in transport by NBUC. Additionally, concomitant with isotherms elevation, below the maximum salinity (and above the 250m), we also observed the elevation of the isohalines (Figure 8b, d).

Figure 8 – Zonal sections of climatological temperature (a, b), salinity (c, d) and current velocity (e, f) centred at the Pernambuco Plateau (8.25°S) for the early fall (left) and late spring (right) context. The dashed line grey line in a, b.



3.2 Seasonal variability of water masses intrusion on the shelf and shelf-break areas

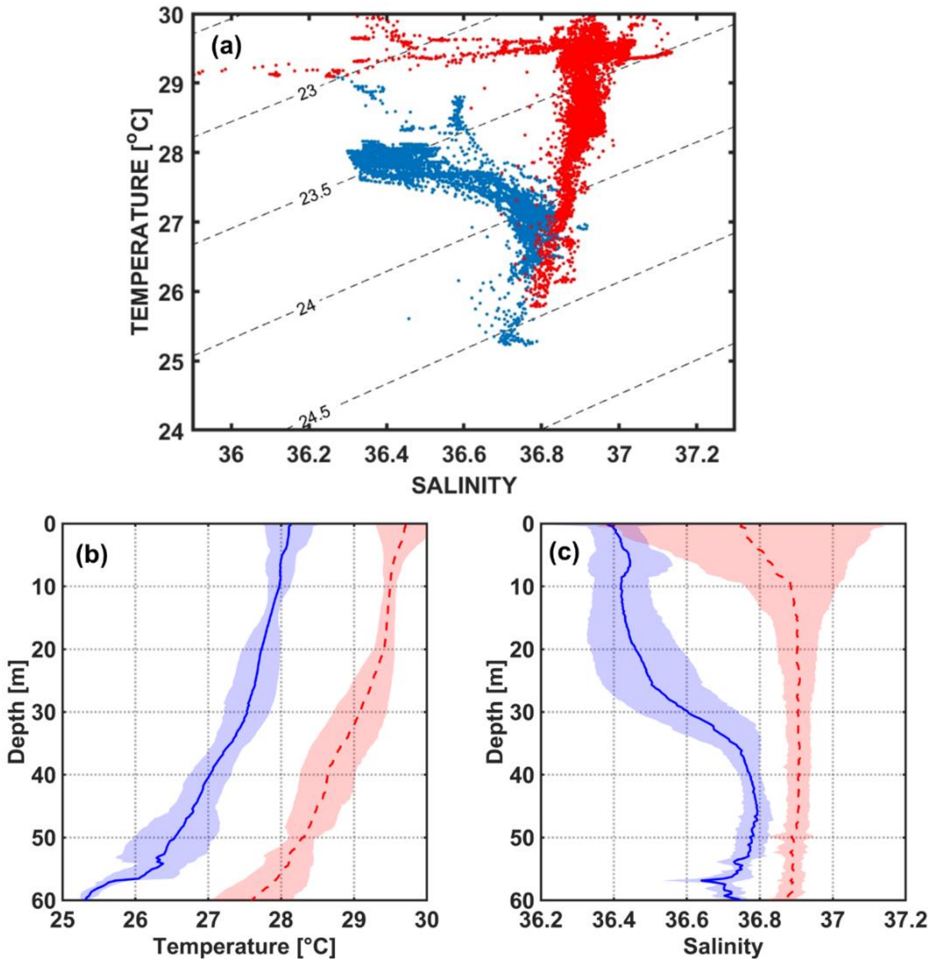
Here, we examine the thermohaline properties observed at the shelf and shelf-break areas during late austral spring 2018 and early fall 2019. To do this, Temperature-Salinity (T-S) diagram (Figure 9a), average vertical profiles of temperature (Figure 9b) and salinity (Figure 9c), and shelf valley stations (Figure 10 and Figure 11) were investigated for both sampling periods.

The T-S diagram (Figure 9a) considering all the stations (Figure 2) revealed the distinct water masses characteristics between the seasons evaluated. The maximum depth for the CTD stations was about 60 meters for the spring and 80 meters for the fall. As we aim to compare both seasons the results presented are relative to the surface down until 60m. The values observed at the T-S diagram, with a temperature above 20°C and salinity above 26, are representative of Tropical Water (TW) (STRAMMA; SCHOTT, 1999), with little to no contribution of Coastal Water (CW) from rivers contribution. However, the diagram shows the intrusion of warmer and saltier waters during the fall (red dots) compared with the spring (blue dots).

Analysis of the temperature profiles (Figure 9b) reveals unexpected thermal amplitude between the superficial and the 60m depth layers. In the late spring (blue line) the average for the superficial layer is ~28°C and 25.6°C in depth (2.4°C difference), while in the early fall (red dashed line) it is of about 29.6°C and 27.6°C (2°C difference) in near surface and 60m, respectively. The variability between the stations for temperature was similar for both seasons, except for depths higher than 55 meters, where the fall presented more variability than the spring. The vertical shape was similar for both seasons.

On the other hand, the case for salinity is quite different, the profile presented a characteristic difference in shape between the seasons (Figure 9c). In the spring (blue line) the profiles presented a well-mixed lower salinity layer (~36.4) down until about 20m depth, where the values start to increase until it reaches almost 36.8 at 45m depth. In the early fall (red dashed line) the salinity is higher (~36.9), and the profile average has no pronounced gradient between the superficial and the deeper layers. The higher variability was confined in the first 15 meters, decreasing with depth, while for the late spring the variability is higher down until about 40 meters.

Figure 9 – Temperature-salinity (T-S) diagram (a), vertical average (line) and standard deviation (shaded) of temperature (b) and salinity (c) of the late spring of 2018 (blue line) and early fall of 2019 (red dashed line) CTD stations.



The selected CTD stations (Figure 2) were analysed as a function of the location, as shelf and shelf-break (inside the SVs), and slope (outside the SVs) stations, during late spring (Figure 10) and early fall (Figure 11). This allows a comparison of salinity and temperature gradient along with the bathymetric change.

During the spring, the temperature profile of the slope presented a "stepwise" structure, indicative of instability in stratification (Figure 10c, f, i). While the mixed layer depth (MLD) is about 32 m and 20m, for ST45 and ST26 respectively, it cannot be determined for ST5 (Figure 10c). This suggests there was an elevation of the thermocline with the corrosion of mixed layer base. The stepwise structure corroborates with this hypothesis.

