FILIPE PEREIRA DOS SANTOS

Physical-biological interactions in the Brazil Current meanders

São Paulo | New Bedford

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Corrected version

Doctoral dissertation presented to the Oceanographic Institute of the University of São Paulo and the School for Marine Science & Technology of the University of Massachusetts Dartmouth in fulfillment of the requirements for receiving the degree of Doctor of Science, Dual Degree Ph.D. Program in Oceanography, concentration in Physical Oceanography — Marine and Atmospheric System Modeling and Analysis.

USP Advisor: Prof. Ilson C. A. da Silveira

UMass Dartmouth Advisor: Prof. Amit Tandon

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Ao sonho de liberdade e dignidade dos meus ancestrais.
Às Vovós Dudu e Chica, e Tia Santa.

To my ancestors' dream of freedom and dignity.
To Grandmas Dudu and Chica, and Aunt Santa.

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"*Èṣù pa ẹyẹ lánà pẹlú ọ̀ṣọ i òkúta lóní*"—"Exú matou um pássaro ontem com uma pedra que só lançou hoje"—esse provérbio iorubá define em grande parte como consegui chegar até este momento. Apesar de tudo, a vida me presenteou com pessoas que tem ajudado na luta contra a *Maafa* com atitudes antirracistas hoje.

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[1] A term of endearment used in Bahia, NE Brazil, to refer to one's mother in an affectionate way.
[2] Same as *Note 1* but to refer to one's father.

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"*A vós homens pretos, por honra de nossa raça, por glória de nossos avós que morreram no árduo trabalho de fazerem a fortuna pública e particular da nossa pátria, pedimos por tudo quanto mais caro que vos possa ser, educai-vos, educai vossos filhos, ensina-lhes o caminho da honra, o caminho do dever que tem por ponto de partida o trabalho e a instrução.*"

"To you black men, for the honor of our race, for the glory of our grandparents who died in the toil of making the public and private fortune of our homeland, we ask for everything that might be most dear to you, educate yourselves, educate your children, and teach them the path to honor, the path to duty, which has work and instruction as its starting point."[a]

(*O Progresso – Orgam dos Homens de Côr*, 24 August 1899, n. 1, p. 3)[b]

[a] Own translation.

[b] 11 years after the abolition of slavery in Brazil.

RESUMO

PEREIRA, Filipe. **Interações físico-biológicas nos meandros da Corrente do Brasil**. 2023. 140 f. Tese (Doutorado) – Instituto Oceanográfico, Universidade de São Paulo, São Paulo, SP, Brasil; e Escola para Ciência do Mar & Tecnologia, Universidade de Massachusetts Dartmouth, Nova Bedfórdia, MA, Estados Unidos.

Esta tese versa sobre a dinâmica básica dos meandros ciclônicos quase-estacionários de mesoescala da Corrente do Brasil e seu impacto na distribuição do plâncton no SE do Brasil. Os sistemas de ressurgência costeira na região promovem intrusões de águas ricas em nutrientes sobre a plataforma continental, facilitadas pela divergência costeira gerada pelos meandros. Realizamos experimentos num modelo quase-geostrófico (QG) de $1^1/_2$ camada baseado em dinâmica de contornos acoplado a um modelo Nutrientes-Fitoplâncton-Zooplâncton (NFZ). Os resultados sugerem que a atividade de mesoescala impacta as populações planctônica no SE do Brasil. Observações *in situ* desses fenômenos são escassas. Nós apresentamos um esforço amostral inédito que revelou processos de submesoescala nas bordas de um meandro. Mostramos que a biota responde a diferentes regimes dinâmicos em partes distintas da feição. Inspirados pelas observações, escolhemos construir uma hierarquia de modelos idealizados acoplados a um modelo NFZ para investigar interações físico-biológicas em mesoescala e submesoescala. Utilizamos um modelo QG de 2 camadas também baseado em dinâmica de contornos, mostrando que a estacionariedade dos meandros se deve à natureza quase puramente baroclínica desse sistema. A advecção lateral transporta águas enriquecidas para o oceano aberto, impactando os campos NFZ juntamente com a ressurgência de mesoescala. Em seguida, um modelo continuamente estratificado é utilizado para investigar a dinâmica de submesoescala. Os resultados sugerem que processos de submesoescala aumentam a heterogeneidade na distribuição do plâncton, com as áreas preferenciais de elevada atividade biológica mudando do centro do vórtice num experimento com 10 km de resolução para as bordas do vórtice num experimento de 1 km de resolução. Por fim, investigamos brevemente fortes vieses na temperatura da superfície do mar (TSM) durante eventos de ressurgência costeira.

Palavras-chave: Ciclones de mesoescala. Sudeste do Brasil. Instabilidade baroclínica. Correntes de contorno oeste. Corrente do Brasil. Interações físico-biológicas. Clorofila. Bombeamento vortical. Modelos idealizados. Dinâmica de contornos. MITgcm. Submesoescala. Modelo NFZ. TSM. Ressurgência costeira. Viés. Cabo de São Tomé. Cabo Frio.

ABSTRACT

PEREIRA, Filipe. **Physical-biological interactions in the Brazil Current meanders**. 2023. 140 pp. Doctoral dissertation – Oceanographic Institute, University of São Paulo, São Paulo, SP, Brazil; and School for Marine Science & Technology, University of Massachusetts Dartmouth, New Bedford, MA, United States.

This doctoral dissertation discusses the basic dynamics of the mesoscale cyclonic quasi-stationary meanders of the Brazil Current and their impact on plankton distribution off SE Brazil. The wind-driven coastal upwelling systems in the region promote intrusions of nutrient-rich waters onto the continental shelf, supported by coastal divergence induced by the meanders. We perform experiments in a $1^1/_2$-layer quasi-geostrophic (QG) model based on contour dynamics coupled to a Nutrients-Phytoplankton-Zooplankton (NPZ) model. The results suggest that mesoscale activity impacts the planktonic populations off SE Brazil. *In situ* observations of these phenomena are scarce. We present an unprecedented sampling effort that revealed submesoscale processes in a meander's rim. We show the biota responds to different dynamic regimes in distinct parts of the feature. Inspired by the observations, we choose to build a hierarchy of idealized models coupled to an NPZ model to investigate physical-biological interactions at mesoscale and submesoscale. We use a 2-layer QG model also based on contour dynamics, showing the meanders' stationarity is due to the almost pure baroclinic nature of this system. The lateral stirring transports enriched waters offshore, impacting the NPZ fields in addition to the eddy-induced upwelling. Then, a continuously stratified model is used to investigate submesoscale dynamics. The results suggest that submesoscale processes increase the heterogeneity in the NPZ distribution, with preferred areas for enhanced biological activity shifting from the eddy center in a 10 km resolution experiment to the eddy rim in a 1 km resolution experiment. Lastly, we briefly investigate strong biases in sea surface temperature (SST) during coastal upwelling events.

Keywords: Mesoscale cyclones. Southeastern Brazil. Baroclinic instability. Western boundary currents. Brazil Current. Physical-biological interactions. Chlorophyll. Eddy pumping. Idealized models. Contour dynamics. MITgcm. Submesoscale. NPZ model. SST. Coastal upwelling. Bias. Cape São Tomé. Cape Frio.

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Chapter 1

General Context

"I've known rivers:

Ancient, dusky rivers."

(*The Negro speaks of rivers. Hughes*, 1971)

Lateral buoyancy gradients—fronts—are ubiquitous in the upper ocean on several scales (*Mahadevan*, 2016), and present intense biological activity with a high abundance of marine organisms (*Olson et al.*, 1994; *Bakun*, 2006). The biota is strongly influenced by intense eddy fields associated with fronts (*e.g., Olson et al.*, 1994; *Lévy et al.*, 2012; *Mahadevan*, 2016; *McGillicuddy*, 2016; *Freilich et al.*, 2022). Such areas can be understood as sites where the physical system increases the biological system's trophic energy by driving each trophic level's productivity from the "minimal net gain" state present in the pelagic zone on a larger scale (*Bakun*, 2006).