Looking at the stations inside the shelf valley is noticeable the intrusion of the water masses coming from the slope in the shelf-break region, mostly in Msv and Csv (Figure 10e, f). The temperature below 30m depth, i.e., below the MLD for both, reaches 26.5°C at 45m depth at Msv and ~27 °C in Csv, for the same depth. Additionally, the corresponding Msv station near the shelf-break is deeper and shows 25.5°C at 60m. The water mass intrusion is still noticeable at the Msv and Csv shelf stations (Figure 10d, g) however, the minimum temperature below the MLD reaches only about 27ºC. Salinity below the MLD is mostly stable and about 36.8 for all stations, except for Zsv shelf and shelf-break stations. The shallow depth of the Zsv stations (Figure 10a, b) does not allow the net visualization of slope water mass intrusion, although there is an indication of a small change in temperature and salinity around 20m depth at the shelf-break station (Figure 10b).

The temperature of the slope stations in early fall shows a smaller difference (~1.6°C) between surface layers and 60m depth when compared with the late spring (~2.7°C). The salinity is high and well mixed for the whole water column at all the stations. The MLD is weaker for almost all stations and highly variable, ranging from 20 m to 50m within the stations. Additionally, the “stepwise” structure is still noticeable, despite the observed smaller gradients.

Although the slope water mass intrusion in Zsv shelf-break station could not be evaluated in spring, during the fall, the intrusion was well observed (Figure 11b). The isotherm of 28.2°C, equivalent to deeper waters than 50m depth in the slope, reaches 50m depth at the shelf and 30m depth at the shelf-break stations (Figure 11a, b), which also suggests vertical water transport. For Msv and Csv shelf-break stations (Figure 11e, h, respectively), we still notice slope water mass intrusion. At 50m depth the isotherm of 28°C (27.5°C at 60m depth) and 28.5°Care found in Msv (Figure 11e) and Csv (Figure 11h), respectively. At the shelf stations for both (Figure 11g) the water mass intrusion is smaller and, below the MLD, the temperature stays above 28.4°C.

Figure 10 – Vertical temperature (black filled) and salinity (red dashed) profiles obtained at selected CTD stations at continental shelf, shelf-break, and slope regions at Zieta (Zsv), Middle (Msv) and Campas (Csv) shelf valleys in late spring 2018.

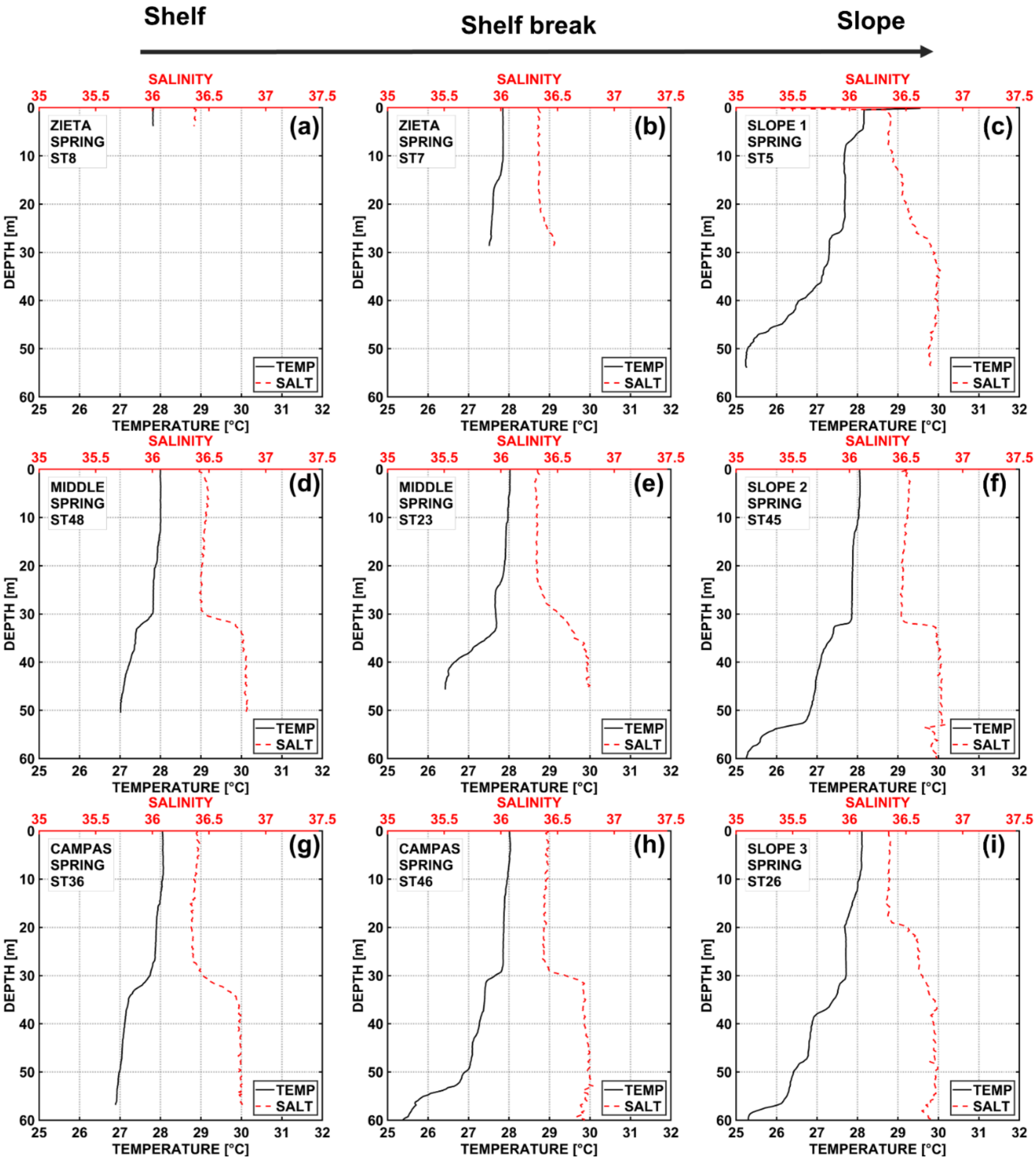
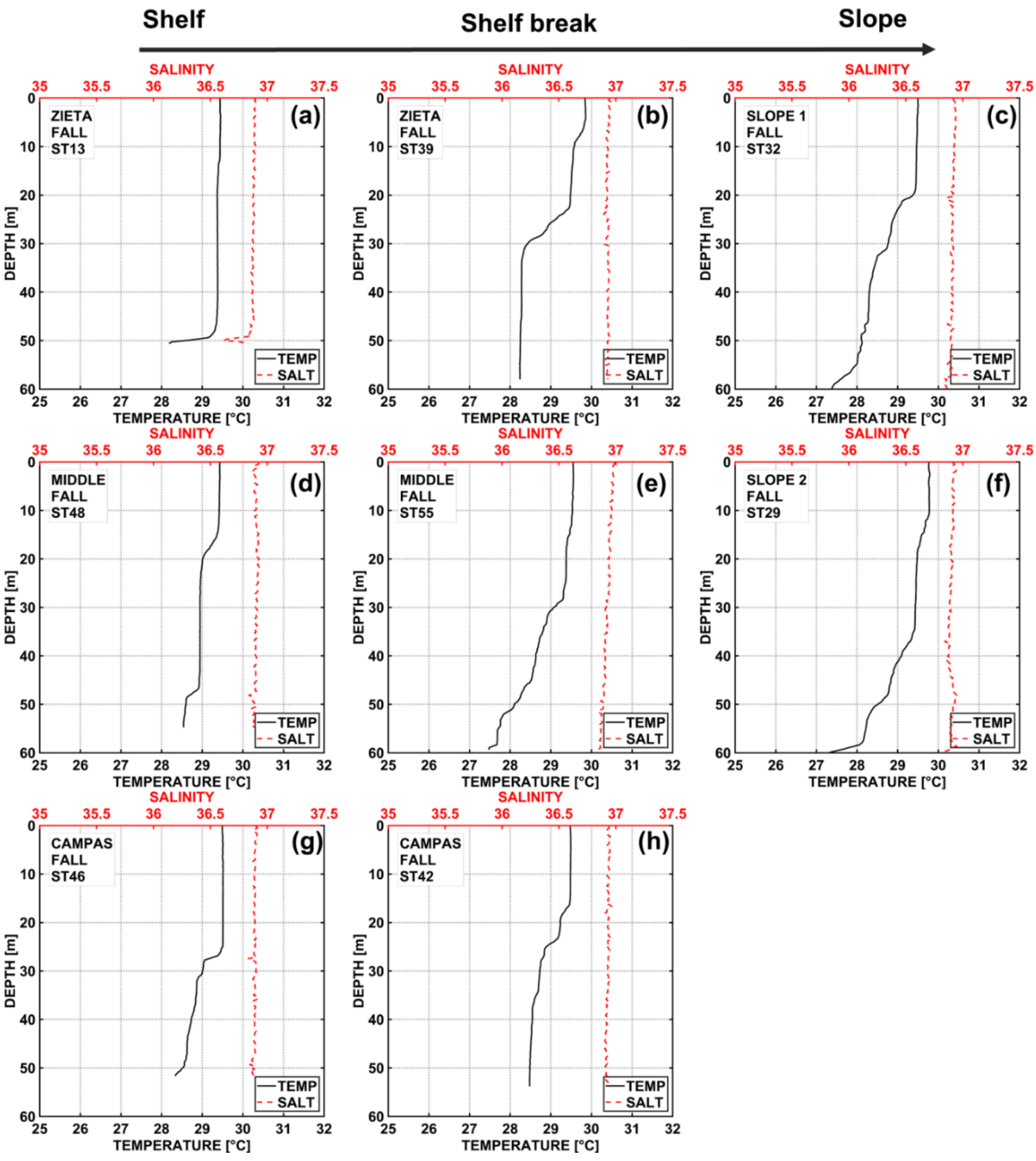