The oceanic mesoscale, where motions are basically under the geostrophic balance, is typically characterized by Rossby numbers of $\mathcal{O}(0.1)$ and length scales of $\mathcal{O}(10\text{–}100\,\text{km})$ (*Cushman-Roisin & Beckers*, 2011, Chapter 1.7). *McGillicuddy* (2016) describes several mechanisms by which mesoscale eddies can influence the chlorophyll distribution in the upper ocean. Besides trapping and lateral transport of the planktonic communities within and by the eddies, some phenomena such as eddy pumping, eddy-wind interaction, and eddy impacts on the mixed layer depths, can modulate the planktonic growth rates, particularly due to nutrient and/or light availability. Additionally, the mesoscale strain and convergence lead to frontogenesis, generating submesoscale processes (*e.g., Mahadevan & Tandon*, 2006; *Mahadevan et al.*, 2008; *Mahadevan*, 2016; *Siegelman et al.*, 2020; *McWilliams*, 2021). At the submesoscale, we escape the geostrophic balance and hydrostatics weakens due to the characteristic Rossby and Richardson numbers of $\mathcal{O}(1)$, and length scales of $\mathcal{O}(1\text{–}10\,\text{km})$ in mid-latitudes (*Lévy et al.*, 2012). This allows for the development of much higher vertical velocities (*Mahadevan et al.*, 2008; *Ramachandran et al.*, 2014), whose timescales are expected to maximize phytoplankton responses (*Freilich et al.*, 2022).

Unlike its northern counterpart that bathes the wealthiest nations of the Global North, the South Atlantic has historically received much less scientific interest (*Commun. Earth*

Environ., 2022). Still, two areas in this ocean basin have garnered more attention from the international scientific community: the Brazil-Malvinas Confluence (∼50°W) and the Agulhas Retroflection (∼20°E). As highlighted by *Rocha & Simoes-Sousa* (2022), these two regions stand out as major hot spots of high eddy kinetic energy, i.e., enhanced mesoscale activity, in the South Atlantic. These authors, however, draw attention to a less studied region where a secondary maximum of eddy kinetic energy appears in the western boundary, between 20°S and 30°S.

The Atlantic continental margin of South America is characterized by an intricate system of western boundary currents, resulting from the multi-banded flow of the southern branch of the South Equatorial Current (*Luko et al.*, 2021) arriving at different latitudes and depths (*Piffer-Braga*, 2019; *Luko et al.*, 2021). Along the continental slope off southeastern Brazil, the Brazil Current serves as the western boundary current of the South Atlantic Subtropical Gyre, transporting warmer and saltier waters poleward at surface and pycnoclinic levels (*Stramma & England*, 1999). Beneath the Brazil Current, the Intermediate Western Boundary Current flows equatorward, carrying fresher and colder waters at depths up to 1000 m (*Böebel et al.*, 1999; *Silveira et al.*, 2004).

The presence of the São Paulo Plateau (22°S–28°S), a topographic feature that replaces the continental rise off Southeast Brazil and reduces the steepness of the continental slope at depths below 2000 m (*Souza & Sgarbi*, 2019), deflects the Deep Western Boundary Current—that transports the North Atlantic Deep Water poleward—further offshore (*cf. Luko et al.*, 2021, Figure 15). This results in a single velocity inversion on the continental slope, thereby forming a first-baroclinic-mode jet by the Brazil Current and the Intermediate Western Boundary Current, known as the BC-IWBC jet, extending from the surface to intermediate depths (*Silveira et al.*, 2008; *Biló et al.*, 2014; *Rocha et al.*, 2014).

The BC-IWBC jet presents strong mesoscale activity due to the change of the continental margin orientation in this region (*Silveira et al.*, 2004; *Calado et al.*, 2006, 2008, 2010). Large frontal meanders are frequently observed off Cape São Tomé (22°S), and Cape Frio (23°S). These features exhibit a quasi-stationary nature (*Garfield*, 1990; *Silveira et al.*, 2008) and are formed roughly 2–4 $year^{-1}$ (*Silveira* et al.*, 2023), eventually pinching off as cyclonic rings. Approximately 20% of the rings translate southwestward following the Brazil Current flow, but 2% may propagate northward (*Silveira* et al.*, 2023), occasionally reaching the latitude of 20°S (*Mill et al.*, 2015; *Silveira* et al.*, 2023). These meanders can evolve for

40–70 days reaching 40–80 km radii, on average (*Silveira* et al.*, 2023; *Uchoa et al.*, 2023). Given their geographical extension and temporal persistence, we expect these Brazil Current mesoscale features to condition the oligotrophic pelagic ecosystem off southeastern Brazil.

The region is also characterized by wind-driven coastal upwelling systems, active primarily during spring and summer, particularly off the two capes (*e.g., Castro & Miranda*, 1998; *Castelao & Barth*, 2006; *Franchito et al.*, 2008; *Dereczynski & Menezes*, 2015; *Chen et al.*, 2019; *Calil et al.*, 2021), and the southern flank of the Abrolhos Bank (19°S) (*Arruda & Silveira*, 2019). Archaeological records suggest that the biological productivity associated with these upwelling systems sustained indigenous populations in the area at least between 1600 and 1200 cal BP (*Macario et al.*, 2016). Although the geonym "*Cabo Frio*" (Cold Cape in English) first appeared in the nautical charts of the Portuguese invaders at the beginning of the 16th century (*Souza & Menezes*, 2011), the earliest scientific reports on the regionally low temperatures off Cape Frio date from the mid-1950s (*Allard*, 1955; *Emílsson*, 1956; *Silva*, 1957). Since then, several studies have investigated the physical mechanisms involved in the coastal upwelling phenomenon and its biological effects (*e.g., Emílsson*, 1961; *Ikeda et al.*, 1974; *Valentin et al.*, 1987; *Matsuura*, 1996; *Carbonel*, 1998; *Franchito et al.*, 2008; *Castelao*, 2012; *Carvalho-Batista et al.*, 2019).

A strong front with a temperature gradient of $\mathcal{O}(10°C)$ over 10 km emerges in the inner shelf during upwelling events in the vicinity of Cape Frio. A coastal jet then develops due to geostrophic adjustment (*Calil et al.*, 2021). The continental shelf narrows at 23°S, and because the Brazil Current can occupy the middle and external portions of the shelf (*Castro & Miranda*, 1998), interactions between the Brazil Current and the shelf waters may occur (*Calado et al.*, 2010; *Palóczy et al.*, 2014) (Figure 1.1).

Fronts are prone to the generation of submesoscale processes (*Mahadevan & Tandon*, 2006; *Mahadevan*, 2016). Such features can modulate exchanges between the continental shelf and the open ocean in the region. They can function as transport corridors (*García-Muñoz et al.*, 2004; *Zhang et al.*, 2023) of the newly-upwelled waters offshore, perhaps reaching the Brazil Current meanders (*Calado et al.*, 2010; *Calil et al.*, 2021). We expect submesoscale processes to play a crucial role in the ecology of the upper ocean off southeastern Brazil in addition to the mesoscale dynamics of the BC-IWBC jet. Also, pelagic particle exports in this region show drastic intra-seasonal fluctuations which have been linked to periodic instabilities of the Brazil Current (*Tura et al.*, 2021). Such instabilities might be the recurrent quasi-