Figure 11 – Vertical temperature (black filled) and salinity (red dashed) profiles obtained at selected CTD stations at continental shelf, shelf-break, and slope regions at Zieta (Zsv), Middle (Msv) and Campas (Csv) shelf valleys in early fall 2019.



3.3 Morphological characteristics

The depth difference of the Bc1 is about 2300 m from the canyon head to the mouth, at the ocean basin boundary. The isobaths are regularly spaced and indicate a regular bathymetric gradient with inclination of 25° degrees. The depth is about 1250 m at the canyon head and 1350 m near the reference isobath, while its mouth has 2660 m depth with the deepest point in 3500 m. Moreover, a "V" shape and adjacent ravines was observed by the cross-section over the canyon. The thalweg is directed toward SE-NW near the mouth and in the central portion of the canyon, while near the canyon head it is toward N-S direction. Thus, it forms an angle of 110° with the reference line at the mouth of the canyon (Figure 3a).

The Bc2 has a depth difference between the head and the mouth about 2210 m with isobaths heterogeneously spaced in some areas. The inclination degree is lower than other canyons, with an average value of 11°. The canyon head depth is 1290 m, and 1355 m near the reference isobaths. In addition, it has 2115 m deep at the mouth and its deepest point reaches the depth of 3500 m. In contrast to Bc1, it has a "U" shape by the cross-section analysis, favouring terraces features near the thalweg and in the central part of the canyon. The thalweg has three different directions, S-N downstream, SW-NE in the central part, and SE-NW upstream. Besides, the angle between the mouth canyon axis direction and the reference line in Bc2 is approximately 140° (Figure 3a).

Furthermore, the Bc3 is distinguished from Bc1 and Bc2. The depth difference between the head and the mouth of the canyon is about 700 m. The isobaths have regular spacing and inclination about 34º being greater than the other plateau canyons. The depth at the canyon head, canyon mouth, and near the reference isobaths are 540, 570, and 770 m, respectively, with the deepest point at 1200 m depth. As in Bc1, the cross-section within the canyon as a "V" shape. However, it cannot be stated whether it has ravines or not, due to the data resolution and size of the interpolation cell. The thalweg is unidirectional toward SE-NW direction and forms a 90º angle from the reference line with mouth of the canyon (Figure 3a).

On the other hand, the Zsv has an average depth of 45 m at shelf-break which decreases toward to continent, reach 51.5 m at the mouth, and its deepest point in 54.1 m. Zsv is located in a less rugged and less inclined area (~0.34°) than the other SVs. The Zsv has a “V” shape bottom along its entire length, and its direction of thalweg is preferentially SE-NW, shifting to E-W and SW-NE near to the coastline (Figure 3b).

The Msv has an average depth of 40 m, ranging from 47.5 m close to the head to 51.7 m to the mouth, and the deepest point is 59.9 m. It is located within a rugged region that has a step of 12 m depth and 0.28° inclination. The Msv has a "V" shape as observed for Zsv, and its thalweg is sinuous at the shelf-break with predominant direction SE-NW, although it changes nearby to the coast SW-NE (Figure 3b).

Finally, the Csv presents an average depth of 45 m, 36.5 m at the head, 51.2 m in the mouth, and 54.1 m at the deepest point. The Csv has a step of 12 m depth difference and slope of 9.6°. It has a “V” shape of bottom, and linear in the SE-NW direction at the shelf-break, becoming more sinuous in the central area which has a direction SE-NW. However, the Csv changes the shape of bottom into “U” even near to the shelf-break Figure 3b).