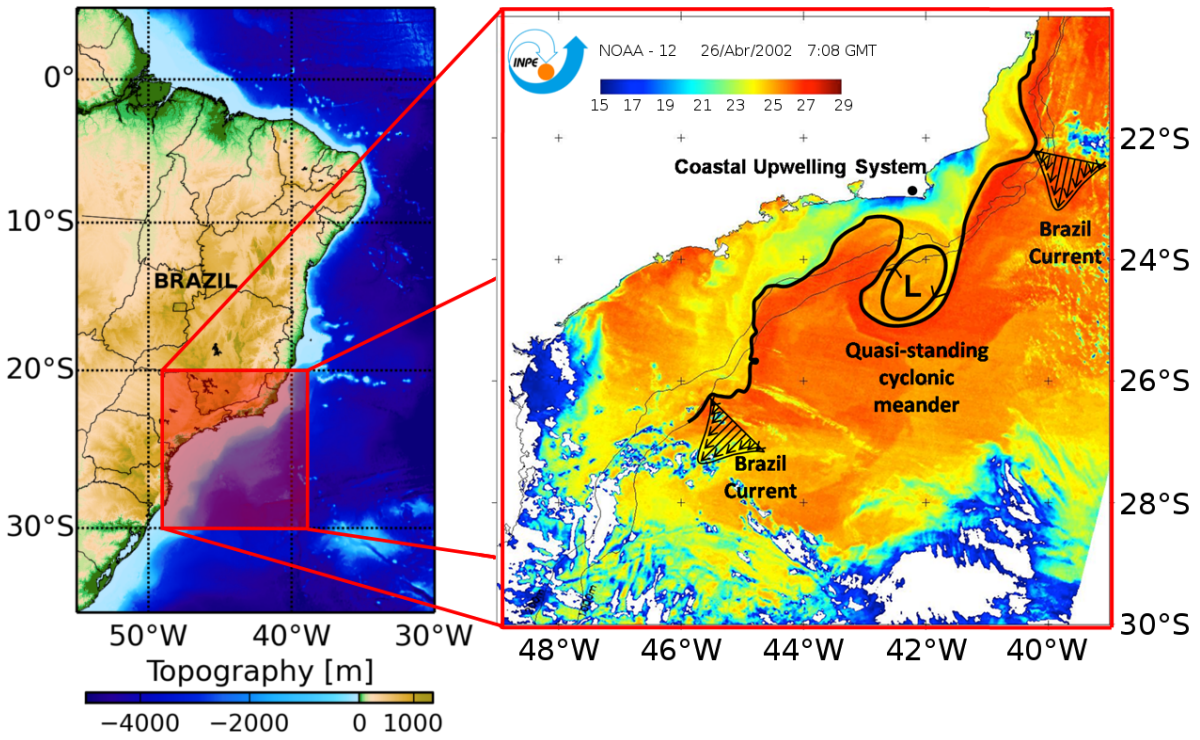

Figure 1.1: Dynamical scenario off southeastern Brazil. The location of its coastal upwelling zones, the Brazil Current, and its meanders. *Courtesy of Gilberto A. O. Watanabe*.

stationary meanders that can impact particle fluxes from the sunlit surface to depth (*Wang et al.*, 2022).

It is worth mentioning that the territorial sea between Cape Frio (23°S) and Vitória (20°S), known as the Campos Basin, is vital for the Brazilian economy. It holds an estimated 89% of the country's oil and gas reserves (*Bruhn et al.*, 2003) and is responsible for about one-third of the national production (*Petrobras*, 2014; *Rodrigues*, 2021). Unfortunately, offshore oil exploration in the Campos Basin caused a significant oil spill in 2011, releasing 3700 m^3 of oil (*Maianti et al.*, 2014; *Zacharias & Fornaro*, 2020; *Gouveia et al.*, 2021) whose environmental impacts were unclear (*Darlington*, 2011). Moreover, it comprises the occurrence range of the Brazilian sardines—*Sardinella brasiliensis* and *Opisthonema oglinum*—whose life cycles are intrinsically connected to the local oceanography (*Matsuura*, 1996; *Gouveia et al.*, 2017). Despite the collapse in the fishing industry (*Jablonski*, 2007), the sardines remain the most landed species (*DEPOP*, 2021; *FIPERJ*, 2021) and are of critical importance to local fishing communities (*Dallagnolo et al.*, 2010; *FIPERJ*, 2021).

Although the occurrence of meanders in the Brazil Current has been reported since the 1970s by *Mascarenhas Jr. et al.* (1971), *in situ* observations during such events are

scarce. Additionally, only a handful of studies have investigated physical-biological interactions in this region (*e.g., Yoshinaga et al.*, 2010; *Namiki et al.*, 2017; *Bonecker et al.*, 2019). Its strategic importance, in both societal and scientific aspects, highlights the need to improve our understanding of the circulation in the Campos Basin and, consequently, the associated physical-biological interactions. The primary objective of this doctoral dissertation is to investigate the basic mechanisms underlying the dynamics of the Brazil Current meanders off southeastern Brazil, including how mesoscale and submesoscale motions can affect the distribution of plankton. We will also propose mechanisms that link the Brazil Current and the continental shelf and briefly address problems related to the use of remote-sensing to monitor the Cape Frio upwelling system. The dissertation is structured as follows:

- In Chapter 2, we initially show that satellite observations of chlorophyll-a in the Brazil Current eddies drastically differ from summer to winter. We then build a quasi-geostrophic (QG) equivalent-barotropic model to study the eddy pinch-off from the Brazil Current coupled to a Nutrients-Phytoplankton-Zooplankton (NPZ) model and study scenarios where we mimic summer and winter conditions;

- In Chapter 3, we go to the sea and explore insights from an unprecedented sampling effort of a Brazil Current meander at the end of the spring of 2019 with one single line of measurements. We describe how the mesoscale and submesoscale motions affect the chlorophyll-a distribution across the transect;

- In Chapter 4, inspired by the observations and based on the literature, we systematically develop a suite of idealized models with increasing complexity coupled to an NPZ model to understand better the physical-biological interactions that may occur in mesoscale and submesoscale in the Brazil Current meanders;

- In Chapter 5, we show an attempt to investigate the Cape Frio upwelling system using Level 4 and Level 2 Sea Surface Temperature products. We demonstrate why this attempt was a failure by relating it to the intrinsic nature of the upwelling process;

- In Chapter 6, we wrap up with a summary and concluding remarks;

- Finally, in Chapter 7, we present abstracts of other scientific projects in which the candidate participated during their Ph.D., which are not necessarily related to the kernel of this dissertation.

Chapter 6

Summary and Closing Remarks

This doctoral dissertation aimed to investigate physical-biological interactions that may occur during meandering events of the Brazil Current as it past capes off southeastern Brazil. The drastic change of the continental margin direction between Cape São Tomé (22°S) and Cape Frio (23°S) leads to the formation of these quasi-stationary perturbations primarily driven by baroclinic instability. Coastal upwelling systems can be active over the continental shelf whose enriched waters can be entrained by the meanders. Therefore, these conspicuous mesoscale features can contribute to fertilizing the western boundary of the oligotrophic subtropical gyre.

We first sought a theoretical approach as a starting point for our studies based on surface chlorophyll-a satellite images of the Brazil Current eddies in winter and summer. We used an idealized Brazil Current structure in a $1^1/_2$-layer contour dynamics model coupled to a simple Nutrients-Phytoplankton-Zooplankton (NPZ) model and imposed different mixed layer depths for winter (deeper) and summer (shallower) to mimic the seasonality. Our goal was to study the eddy necking-off process with the simplest dynamics possible. Our experiments evolved into a special case, already reported in the literature, where the rings pinch off and propagate upstream. The biological model results showed that deeper mixed layers, hence higher nutrient availability, induce stronger responses in the NPZ fields which correspond to the satellite images during winter where we find stronger signals of surface chlorophyll-a when compared to summertime images.

The conceptual ideas brought from this initial theoretical study could be broadened by the unique opportunity of the ILHAS 3 cruise, where we could survey an eddy off Cape São Tomé at the end of the spring of 2019. The satellite images showed a belt of high surface chlorophyll-a along the meander's rim. We designed an experiment that unveiled new perspectives on the physical processes acting in the plankton distribution. Despite the technological limitations, we presented the more detailed and complete survey on record, showing the first direct measurements of velocities in a Brazil Current quasi-stationary meander. Our results suggest that the meander was compressed against the continental slope and indeed entrained

shelf water.

The relatively high horizontal resolution of the transect revealed convex-shaped isopycnal distortions in the meander's edges that deviate from the expected cyclonic signature. We interpreted such features as the signature of submesoscale filaments enveloping the meander. Although downstream responses could not be assessed, the filament clearly impacted phytoplankton distribution across the transect as cross-isopycnal upward ejections of chlorophyll were captured. Still, we unequivocally identify that eddy pumping drove the chlorophyll response in the eddy center with a prominent deep chlorophyll maximum identified below the mixed layer, a distinct scenario from the one anticipated by the satellite image.

Our findings suggest that chlorophyll distribution across the meander can be related to different dynamic regimes in different parts of the meander, namely: eddy stirring within the mixed layer, eddy pumping at subsurface below the mixed layer, and intense vertical velocities agitating the meander's periphery due to submesoscale processes. We also hypothesized that less stratified water columns and deeper mixed layers in winter could facilitate the eddy pumping signature in chlorophyll to cross the mixed layer base and reach the surface, which could explain why satellite-derived surface chlorophyll-a is higher in wintertime compared to summer conditions.

Later, we took advantage of the known first baroclinic mode structure of the western boundary current system off southeastern Brazil to develop a two-layer quasi-geostrophic model, also based on the contour dynamics technique and coupled to a modified NPZ model. Here we sought to take a step back and investigate the formation of the quasi-stationary meanders and the associated lateral stirring effect on the NPZ fields. Our simple model was able to induce baroclinic instability and could represent the quasi-stationary behavior during the meander's growth, which we attributed to the almost pure first baroclinic mode structure of the jet composed by the Brazil Current and the Intermediate Western Boundary Current in mean terms. The NPZ model results showed that an enriched western boundary acted as a source of tracers to the model's domain due to lateral advection shown by a tongue of higher concentration along the northern edge of the simulated meander, in addition to the plankton growth due to the mixed layer shallowing due to eddy-induced upwelling within the meander.

Of course, the QG model had severe limitations and was unable to represent submesoscale processes that the observations showed to be relevant. We then built upon the two-layer structure using the equivalence between a two-layer system and one continuously

stratified truncated to the barotropic and first baroclinic modes. This system was solved using a primitive equation model used to force the same modified NPZ model. Two experiments were performed: one with a 10 km horizontal resolution, which corresponds to roughly a third of the first baroclinic deformation radius off southeastern Brazil and is coarse enough to resolve basically the mesoscale dynamics; and one with a 1 km horizontal resolution expected to resolve the upper limit of the submesoscale dynamics.

The 10 km resolution experiment had an overall behavior similar to the two-layer model. The Rossby number, Ro, was generally small so we reproduced mesoscale processes. The 1 km resolution experiment evolved into a profusion of smaller-scale eddies and filaments along the meander's rim with submesoscale cyclones and anticyclones identified by spots of high Ro in the mixed layer. The meander dynamics strongly influenced the NPZ tracers' distribution. Our results showed a shift in the areas of the meander where we found higher biological activity: the eddy center in 10 km resolution experiment, whereas, in the 1 km resolution experiment, the meander's periphery showed higher activity.

Lastly, we attempted to investigate the frontal dynamics of the Cape Frio Upwelling System using Level 4 and Level 2 Sea Surface Temperature (SST) satellite products since the Brazil Current can takeover the middle and inner shelf and then interact with the coastal upwelling systems, particularly during meandering events. However, the satellite-derived SST had discrepancies in both the magnitude and temporal variability when compared to *in situ* observations. We found strong biases, of $\sim$4°C, during upwelling events which hinder the use of L2, and especially L4 products, to study the coastal upwelling.

This dissertation presents a comprehensive set of studies aimed at investigating the physical-biological processes in the Brazil Current quasi-stationary meanders. Our research demonstrates that despite simple, idealized models can prove to be remarkably beneficial in gaining insight into oceanographic processes and in inspiring ideas for the design of field experiments. Specifically, the continuously stratified model of the quasi-stationary meanders holds promise as a tool for examining both physical and biological processes in this system, provided appropriate modifications are incorporated in the future. We hope our findings have highlighted the vast array of interdisciplinary problems that remain to be explored off southeastern Brazil.

"Simplicity is the ultimate sophistication"

(*Gaddis*, 1955, p. 457)

Chapter 7

Collaborations

7.1 Publications

Effects of the seasonality of mesoscale eddies on the planktonic dynamics off eastern Brazil

Published in **Dynamics of Atmospheres and Oceans** (2022). Co-authored by Caique D. Luko, **Filipe Pereira**, Ilson C. A. da Silveira, Amit Tandon, and Glenn R. Flierl. DOI: 10.1016/j.dynatmoce.2022.101299.

Abstract:

The South Equatorial Current's southern branch (SSEC) reaches the Brazilian continental margin through several bands between 30°S and 10°S. As the SSEC 14°S band reaches the Brazilian continental margin, it bifurcates into the poleward-flowing Brazil Current (BC), and the surface portion of the equatorward-flowing North Brazil Undercurrent (NBUC). Some semi-permanent eddies are formed in association with the bifurcation, and their variability is controlled by the seasonality of the SSEC bands. This work aims to investigate the role of the seasonality of these mesoscale eddies on the regional phytoplanktonic dynamics. We analyze chlorophyll-a satellite observations and perform two experiments using a Nutrients–Phytoplankton–Zooplankton (NPZ) model coupled to a $1^1/_2$-layer quasi-geostrophic model. The results show that the phytoplankton annual cycle off eastern Brazil is mainly controlled by the seasonally varying advection of material offshore caused by the mesoscale eddies. Such a mechanism may represent an important source of material to the tropical oligotrophic ocean.

Keywords: Physical-biological interactions. Eastern Brazilian coast. Mesoscale eddies. Eddy stirring. Surface chlorophyll. Upper ocean.

Mixed layer eddies supply nutrients to enhance the spring phytoplankton bloom

Published in **Frontiers in Marine Science** (2022). Co-authored by Iury T. Simoes-Sousa, Amit Tandon, **Filipe Pereira**, Cauê Z. Lazaneo, and Amala Mahadevan.
DOI: 10.3389/fmars.2022.825027

Abstract:

Mixed layer eddies resulting from baroclinic instability of fronts convert horizontal buoyancy gradients into vertical stratification, shoaling the mixed layer. In light-limited regimes – high-latitudes – this process can initiate phytoplankton blooms prior to the springtime warming. The question is whether mixed layer eddies can enhance the spring bloom by delivering nutrients from beneath the mixed layer. We couple a submesoscale-resolving model (SUB) with a simple ecosystem model and examine the role of mixed layer eddies on the development of the spring bloom. We compare the SUB simulation to two coarser resolution (10km) simulations, one that includes a mixed layer eddy parameterization (MLE) and another that prescribes the restratification from SUB and advects the biogeochemical tracers using geostrophic velocities (NVF). The MLE simulates restratification of the mixed layer and bloom onset, but the spring bloom has a deficit of 10–13% in the new production compared to SUB. The NVF has the same restratification as SUB, and with no vertical flux of nutrients, leads to a spring bloom with a 32–40% new production deficit compared to SUB. Submesoscale processes lead to exchange across the mixed layer base, which is not represented in coarse resolution model simulations, even with mixed layer eddy parameterizations. Our results show that nutrients supplied by mixed layer eddies are important to enhance the spring bloom.

Keywords: Submesoscale. Nutrient fluxes. Phytoplankton. Vertical transport. Upper ocean. Mixed layer. Eddy parameterization. Restratification.