Morphological characteristics obtained for the plateau blind canyons and the Zieta, Middle and Campas shelf valleys are presented in Table 3. L/W_{sb} correspond to the dimensionless number aspect ratio (Table 2).

Table 2 – Morphological numbers shelf-break depth (H_s), depth at head of the canyon (H_h), depth change across the canyon mouth (H_c), length of the canyon (L), width of the canyon at half-length (W), radius of curvature ($\mathcal{R}$) and the width of the canyon at the reference line (W_{sb}), obtained from the plateau blind canyons (Bc1, Bc2 and Bc3), and the shelf Zieta (Zsv), Middle (Msv) and Campas(Csv) canyons. $L/W_{sb}$is the dimentionless number aspect ratio.

Number	BcPC1	Bc2	Bc3	Zsv	Msv	Csv	Units
$\boldsymbol{H_s}$	1350	1355	570	51.5	51.7	51.2	[m]
$\boldsymbol{H_h}$	1250	1290	540	45.5	47.5	36.5	[m]
$\boldsymbol{H_c}$	2660	2115	770	54.1	59.9	54.1	[m]
$\boldsymbol{L}$	21.2	31.8	4.3	9.35	7.2	8.3	[km]
$\boldsymbol{W}$	47.1	50.5	1.8	0.72	0.4	0.5	[km]
$\boldsymbol{\mathcal{R}}$	8.9	5.9	2.2	0.17	0.4	0.2	[km]
$\boldsymbol{W_{sb}}$	65.9	55.5	5.9	5	3.1	2.5	[km]
$\boldsymbol{L/W_{sb}}$	0.32	0.57	0.73	1.87	2.32	3.32	

In summary, the blind canyons of the Pernambuco Plateau are 26 times deeper in the region of the shelf-break depth (H_s), 3 times longer (L), and 110 times wider than the SVs over the shelf (W). However, we have the exception of Bc3, which is 1 time shorter and only 2.5 times wider than the SVs on the continental shelf. Therefore, we highlight the difference in scale of two groups of the morphological seafloor. The first, belonging to the blind canyons of the Pernambuco Plateau, which present features of deep blind canyons, despite of exception in Bc3 that has submarine canyon morphological character. On other hand, the second group present morphological characteristic from shelf valley, and aspects of shallow and narrow channels (Table 2).

3.4 Dimensionless parameters

The dimensionless numbers obtained for the SVs and blind canyons are presented in Table 4. Starting with the Rossby number (R_0), in both seasons (late spring and early fall), the highest values were found in the shelf canyons, mostly at Zsv and Csv, with equivalent values, and the lowest Rossby number at Bc1. Besides, almost all the values obtained during fall were higher than the spring values, except for Bc3 that presented an opposite pattern. The difference between spring and fall was higher among shelf and plateau canyons, which presented, in both seasons, one order of magnitude higher values, especially on Plateau canyons Bc1 and Bc2. Here, we also observed that early fall Rossby numbers are higher than late spring, analysing only the continental shelf area (Table 3).

Considering Rossby number as length function (R_l), similar to R_0, the values for fall were in general higher than the spring, except for Bc1. On other hand, the higher values in both seasons were found in Bc3, still with one order of magnitude higher than those found to Bc1 and Bc2, although the same magnitude when compared to three SVs. Within the SVs, Msv followed by Csv, presented slightly higher values than Zsv.

Table 3 – Dimensionless Rossby number (R_0), Rossby number as length function (R_l), Rossby number as width function (R_w), Burger number (B_u) and aspect function of R_0(Ɏ), obtained for the plateau blind canyons (Bc1, Bc2 and Bc3), and the Zieta (Zsv), Middle (Msv) and Campas (Csv) shelf valleys, during the late spring and early fall.

Number	Season	Bc1	Bc2	Bc3	Zsv	Msv	Csv
$\boldsymbol{R_0}$	Spring	0.11	0.28	13.57	66.68	32.61	65.49
	Fall	0.39	0.58	13.19	130.87	55.63	111.71
$\boldsymbol{R_l}$	Spring	0.05	0.05	6.94	1.21	1.81	1.58
	Fall	0.16	0.11	6.75	2.38	3.09	2.69
$\boldsymbol{R_w}$	Spring	0.01	0.03	5.06	2.27	4.21	5.24
	Fall	0.05	0.06	4.92	4.45	7.18	8.94
$\boldsymbol{B_u}$	Spring	8.43	8.33	127	20.41	37.35	29.71
	Fall	8.43	8.33	127	20.41	80.69	64.19
Ɏ	Spring	0.22	0.56	-	-	-	-
	Fall	0.77	-	-	-	-	-

For Rossby number as width function (R_w) almost all values are higher in fall with the highest values were found for Csv in both seasons. During fall the second-highest value was observed in Msv and during spring, in Bc3. A comparison between the SVs leads to values that seem to increase from Zsv towards Csv. On the plateau, the same seems to be true, and the values increase from Bc1 to Bc3. The last presented values one and two magnitude orders higher than Bc2 and Bc1, respectively, in both seasons.

Burger number did not change much between periods, as the comparison between spring and fall showed equal values for the three blind canyons on plateau, and one shelf valley (Zsv). Only in Msv (B_u= 80.69) and Csv (B_u= 64.19) did they present differences with higher values during the early fall. The highlight is Bc3 (B_u= 127) with the highest Burger values in an order of magnitude greater than Bc1 (B_u= 8.43) and Bc2 (B_u= 8.33).

The comparison between the stations revealed equal values for as seem for the Burger number. Only Msv and Csv show differences in Burger with similar values. The highlight is Bc3 with the highest Burger values in an order of magnitude more than Bc1 and Bc2. Comparing the SVs, we have the highest values during the fall for Msv and Csv, where the first has the highest value. The Zsv still remains the same values in relation to the other two SVs.

Last, the aspect function of R_0(Ғ) is only considered if R_0<0.5 (ALLEN; HICKEY, 2010). Comparing the plateau blind canyons, the values increase from Bc1 to Bc2 in spring and the canyon Bc1 presents seasonal differences with higher value in the fall.

4. Discussion

The dynamical scaling analysis can serve as useful tool to investigate flow-topography interactions, helping to identifying potential upwelling, and water masses intrusion along the slope, shelf-break and shelf regions (ALLEN, 2004; ALLEN AND DURRIEU DE MADRON, 2009; JORDA et al., 2013; THÉVENIN et al., 2019). Besides, dynamic exchange between the shallow and the deepest areas is shaped by the geometry of submarine canyons, according to their length, width, depth, the bottom shape, and its disposition concerning the predominant flow direction (ALLEN, 2004).