The Brazil Current quasi-stationary unstable meanders at 22°S–23°S

Published in **Progress in Oceanography** (2023). Co-authored by: Ilson C. A. da Silveira[1], **Filipe Pereira**[1], Glenn R. Flierl, Iury T. Simoes-Sousa, André Palóczy, Milton Borges-Silva, and César B. Rocha.

DOI: 10.1016/j.pocean.2022.102925

Abstract:

The most conspicuous oceanographic features off Southeastern Brazil are the quasi-stationary eddies formed off Capes São Tomé (CSTE) and Frio (CFE) associated with the Brazil Current (BC). We use SST and SSH products to infer eddy growth rates. These two independent data sets reveal an average growth rate of 0.06 day^{-1}, and propagation speeds are virtually null. CFE tends to be more unstable and frequent than CSTE (3.5 vs. 2.3 events per year). CSTE can propagate toward the north or south while CFE only propagates southward. We perform potential vorticity (PV) inversion calculation using hydrographic data to understand how the meander growth occurs in the baroclinic jet formed by the BC and the Intermediate Western Boundary Current (IWBC). PV anomalies in one layer enhanced the anomalies on the other. This result offered in situ evidence of baroclinic conversion occurring during the eddy event captured in the observations. We then build a theoretical two-layer model calibrated with the observations seeking to explain why the eddies grow in place, and no accompanying unstable anticyclones are formed. The experiments lead us to conclude that the eddies' quasi-stationarity is due to the almost pure baroclinic nature of the BC-IWBC jet. We also find that the western boundary inhibits the formation of anticyclones. As observed in satellite imagery, the meanders develop as isolated disturbances that may grow simultaneously or not.

Keywords: Brazil Current. Baroclinic instability. Mesoscale eddies. Western boundary currents. Conservation of potential vorticity. Contour dynamics. South Atlantic. Cape Frio. Cape São Tomé.

[1]Contributed equally to this work and share the first authorship.

Topographically-generated submesoscale shear instabilities associated with Brazil Current meanders

Published in **Journal of Physical Oceanography** (2023). Co-authored by: Caique D. Luko, Cauê Z. Lazaneo, Ilson C. A. da Silveira, **Filipe Pereira** and Amit Tandon.
DOI: 10.1175/JPO-D-22-0122.1

Abstract:

The western boundary current system off southeastern Brazil is composed of the poleward flowing Brazil Current (BC) in the upper 300 m and the equatorward flowing Intermediate Western Boundary Current (IWBC) underneath it, forming a first-baroclinic mode structure in the mean. Between 22°S and 23°S, the BC-IWBC jet develops recurrent cyclonic meanders that grow quasi-stationarily via baroclinic instability, though their triggering mechanisms are not yet well understood. Our study thus aims to propose a mechanism that could initiate the formation of these mesoscale eddies by adding the submesoscale component to the hydrodynamic scenario. To address this, we perform a regional 2-km resolution numerical simulation using CROCO (Coastal and Regional Ocean COmmunity model). Our results indicate that incoming anticyclones reach the slope upstream of separation regions and generate submesoscale barotropic shear instability that triggers the meanders' formation. Subsequently, this process generates submesoscale cyclones that contribute, along with baroclinic instability, to the meanders' growth resulting in a submesoscale-to-mesoscale inverse cascade. Lastly, as the mesoscale cyclones grow, they interact with the slope generating inertially and symmetrically unstable anticyclonic submesoscale vortices and filaments.

Keywords: Brazil Current. Mesoscale cyclones. Cape São Tomé. Cape Frio. Barotropic instability. Baroclinic instability. Symmetric instability. Inertial instability. Submesoscale coherent vortices. Inverse cascade.

7.2 Mentorship

B.Sc. Thesis: Physical-biological interactions in the mesoscale features of the northern branch of the South Equatorial Current Bifurcation (2019)

Student: Caique D. Luko; Advisors: Prof. Ilson C. A. da Silveira, Prof. Amit Tandon, Prof. Glenn R. Flierl, **Filipe Pereira**.

Abstract:

The large-scale circulation in the South Atlantic Ocean is characterized by a large anticyclonic gyre, and the current that limits this gyre to the north is the South Equatorial Current (SEC). When the southern branch of the SEC reaches the Brazilian continental margin, this current bifurcates. The most known patterns regarding the South Equatorial Current Bifurcation (SECBi) are of large scale. In the upper ocean, the mesoscale patterns are best known in the southern branch of the SECBi, which is associated with the formation of the Brazil Current. There are no studies on the mesoscale activity associated with the northern branch of the surface layer SECBi or on the physical-biological interactions within these mesoscale structures. This work aims to characterize the mesoscale structures associated with the surface layer SECBi northern branch as well as the effect of these structures on the dynamics of the phytoplankton and the zooplankton. To accomplish that, we analyze: i) the mesoscale structures climatological patterns and annual cycle using data from altimetric satellites; and ii) the results of a Nutrients-Phytoplankton-Zooplankton (NPZ) forced by a 1 1 / 2 layer hydrodynamical model under quasi-geostrophic approximation. We show that the mesoscale activity of the SECBi northern branch occurs as an elliptical cyclone with a climatological signature in autumn and winter (Aracaju Cyclone), and an anticyclone with an annual climatological signature that is formed by the SEC meandering over the Stocks Seamounts (Stocks Anticyclone). These mesoscale structures cause an increase in chlorophyll-a concentration in the region during autumn and winter by combined effects of the advection of material from the coast and the variations in the mixed layer thickness on the NPZ dynamics.

B.Sc. Thesis: Comparison of chemosynthetic primary production around the Vitória-Trindade Ridge, Cape São Tomé and Cape Frio, Southwest Atlantic Ocean (2022)

Student: Beatriz R. Pinheiro; Advisors: Prof. Camila N. Signori, **Filipe Pereira**.

Abstract:

The Brazilian coast is dominated by several oceanographic phenomena that have the potential to cause upwelling. The interaction of the southern branch of the South Equatorial Current with the seamounts of the Vitória-Trindade Seamount Ridge, the Cape São Tomé eddy, and the coastal upwelling in Cape Frio can increase the chemosynthetic primary productivity of these regions due to the elevation of the isopycnal and the supply of nutrients to the euphotic zone. The main objectives of this study were to compare chemosynthesis in the epipelagic zone (0–200 m) of the three areas and, to evaluate the distribution of chemosynthesis throughout the water column in the Vitória-Trindade Seamount Chain (0–2900 m) and the Cape São Tomé eddy (60–500 m). The samples were collected in February 2017 and December 2019 onboard the R/V *Alpha Crucis*. Water samples were collected using Niskin bottles coupled to the CTD-Rosette system. The chemosynthesis was measured with the radioisotope ^{14}C-bicarbonate and temperature, salinity, dissolved oxygen, fluorescence, and inorganic nutrients were also collected. Throughout the water column, chemosynthesis rates varied between 0.001 and 0.57 μg C L^{-1} h^{-1}. In the euphotic zone, the highest rate of 0.34 μg C L^{-1} h^{-1} was found at 5 m in Cape Frio. Considering the vertical profile, the chemosynthesis rates in the VTR and CSTE were higher in the meso- and bathypelagic, with values reaching 0.57 μg C L^{-1} h^{-1} at 120 m and 0.48 μg C L^{-1} h^{-1} 1500 m. Chemosynthesis showed no significant correlation with temperature, salinity, dissolved oxygen, and inorganic nutrients, which may be an indication that there was a mixing of isopycnal. With this, it can be concluded that the chemosynthesis rates of the three regions respond in different ways to the three oceanographic processes that depend on the vertical velocities. Although the chemosynthetic rates found in this work are relatively low when compared to other oceanic regions, such as the North Atlantic, and typical environments, it is recommended to include this process in quantitative studies of total primary production and for a better understanding of the marine Carbon cycle.