The main subsurface flow in our region is equatorward, representative of the NBUC, that is the southern branch bifurcation of the South Equatorial Current (sSEC) (DENGLER et al., 2004; HUMMELS et al., 2015; SCHETTINI et al., 2017; SCHOTT et al., 2005). The sSEC carries the waters from the Southeast Tropical Atlantic (RAY; STRAMMA, 1991; STRAMMA, 1999; STRAMMA; SCHOTT, 1999) across the Atlantic and bifurcates in the Northeast Brazil coast. The bifurcation oscillates meridionally throughout the year, alternating at the most northern latitude ~11°S during summer and more south ~20°S in winter (STRAMMA et al., 1995; SCHOTT et al., 2005; RODRIGUES et al., 2007; SILVA et al., 2009; SOUTELINO et al., 2011), reflecting in the variability of the NBUC. Moreover, subtropical water masses within the Southern Atlantic Ocean Circulation (AMOC) at latitude ~30° feed the NBUC core (~21.4 Sv) (CABRÉ; PELEGRÍ; VALLÈS-CASANOVA, 2019). Our study region comprises the latitude band between 8°S and 7°S were the NBUC have intensifies, with its mean velocity reaching 1 m.s^{-1}. The NBUC velocity core extends from ~120 m to more than 600 m depth and from the shelf-break to 20km offshore nearby the SPCS. In spring, the core velocity increases from 0.8 to 1.2 m.s^{-1} from 9°S to 7°S. In addition, the upper limit depth decreases from 160 to 105m from 9°S to 6°S due to the strong vertical shear. During the fall, at SPCS, the NBUC velocity core is centered around 70–440 m depth and extends between the shelf-break and 30 km offshore, with velocity up to 0.7 m.s^{-1} (DOSSA et al., 2021). The local wind regime is controlled by the semi-permanent, high-pressure system of the South Atlantic Ocean. The mean monthly wind velocity varies from 7.5 m.s^{-1} in summer (December and January) decreasing to a minimum around April to almost 10 m.s^{-1} in winter (August and September), with predominant E/SE direction (DOMINGUES et al., 2017; SCHETTINI et al., 2017).

In terms of continental margin characteristics, the northeast Brazilian region presents a shallow shelf, with average 40km width and shelf-break depth between 40–80 m (MARTINS; COUTINHO, 1981). In addition, the shelf is considered as sediment-starved due to the low sediment input and reduced sedimentation rates as well as predominantly oligotrophic and covered by biogenic carbonates (CAMARGO et al., 2015; DA SILVEIRA et al., 2020). The morphology analyses for the shelf-break SVs (Zsv, Msv, and Csv) and for plateau blind canyons Bc1 and Bc3 shows the predominance of short canyons with “V” shape bottom. However, only Bc2 present submarine canyon aspects with “U” shape bottom. While the plateau blind canyons cannot be considered submarine canyons its properties are similar to short and long canyons.

In our investigation for some evidence of upwelling related to the blind canyons feature, we found instead, the uplift of colder water masses at the slope. The observed low vertical temperature and salinity gradient in the first 30 meters or more within the SVs can be attributed to the mixing of water masses between TW and of the SACW (ARAUJO et al., 2011; 2018). This is verified by the TS diagram analysis, which shows water masses signature limits of CW, TW and SACW (DOMINGUES et al., 2017; OLIVEIRA FILHO et al., 2017; CABRÉ et al., 2019) (Figure 9). While the late spring profiles show the largest vertical gradients of temperature and salinity, the shallow and weaker mixed layer allows the isopycnals to reach shallower depths during the late fall. Furthermore, individual analysis of the vertical gradient profiles shows well-marked disturbances below the mixing layer, mainly at the 40 and 50 m depth during both seasons. This is a typical presentation in intrusion of water masses through submarine canyons (AGUIAR et al., 2018; CANALS et al., 2013; KÄMPF, 2012; WALTER;

PHELAN, 2016). Although, we cannot discard the probability of instability driven by propagation and internal waves break at the shelf-break (KUNZE ET AL., 2002; ALLEN AND DURRIEU DE MADRON, 2009; LEE et al., 2009; HOWATT AND ALLEN, 2013). Further, the mixing through turbulence seems to increase during the fall when compared with the winter. This is evidenced by the increased observation of stepwise thermohaline structure, which was also observed by ASSUNÇÃO et al., (2020).

Despite that uplift process does not have a superficial temperature expression, it can have the same importance as upwelling for productivity in oligotrophic regions (AGUIAR et al., 2018; ROCHFORD, 1991). Some process can account for upwelling within the slope, such as current driven Ekman bottom transport and wind-driven Ekman pumping (AGUIAR et al., 2018; CASTELAO, 2011; OKE; MIDDLETON, 2000; ROUGHAN; MIDDLETON, 2002). However, for our region, neither the current nor the wind direction favours upwelling. Indeed, the wind is predominant south/southeast along the year (DOMINGUES et al., 2017; SCHETTINI et al., 2017) and the main current is equatorward (NBUC), which should inhibit upwelling surface expression. Moreover, although we expected the blind canyons to be the main topographic features responsible for the uplift at the slope, the results points to another direction. The uplift, besides the Pernambuco Plateau region, was observed at both, south and north of the Plateau always close to the slope. Its parallel to the slope band pattern and position in relation the NBUC points to a dynamical flow-slope interaction control. However, the scope of our investigation does not allow for further inferences.

Another interesting finding was that not all the CTD profiles presented the expected isothermal and isohaline patterns resulting of the well mixed water column over the continental shelf. At some stations, we observed the intrusion of colder water within the shelf and SVs, especially at the shelf-break and slope section (Figure 10 and Figure 11). This intrusion was also previously reported at the southern Pernambuco outer shelf by (DOMINGUES et al., 2017; SCHETTINI et al., 2017). The authors observed higher gradients for temperature, at the bottom in the outer shelf of the SPCS when compared with the northern Pernambuco continental shelf (DOMINGUES et al., 2017; SCHETTINI et al., 2017). However, to our kwnoledge, no atempt was made to investigate the driving mechanism resulting in this observation.