References

Adcroft, A., C. Hill, J.-M. Campin, J. Marshall, & P. Heimbach (2004), Overview of the formulation and numerics of the MIT GCM, in *Proceedings of the ECMWF Seminar Series on Numerical Methods, Recent Developments in Numerical Methods for Atmosphere and Ocean Modelling*, pp. 139–149.

Allard, P. (1955), Anomalies dans le temperature de l'eau de la mer observeés au Cabo Frio au Brésil, *Bulletin d'Information du Comité Central d'Océanographie et d'Étude de Cótes*, *7*(2), 58–63.

Armstrong, F. A. J., C. R. Stearns, & J. D. H. Strickland (1967), The measurement of upwelling and subsequent biological process by means of the Technicon Autoanalyzer® and associated equipment, *Deep Sea Research and Oceanographic Abstracts*, *14*(3), 381–389, doi:10.1016/0011-7471(67)90082-4.

Arruda, W. Z., & I. C. A. d. Silveira (2019), Dipole-induced Central Water extrusions south of Abrolhos Bank (Brazil, 20.5°S), *Continental Shelf Research*, *188*, 103,976, doi:10.1016/j.csr.2019.103976.

Bakun, A. (2006), Fronts and eddies as key structures in the habitat of marine fish larvae: Opportunity, adaptive response and competitive advantage, *Scientia Marina*, *70*(S2), 105–122, doi:10.3989/scimar.2006.70s2105.

Biló, T. C., I. C. A. d. Silveira, W. C. Belo, B. M. de Castro, & A. R. Piola (2014), Methods for estimating the velocities of the Brazil Current in the pre-salt reservoir area off Southeast Brazil (23°S – 26°S), *Ocean Dynamics*, *64*(10), 1431–1446, doi:10.1007/s10236-014-0761-2.

Böebel, O., R. E. Davis, M. Ollitraut, R. G. Peterson, P. L. Richard, C. Schmid, & W. Zenk (1999), The intermediate depth circulation of the Western South Atlantic, *Geophysical Research Letters*, *26*(21), 3329–3332, doi:10.1029/1999GL002355.

Bonecker, A. C. T., M. Katsuragawa, M. S. Castro, C. Namiki, M. L. Zani-Teixeira, I. Uchoa, & I. C. A. d. Silveira (2019), Seasonal variability of ichthyoneuston assemblage on the continental shelf and slope of the southwest atlantic ocean, brazil (20°–23°s), *Journal of Applied Ichthyology*, *35*(3), 655–671, doi:10.1111/jai.13890.

Bouali, M., O. T. Sato, & P. S. Polito (2017), Temporal trends in sea surface temperature gradients in the South Atlantic Ocean, *Remote Sensing of Environment*, *194*, 100–114, doi:10.1016/j.rse.2017.03.008.

Bouali, M., P. S. Polito, O. T. Sato, & J. Vazquez-Cuervo (2019), On the use of NLSST and MCSST for the study of spatio-temporal trends in SST gradients, *Remote Sensing Letters*, *10*(12), 1163–1171, doi:10.1080/2150704X.2019.1666312.

Brandini, F. P., P. M. Tura, & P. P. G. M. Santos (2018), Ecosystem responses to biogeochemical fronts in the South Brazil Bight, *Progress in Oceanography*, *164*, 52–62, doi:10.1016/j.pocean.2018.04.012.

Bruhn, C. H. L., J. A. T. Gomes, C. Del Lucchese Jr., & P. R. S. Johann (2003), Campos Basin: Reservoir characterization and management – Historical overview and future challenges, in *Proceedings of the Offshore Technology Conference*, Houston, United States, doi:10.4043/15220-MS.

Buckingham, C. E., A. C. Naveira Garabato, A. F. Thompson, L. Brannigan, A. Lazar, D. P. Marshall, A. J. George Nurser, G. Damerell, K. J. Heywood, & S. E. Belcher (2016), Seasonality of submesoscale flows in the ocean surface boundary layer, *Geophysical Research Letters*, *43*(5), 2118–2126, doi:10.1002/2016GL068009.

Buckingham, C. E., J. Gula, & X. Carton (2021), The role of curvature in modifying frontal instabilities. Part I: Review of theory and presentation of a nondimensional instability criterion, *Journal of Physical Oceanography*, *51*(2), 299–315, doi:10.1175/JPO-D-19-0265.1.

Calado, L., A. Gangopadhyay, & I. C. A. d. Silveira (2006), A parametric model for the Brazil Current meanders and eddies off Southeastern Brazil, *Geophysical Research Letters*, *33*(12), doi:10.1007/s10236-019-01307-w.

Calado, L., A. Gangopadhyay, & I. C. A. d. Silveira (2008), Feature-oriented regional modeling and simulations (FORMS) for the western South Atlantic: Southeastern Brazil region, *Ocean Modelling*, *25*(1), 48–64, doi:10.1016/j.ocemod.2008.06.007.

Calado, L., I. C. A. d. Silveira, A. Gangopadhyay, & B. M. Castro (2010), Eddy-induced upwelling off Cape São Tomé (22°S, Brazil), *Continental Shelf Research*, *30*(10), 1181–1188, doi:10.1016/j.csr.2010.03.007.

Calil, P. H. R., N. Suzuki, B. Baschek, & I. C. A. d. Silveira (2021), Filaments, fronts and eddies in the Cabo Frio Coastal Upwelling System, Brazil, *Fluids*, *6*(2), 54, doi:10.3390/fluids6020054.

Campos, E. J. D., J. E. Gonçalves, & Y. Ikeda (1995), Water mass characteristics and geostrophic circulation in the South Brazil Bight: Summer of 1991, *Journal of Geophysical Research: Oceans*, *100*(C9), 18,537–18,550, doi:10.1029/95JC01724.

Campos, E. J. D., Y. Ikeda, B. M. Castro, S. A. Gaeta, J. A. Lorenzzetti, & M. R. Stevenson (1996), Experiment studies circulation in the Western South Atlantic, *Eos, Transactions, American Geophysical Union*, *77*(27), 253–259, doi:10.1029/96EO00177.

Campos, E. J. D., D. Velhote, & I. C. A. d. Silveira (2000), Shelf break upwelling driven by Brazil Current cyclonic meanders, *Geophysical Research Letters*, *27*(6), 751–754, doi:10.1029/1999GL010502.

Capuano, T. A., S. Speich, X. Carton, & B. Blanke (2018), Mesoscale and submesoscale processes in the Southeast Atlantic and their impact on the regional thermohaline structure, *Journal of Geophysical Research: Oceans*, *123*(3), 1937–1961, doi:10.1002/2017JC013396.

Carbonel, C. (1998), Modelling of upwelling in the coastal area of Cabo Frio (Rio de Janeiro-Brazil), *Revista Brasileira de Oceanografia*, *46*(1), 01–17, doi:10.1590/S1413-77391998000100001.

Carvalho-Batista, A., J. A. F. Pantaleão, A. L. Castilho, & R. C. d. Costa (2019), The Cabo Frio upwelling overrides geographical patterns in the population dynamics of the shrimp *Artemesia longinaris* Spence Bate, 1888 (Decapoda: Penaeidae), *Marine Ecology*, *40*(2), e12,534, doi:10.1111/maec.12534.

Castelao, R. M. (2012), Sea surface temperature and wind stress curl variability near a cape, *Journal of Physical Oceanography*, *42*(11), 2073–2087, doi:10.1175/JPO-D-11-0224.1.

Castelao, R. M., & J. A. Barth (2006), Upwelling around Cabo Frio, Brazil: The importance of wind stress curl, *Geophysical Research Letters*, *33*(3), doi:10.1029/2005GL025182.

Castro, B. M., & L. B. Miranda (1998), Physical oceanography of the Western Atlantic Continental Shelf located between 4°N and 34°S, in *The Sea*, edited by A. R. Robinson & K. H. Brink, 11 ed., cap. 8, pp. 209–251, John Wiley and Sons, New York, United States.