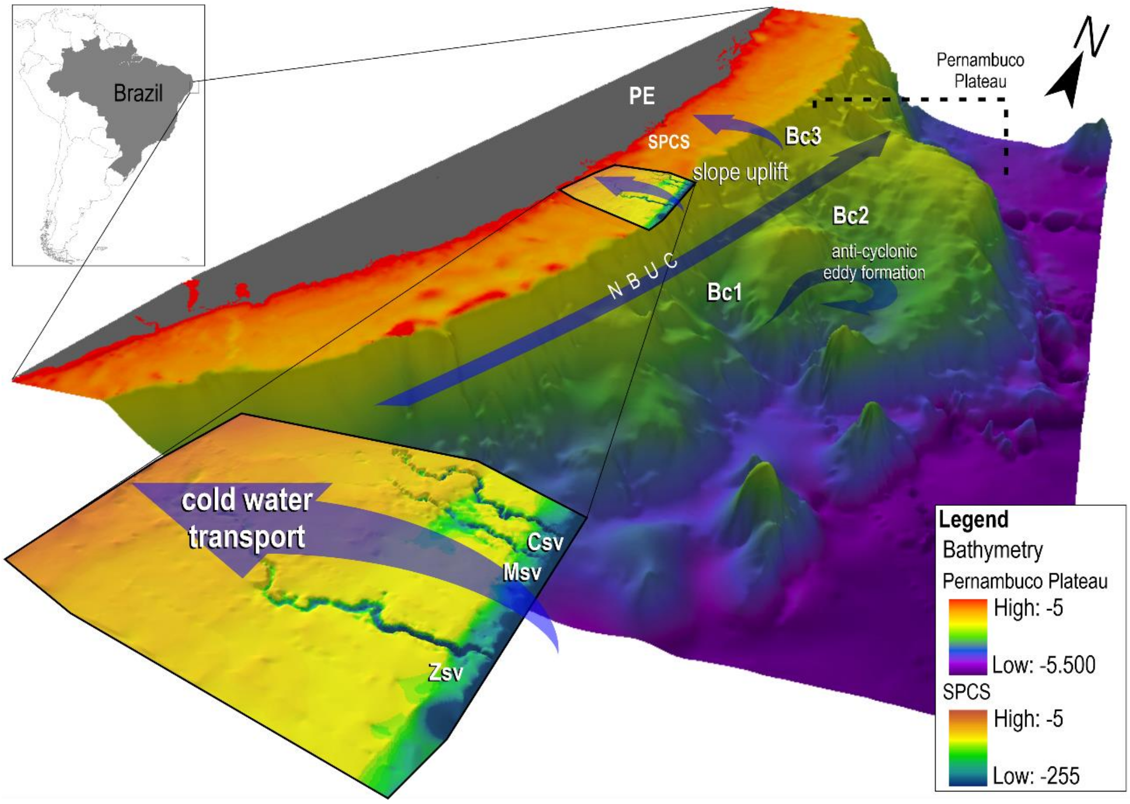
Our hypothesis is that the SVs might play a role in conducting the uplifted slope water coast-ward. In short canyons, water rises through the canyon slope due to imbalance pressure gradient force as the geostrophic currents cross the canyon head (FREELAND; DENMAN, 1982). On other hand, in long canyons the advection-driven upwelling is also associated to isobaths disposition, presenting greater convergence close to shelf-break, inducing water masses intrusion due to low Rossby number (ALLEN, 2000; WATERHOUSE; ALLEN; BOWIE, 2009).

Although the occurrence of upwelling at low Rossby is usually reported for many canyons, higher Rossby numbers can promote strong advection-driven upwelling through cross isobath flows (ALLEN, 2004; PERÉNNE et al., 1997). Our study region presented a weak geostrophic balance which induces a high Rossby number and may drive the cross-shore advection of colder waters. This seems to be true for the shallower canyons, due to their depth and shape, they are subjected to higher flows across isobath, and are influenced by the NBUC core. It becomes clear if we compare the higher Rossby numbers for Csv, Zsv, Msv, and Bc3 in decrease order with the lowest from Bc1 and Bc2.

Rossby and Burger numbers for the blind canyons indicate a weak geostrophic balance at the canyon rim, and instability of the horizontal length scale of the pressure gradient force. Which means that with a high Burger and Rossby numbers, as seen in the shelf-break for B_u >> 1 (STUART; SUNDERMEYER; HEBERT, 2011), and for R_0 >> 1 (ALLEN AND HICKEY, 2010) respectively, the flow tends to cross the blind canyon isobaths. The reanalysis product results showed the formation of an anti-cyclonic eddy in Bc2's mouth nearby (Figure 7). The vorticity is expected for the large vertical displacements observed in the water column nearby the rim toward to upstream of the canyons (WATERHOUSE; ALLEN; BOWIE, 2009). The vorticity changes the geostrophic balance, the pressure gradient force and modify the barotropic conditions which influence the flow displacement for advection-driven upwelling, favouring the water masses intrusion from deepest to shallowest areas as the shelf-break (ALLEN, 2004; ALLEN AND HICKEY, 2010; MALAUENE et al., 2018; THÉVENIN et al., 2019). However, the observed anti-cyclonic eddy does not favour upwelling and, due to is depth, well below the euphotic zone, should not affect primary productivity.

The seasonal control also appears as stratification and variability of the NBUC. The stratification is stronger during late spring and weaker with shallow mixing layer during the early fall (SILVA et al., 2009; ARAUJO et al., 2011; HUMMELS et al., 2015; ASSUNÇÃO et al., 2020). On the other hand, although the stronger stratification, colder isotherms were uplifted during the late spring than during the fall. The dampening of colder water intrusion effect might be a result of the increase of the current-driven mixing in the early fall. All the SVs showed some seasonal pattern in the Burger number which was B_u >> 1 (Table 3). The eddy formation parameter is primarily determined by the inverse of the Burger number that indicate deep rim eddy are not generated (ALLEN; HICKEY, 2010), specially for the SVs area. Also, it is important to mention that even for B_u >> 1, the adjustment can still proceed to a stable and geostrophically balanced state, if the Ekman number is small (STUART; SUNDERMEYER; HEBERT, 2011). The lack of seasonal pattern was expected for the blind canyons due to their depth and the low seasonality revealed by the model results (Figure 6e, f and Figure 7), but not for the SVs. For the latter, the difference it is mostly likely a consequence of the temperature and thermocline depth (ALLEN et al., 2001; ASSUNÇÃO et al., 2020; WALTER; PHELAN, 2016), as the current for the reference isobath depth did not show marked seasonality (Figure 6e, f). On other hand, the NBUC variability is clear and represented by the increase of the Rossby, during the early fall, when the current is stronger (in relation to the reference isobath depth) and shallower when compared to late spring (STRAMMA et al., 1995; SCHOTT et al., 2005; RODRIGUES et al., 2007; SILVA et al., 2009; VELEDA et al., 2012). The small increase in R_0 from late spring to early fall in Bc3 are resulting from a small increase in the model current data. The intrusion of colder and saltier waters observed in the CTD stations suggest uplift of water masses within the SVs for the late spring which are corroborated by the high Rossby and Burger numbers. However, for the early fall, the slope water intrusion was warmer than the expected. Once again, this might be a consequence of the current-driven mixing with the warmer waters above. Figure 12 presents a schematic 3D view of the SVs, blind canyons and the processes observed above.

Figure 12 – 3D view of the morphology with emphasis on the interaction of the North Brazil Undercurrent (NBUC) with the topography of the blind canyons (Bc1, Bc2, and Bc3) and shelf valleys (Zsv, Msv, and Csv). In the subsurface, slope-NBUC interactions uplifts waters and shelf valleys serve as conductors of this water shelf ward. In depth, the deeper and slower current interaction with Bc2 leads to anti-cyclonic eddy formation. The topography comprises the GEBCO 30-arc sec and the *in-situ* data for the shelf valleys.



We should expect the uplift to have some impact on the environment and biological communities just as upwelling (ALLEN et al., 2001; BOSLEY et al., 2004; JORDI et al., 2005; RENNIE et al., 2009; JORDA et al., 2013; HOSEGOOD et al., 2017; GONZÁLEZ-GALISTEO et al., 2019; BARGAIN et al., 2018), if the uplift reaches depths shallower than the euphotic zone. Although investigations are still being conducted in order to identify bottom-up control in the plateau blind canyons and SVs region, a recent work by Eduardo et al., 2018, identified changes in diversity and biomass of fish south of 8°S. Thus, we can only hypothesize that this change can be a consequence of the processes presented above. The intrusion of water masses on the shelf changes the oceanographic conditions, may influence biogeochemical aspects, sediment flow (platform-slope transport, in both directions), nutrient input and finally fertilization in oligotrophic regions (HOSEGOOD et al., 2017). Additionally, the study region presented here, is inserted within several Marine Protected Areas (e.g. 'MPA Costa dos Corais') (FERREIRA; MAIDA, 2007; PRATES et al., 2007), which raises the questions of how the uplift and transport affect the productivity and ecology of fisheries resources, as well as cross-shore ocean/shelf connectivity with coral reefs.

Finally, despite the GLORYS12V1 product showing the deep vortex formation related to the blind canyons, the velocity field over the bottom topography from the product is known to be biased for deep current dynamics (see quality information document for GLORYS12V1 in https://marine.copernicus.eu/). Additionally, the ETOPO1 bathymetry used in the model does not allow for good resolution close to the slope and bottom boundary. Therefore, we should highlight the need to apply an ocean model with higher resolution at the bottom and the surface to further investigate the role the Pernambuco Plateau and the associated Gaibu High and blind canyons plays in changing deep current dynamics.

5. Summary and final considerations

In the present work we use *in situ* measurements, reanalysis product and dynamical scaling analysis to investigate upwelling and transport through blind canyons over the Southern Pernambuco Continental Shelf.

Thermohaline data indicated a difference in temperature between the upper (28°C) and the bottom (25.6°C) layers during the late spring, while a less vertical variation of temperature was observed during the early fall in the water column, with 29.6°C upper and 27.6° C in the bottom. In the late spring, the water column has low salinity in the well-mixed layer up to 20 m (36.4), which rises near 36.8 at 45 m depth, becoming unstable after 45 m depth. On the other hand, in the early fall, the salinity is higher (36.9), with greater variability in the first 15 m, maintaining the average without major changes after 15 m depth. CTD profiles also confirm seasonal variation and intrusion of water masses on the continental shelf, especially at the shelf-break within the Middle (Msv) and Campas (Csv) shelf valleys during the late spring. Moreover, a stepwise structure was observed indicating instability and stratification (variability of 2.7°C) with mixed layer depth (MLD) up to 32 and 20 m for Msv and Csv respectively, suggesting elevation of the thermocline and erosion of mixed layer. On other hand, during the fall, smaller temperature gradients (variability 1.6°C) were identified, where the MLD is weak in almost all observation points and highly variable between 20 m and 50 m depths. The stepwise structure is still observed between the surface layers up to 60 m, even though a small temperature difference. Therefore, we still have the intrusion of water masses over the shelf and shelf-break below the MLD with temperatures below 28.4°C within the SVs. In addition to the Isotherm presence (28.2°C) at 50 m on the slope and shelf at 30 m nearby the shelf-break (suggesting vertical transport) and high and well-mixed salinity throughout the entire water column in almost all CTD stations.

The morphological characteristics analysis showed two main seafloor bedforms which presents feature of deep and wide blind canyons at the Pernambuco Plateau, despite of exception in Bc3 (likely a submarine canyon), and those that show shelf valley characteristic or shallow and narrow channels over the continental shelf area. The blind canyons at the Pernambuco Plateau are 26-fold deeper at the shelf-break depth, 3-fold longer, and 110-fold wider than the SVs over the continental shelf. The calculated dimensionless parameters reveal a difference between the Rossby numbers of the canyons found on plateau and on the continental shelf. The highest Rossby values belong to the continental shelf, mainly in Zsv (R_0=130.87) and Csv (R_0=111.71) during the early fall (similar values), while the lowest belong to the plateau blind canyons (especially in Bc1). Thus, at the Pernambuco Plateau, the Rossby number is dominated by depth once the flow follows through the blind canyons. On other hand, with a high Burger and Rossby numbers, as seen in the shelf-break for B_u >> 1 (STUART; SUNDERMEYER; HEBERT, 2011), and for R_0 >> 1 (ALLEN AND HICKEY, 2010). This means we should expect a weak geostrophic balance at the canyon rim, and instability of the horizontal length scale of the pressure gradient force i.e., the flow tends to cross the blind canyon isobaths. The presence of an anti-cyclonic eddy observed in the reanalysis product shows the tendency of vorticity control over Bc2's mouth and favouring downwelling.