Cerda, C., & B. M. Castro (2014), Hydrographic climatology of South Brazil Bight shelf waters between São Sebastião (24°S) and Cabo São Tomé (22°S), *Continental Shelf Research*, *89*, 5–14, doi:10.1016/j.csr.2013.11.003.

Chao, Y., Z. Li, J. D. Farrara, & P. Hung (2009), Blending sea surface temperatures from multiple satellites and *in situ* observations for coastal oceans, *Journal of Atmospheric and Oceanic Technology*, *26*(7), 1415–1426, doi:10.1175/2009JTECHO592.1.

Chen, D., A. J. Busalacchi, & L. M. Rothstein (1994), The roles of vertical mixing, solar radiation, and wind stress in a model simulation of the sea surface temperature seasonal cycle in the Tropical Pacific Ocean, *Journal of Geophysical Research: Oceans*, *99*(C10), 20,345–20,359.

Chen, H.-H., Y. Qi, Y. Wang, & F. Chai (2019), Seasonal variability of SST fronts and winds on the southeastern continental shelf of Brazil, *Ocean Dynamics*, *69*(11-12), 1387–1399, doi:10.1007/s10236-019-01310-1.

Chin, T. M., J. Vazquez-Cuervo, & E. M. Armstrong (2017), A multi-scale high-resolution analysis of global sea surface temperature, *Remote Sensing of Environment*, *200*, 154–169, doi:10.1016/j.rse.2017.07.029.

Commun. Earth Environ. (2022), Ocean science in the South Atlantic, `https://www.nature.com/collections/aiaehjdjcb`, accessed: 2023-03-05.

Cushman-Roisin, B., & J.-M. Beckers (2011), *Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects*, *International Geophysics Series*, vol. 101, 2 ed., 875 pp., Academic Press.

Dallagnolo, R., P. R. Schwingel, & J. A. A. Perez (2010), Estimativas de produção anual de sardinha-verdadeira (*Sardinella brasiliensis*) em Santa Catarina: Um modelo de projeção de capturas a partir dos padrões mensais de desembarque no estado, *Brazilian Journal of Aquatic Science and Technology*, *14*(2), 95–104, doi:10.14210/bjast.v14n2.p95-104.

Darlington, S. (2011), Brazilian police probe Chevron oil spill, `https://www.cnn.com/2011/11/17/world/americas/brazil-chevron-spill/index.html`, accessed: 2022-08-16.

de Boyer Montégut, C., G. Madec, A. S. Fischer, A. Lazar, & D. Iudicone (2004), Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, *Journal of Geophysical Research: Oceans*, *109*(C12), doi:10.1029/2004JC002378.

DEPOP (2021), Relatório final do Comitê Científico de Avaliação das Medidas de Gestão Aplicadas à Pesca de Cerco/Traineira da Sardinha-verdadeira (*Sardinella brasiliensis*) e da Sardinha-laje (*Opisthonema oglinum*).

Dereczynski, C. P., & W. F. Menezes (2015), Meteorologia da Bacia de Campos, in *Meteorologia e Oceanografia: Caracterização Ambiental Regional da Bacia de Campos, Atlântico Sudoeste*, vol. 2, edited by R. P. Martins & G. S. Grossmann-Matheson, cap. 1, pp. 1–54, Elsevier, Rio de Janeiro, Brazil, doi:10.1016/B978-85-352-6208-7.50008-8.

Dufois, F., P. Penven, C. P. Whittle, & J. Veitch (2012), On the warm nearshore bias in Pathfinder monthly SST products over Eastern Boundary Upwelling Systems, *Ocean Modelling*, *47*, 113–118, doi:10.1016/j.ocemod.2012.01.007.

Edwards, A. M., & J. Brindley (1996), Oscillatory behaviour in a three-component plankton population model, *Dynamics and Stability of Systems*, *11*(4), 347–370, doi:10.1080/02681119608806231.

Emílsson, I. (1956), *Relatório e Resultados Físico-químicos de Três Cruzeiros Oceanográficos em 1956*, 1, 1–70 pp., Contruções Instituto Oceanográfico, Universidade de São Paulo, série Oceanografia Física.

Emílsson, I. (1961), The shelf and coastal waters off Southern Brazil, *Boletim do Instituto Oceanográfico*, *11*(2), 101–112, doi:10.1590/S0373-55241961000100004.

Falkowski, P. G., D. Ziemann, Z. Kolber, & P. K. Bienfang (1991), Role of eddy pumping in enhancing primary production in the ocean, *Nature*, *352*(6330), 55–58, doi:10.1038/352055a0.

Fanton d'Andon, O., A. Mangin, S. Lavender, D. Antoine, S. Maritorena, A. Morel, G. Barrot, J. Demaria, & S. Pinnock (2009), GlobColour – the European Service for Ocean Colour, in *Proceedings of the 2009 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, IEEE Geoscience and Remote Sensing Society, IEEE, Cape Town, South Africa.

FIPERJ (2021), Relatório Anual, *Fundação Instituto de Pesca do Estado do Rio de Janeiro. Governo do Estado do Rio de Janeiro, Brasil*.

Firing, E. (1995), Processing ADCP data with the CODAS software system version 3.1, *Joint Institute for Marine and Atmospheric Research, University of Hawai'i & National Oceanographic Data Center.*

Flierl, G. R. (1978), Models of vertical structure and the calibration of two-layer models, *Dynamics of Atmospheres and Oceans*, *2*(4), 341–381, doi:10.1016/0377-0265(78)90002-7.

Flierl, G. R. (1999), Thin jet and contour dynamics models of Gulf Stream meandering, *Dynamics of Atmospheres and Oceans*, *29*(2-4), 189–215, doi:https://doi.org/10.1016/S0377-0265(99)00006-8.

Flierl, G. R., & C. S. Davis (1993), Biological effects of Gulf Stream meandering, *Journal of Marine Research*, *51*(3), 529–560, doi:10.1357/0022240933224016.

Flierl, G. R., & D. J. McGillicuddy (2002), Mesoscale and submesoscale physical-biological interactions, in *The Sea*, edited by A. R. Robinson, J. J. McCarthy, & B. J. Rothschild, cap. 4, pp. 113–185, John Wiley & Sons, New York, United States.

Franchito, S. H., T. O. Oda, V. B. Rao, & M. T. Kayano (2008), Interaction between coastal upwelling and local winds at Cabo Frio, Brazil: An observational study, *Journal of Applied Meteorology and Climatology*, *47*(6), 1590–1598, doi:10.1175/2007JAMC1660.1.

Franks, P. J. S. (2002), NPZ models of plankton dynamics: Their construction, coupling to physics, and application, *Journal of Oceanography*, *58*(2), 379–387, doi:10.1023/A:1015874028196.

Franks, P. J. S., & C. Chen (2001), A 3-D prognostic numerical model study of the Georges Bank ecosystem. Part II: Biological-physical model, *Deep Sea Research Part II: Topical Studies in Oceanography*, *48*(1-3), 457–482, doi:10.1016/S0967-0645(00)00125-9.

Freilich, M. A., G. R. Flierl, & A. Mahadevan (2022), Diversity of growth rates maximizes phytoplankton productivity in an eddying ocean, *Geophysical Research Letters*, *49*(3), e2021GL096,180, doi:10.1029/2021GL096180.

Gaddis, W. (1955), *The Recognitions*, Penguin Books.

Gaeta, S. A., & F. P. Brandini (2006), Produção primária do fitoplâncton na região entre o Cabo de São Tomé (RJ) e o Chuí (RS), in *O Ambiente Oceanográfico da Plataforma Continental e do Talude na Região Sudeste-Sul do Brasil*, edited by C. L. B. Rossi-Wongtschowski & L. S. P. Madureira, pp. 219–264, Editora da Universidade de São Paulo, São Paulo, Brazil.