This work is the first effort to investigate the possibility of upwelling effect in response to blind canyons in the western tropical Atlantic boundary under the influence of the North Brazil Undercurrent. Here, we identified slope uplift not related to the blind canyons, and intrusion of water masses within the SVs. We suggest that the latter is a consequence of NBUC interaction with the SVs. Our results implicate, in some instance, the changing paradigm that shelf and coastal waters off north-eastern Brazil are mostly oligotrophic. This seems to be true only in the surface, which should be further considered with conscious in future works. We recommend the conscious choice of subsurface measurements against the commonly used, remote sense observation. Still, the region should benefit of more multiparameter measurements, such as nutrients, and chlorophyll at the slope to infer the impacts of the slope uplift. Due to the scope of our work, it was not possible to infer which mechanism is responsible for the uplift on the slope, although the chances are high that is a NBUC-slope driven mechanism. In addition to this, other seasonal aspects should be investigated, as our results are constrained to the late spring, early fall context. Lastly, research concerning the effects of internal waves propagation along the blind canyons, process-oriented regional modelling studies, and the evaluation of biologic implications to better understanding of dynamical interaction between physical and biogeochemical processes are underway.

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5 CONSIDERAÇÕES FINAIS

A integração dos principais resultados e conclusões é baseada no cumprimento dos objetivos e seus respectivos propósitos, anteriormente mencionados na estrutura da tese inserida no primeiro capítulo. Assim, conseguimos definir o cumprimento de cada objetivo pelo desenvolvimento dos capítulos.

Portanto, no primeiro capítulo temos a introdução dos estudos dos cânions submarinos como uma importante ferramenta para avaliar o comportamento dinâmico de submesoescala no litoral Nordeste do Brasil. Isso para cumprir o objetivo geral, o qual busca *estimar o potencial de levantamento e transporte de massas de água fria sobre a plataforma e borda da plataforma continental devido a presença de cânions submarinos ao longo da costa do Nordeste brasileiro*. Este capítulo apresenta pelo menos três informações necessárias para a compreensão do processo da dinâmica de fluxo em cânions, como: 1) as características morfológicas dos cânions submarinos, divididas em cânions submarinos comuns e cânions submarinos cegos; 2) Os diferentes tipos de processos em aspectos oceanográficos que podem ser gerados pela presença dos cânions submarinos; e 3) A interação fluxo-topografia (apresentada de maneira mais detalhada no terceiro capítulo), modificando as condições do meio e o desenvolvimento das comunidades locais no contexto de biodiversidade.

O segundo capítulo surge no cumprimento do segundo objetivo específico, o qual busca *relacionar, através de levantamento bibliográfico, a evolução das características dos estudos de cânions submarinos na América do Sul dentro do panorama global*. Entretanto, o capítulo foi mais além dessa proposta, pois foi verificado com um estudo de revisão para toda a América do Sul que os estudos com cânions submarinos estão se modificando ao longo dos anos. Também é observado uma diferença na distribuição espacial dos estudos com cânions e que essa distribuição está associada ao aspecto morfológico do tipo de margem continental, ou seja, mudança nos estudos inseridos na margem ativa e margem passiva. Paralelamente, foram evidenciados quatro focos principais dos estudos com cânions, divididos em seis especificidades por ordem de desenvolvimento ao longo do tempo: 1) Geodinâmicos (morfotectônicos, sistemas deposicionais e geohazards); 2) Físicos (interações hidrodinâmicas); 3 Biológicos (conhecimento das comunidades biológicas); e 4) Social (poluição). Cada foco é enquadrado dentro de um momento na construção da linha temporal dos estudos com cânions submarinos, porém uma das contribuições de destaque para o segundo capítulo é a relação entre a evolução dos estudos com cânions submarinos na América do Sul e os resultados propostos pela Década Oceânica.

O terceiro capítulo é apresentado no cumprimento do primeiro e terceiro objetivos específicos, os quais pretendem respectivamente *identificar regiões onde as condições dinâmicas apresentem indícios para o soerguimento de massas de água próximo a cânions submarinos, na Plataforma Continental Sul de Pernambuco* e *classificar, através da análise de escala, o comportamento dinâmico de massas de água e sua interação com a topografia de fundo próximo a região da quebra da plataforma continental, na costa Nordeste do Brasil*. Nesse capítulo é detalhado a interação fluxo-topografia representados respectivamente pela interação entre a Subcorrente Norte do Brasil ou NBUC (*North Brazil Undercurrent*) e a topografia de cânions submarinos cegos inseridos no Platô de Pernambuco. O objetivo foi investigar o efeito de bombeamento das massas de água centrais através de cânions cegos sobre a Plataforma Continental Sul de Pernambuco (PCSP), discernindo a interação entre a morfologia e os padrões de fluxo da fronteira oeste do Platô de Pernambuco até a quebra da plataforma. Como principais contribuições para esse capítulo podemos destacar: 1) Identificação dos cânions submarinos cegos do Platô de Pernambuco, alterando a direção do fluxo e favorecendo o transporte de massas d'água mais frias e salinas de área mais profundas no Platô de Pernambuco até a quebra da PCSP; 2) Variação sazonal e a intrusão de massas de água na plataforma continental, especialmente na quebra da plataforma nos vales das plataformas Médio (Msv) e Campas (Csv) durante o final da primavera; 3) Variação vertical indicando instabilidade e estratificação na profundidade de camada mista ou Mixed Layer Depth (MLD) para Msv e Csv, sugerindo elevação da termoclina e desaparecimento da MDL de superfície; 4) Valores dos números de Rossby e Burger mais elevados na região da quebra da plataforma, facilitando o transporte advectivo de massas d'água do platô para a plataforma, principalmente pela indução do fluxo através dos cânions submarinos cegos até os vales de plataforma.

Finalmente, podemos considerar que a principal contribuição desta tese foi elucidar a importância dos cânions submarinos e seus efeitos no ambiente e sociedade vistos através dos aspectos oceanográficos. A interação fluxo-topografia é um dos pontos chave para a descrição de processos que ocorrem no ambiente marinho costeiro, de maneira que a alteração de fluxo ou topografia irá ter efeitos nos mesmos. Além disso, cânions submarinos são modeladores de fluxo e servem como elo entre as áreas mais profundas e as mais rasas. Na região do litoral Nordeste do Brasil, temos a composição de dois fatores essenciais para tornar o ambiente ainda mais complexo, a presença da NBUC e os cânions submarinos cegos do platô. A composição desses fatores gera o ambiente fluxo-topografia ideal, induzindo o processo de bombeamento sazonal (maior intensidade no verão) de massas d'água mais frias e salinas das áreas mais profundas até as mais rasas, através da interação entre a NBUC e os cânions submarinos cegos do Platô de Pernambuco. Através desse resultado, temos a fertilização sazonal das águas do litoral Nordeste do Brasil, quebrando o paradigma de ambiente exclusivamente oligotrófico e colocando em pauta um viés diferente de discussão e desenvolvimento de trabalhos futuros para a nossa área, sejam esses relacionados aos cânions submarinos ou não.

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