Gaeta, S. A., J. A. Lorenzzetti, L. B. Miranda, S. M. Susini-Ribeiro, M. Pompeu, & C. E. Araujo (1999), The Vitória Eddy and its relation to the phytoplankton biomass and primary productivity during the austral fall of 1995, *Archive of Fishery and Marine Research*, *47*(2/3), 253–270.

Garcia, H. E., R. A. Locarnini, T. P. Boyer, J. I. Antonov, O. K. Baranova, M. M. Zweng, J. Reagan, & D. R. Johnson (2014), World Ocean Atlas 2013, Volume 4: Dissolved Inorganic Nutrients (Phosphate, Nitrate, Silicate), NOAA Atlas NESDIS, vol. 76, edited by S. Levitus, 25 pp., *US Gov. Print. Off., Washington, DC*.

García-Muñoz, M., J. Arístegui, M. F. Montero, & E. D. Barton (2004), Distribution and transport of organic matter along a filament-eddy system in the Canaries–NW Africa coastal transition zone region, *Progress in Oceanography*, *62*(2–4), 115–129, doi:10.1016/j.pocean.2004.07.005.

Garfield, N. T. (1990), The Brazil Current at subtropical latitudes, Doctoral dissertation, University of Rhode Island, Kingston, United States, 122 pp.

Gaube, P., D. J. McGillicuddy, D. B. Chelton, M. J. Behrenfeld, & P. G. Strutton (2014), Regional variations in the influence of mesoscale eddies on near-surface chlorophyll, *Journal of Geophysical Research: Oceans*, *119*(12), 8195–8220, doi:10.1002/2014JC010111.

Gentemann, C. L., M. R. Fewings, & M. García-Reyes (2017), Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 Northeast Pacific Marine Heat Wave, *Geophysical Research Letters*, *44*(1), 312–319, doi:10.1002/2016GL071039.

Gouveia, M. B., D. F. M. Gherardi, C. A. D. Lentini, D. F. Dias, & P. C. Campos (2017), Do the Brazilian sardine commercial landings respond to local ocean circulation?, *Plos One*, *12*(5), e0176,808, doi:10.1371/journal.pone.0176808.

Gouveia, M. B., R. Duran, J. A. Lorenzzetti, A. T. Assireu, R. Toste, L. P. d. F. Assad, & D. F. M. Gherardi (2021), Persistent meanders and eddies lead to quasi-steady Lagrangian transport patterns in a weak western boundary current, *Scientific Reports*, *11*(1), 1–18, doi:10.1038/s41598-021-89612-7.

Grasshoff, K., K. Kremling, & M. Ehrhardt (2009), *Methods of Seawater Analysis*, 3 ed., John Wiley & Sons.

Hughes, L. (1971), The Negro speaks of rivers, in *The Black Poets*, edited by D. Randall, Bantam Books, New York, United States.

Huisman, J., N. N. P. Thi, D. M. Karl, & B. Sommeijer (2006), Reduced mixing generates oscillations and chaos in the oceanic deep chlorophyll maximum, *Nature*, *439*(7074), 322–325, doi:10.1038/nature04245.

Huntley, M., & C. Boyd (1984), Food-limited growth of marine zooplankton, *The American Naturalist*, *124*(4), 455–478, doi:10.1086/284288.

Ikeda, Y., L. B. Miranda, & N. J. Rock (1974), Observations on stages of upwelling in the region of Cabo Frio (Brazil) as conducted by continuous surface temperature and salinity measurements, *Boletim do Instituto Oceanográfico*, *23*, 33–46, doi:10.1590/S0373-55241974000100003.

Jablonski, S. (2007), The Brazilian sardine. Is there any room for modelling?, *Pan-American Journal of Aquatic Sciences*, *2*(2), 86–93.

James, I. N. (1987), Suppression of baroclinic instability in horizontally sheared flows, *Journal of the Atmospheric Sciences*, *44*(24), 3710–3720, doi:10.1175/1520-0469(1987)044<3710:SOBIIH>2.0.CO;2.

Kara, A. B., P. A. Rochford, & H. E. Hurlburt (2000), An optimal definition for ocean mixed layer depth, *Journal of Geophysical Research: Oceans*, *105*(C7), 16,803–16,821, doi:10.1029/2000JC900072.

Landry, M., R. P. Hassett, V. Fagerness, J. Downs, & C. J. Lorenzen (1984), Effect of food acclimation on assimilation efficiency of *Calanus pacificus*, *Limnology and Oceanography*, *29*(2), 361–364, doi:10.4319/lo.1984.29.2.0361.

Lévy, M., R. Ferrari, P. J. S. Franks, A. P. Martin, & P. Rivière (2012), Bringing physics to life at the submesoscale, *Geophysical Research Letters*, *39*(14), doi:10.1029/2012GL052756.

Li, Z., Y. Chao, & J. C. McWilliams (2006), Computation of the streamfunction and velocity potential for limited and irregular domains, *Monthly Weather Review*, *134*(11), 3384–3394, doi:10.1175/MWR3249.1.

Locarnini, R. A., A. V. Mishonov, O. K. Baranova, T. P. Boyer, M. M. Zweng, H. E. Garcia, J. R. Reagan, D. Seidov, K. Weathers, C. R. Paver, & I. V. Smolyar (2018), World Ocean Atlas 2018, Volume 1: Temperature. A. V. Mishonov, Technical Editor, *NOAA Atlas NESDIS 81, 52 pp.*

Luko, C. D., I. C. A. d. Silveira, I. T. Simoes-Sousa, J. M. Araujo, & A. Tandon (2021), Revisiting the Atlantic South Equatorial Current, *Journal of Geophysical Research: Oceans*, *126*(7), e2021JC017,387, doi:10.1029/2021JC017387.

Luko, C. D., C. Z. Lazaneo, I. C. A. d. Silveira, F. Pereira, & A. Tandon (2023), Topographically-generated submesoscale shear instabilities associated with Brazil Current meanders, *Journal of Physical Oceanography*, doi:10.1175/JPO-D-22-0122.1.

Macario, K. D., E. Q. Alves, I. S. Chanca, F. M. Oliveira, C. Carvalho, R. Souza, O. Aguilera, M. C. Tenório, L. C. Rapagna, K. Douka, et al. (2016), The Usiminas shellmound on the Cabo Frio Island: Marine reservoir effect in an upwelling region on the coast of Brazil, *Quaternary Geochronology*, *35*, 36–42, doi:10.1016/j.quageo.2016.05.003.

Magalhães, F. C., J. L. L. Azevedo, & L. R. Oliveira (2017), Energetics of eddy-mean flow interactions in the Brazil Current between 20°S and 36°S, *Journal of Geophysical Research: Oceans*, *122*(8), 6129–6146, doi:10.1002/2016JC012609.

Mahadevan, A. (2016), The impact of submesoscale physics on primary productivity of plankton, *Annual Review of Marine Science*, *8*, 161–184, doi:10.1146/annurev-marine-010814-015912.

Mahadevan, A., & A. Tandon (2006), An analysis of mechanisms for submesoscale vertical motion at ocean fronts, *Ocean Modelling*, *14*(3–4), 241–256, doi:10.1016/j.ocemod.2006.05.006.

Mahadevan, A., L. N. Thomas, & A. Tandon (2008), Comment on "Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms", *Science*, *320*(5875), 448–448, doi:10.1126/science.1152111.

Maianti, P., M. Rusmini, R. Tortini, G. Dalla Via, F. Frassy, A. Marchesi, F. Rota Nodari, & M. Gianinetto (2014), Monitoring large oil slick dynamics with moderate resolution multispectral satellite data, *Natural Hazards*, *73*, 473–492, doi:10.1007/s11069-014-1084-9.

Mano, M. F., A. M. Paiva, A. R. Torres Jr, & A. L. Coutinho (2009), Energy flux to a cyclonic eddy off Cabo Frio, Brazil, *Journal of Physical Oceanography*, *39*(11), 2999–3010, doi:10.1175/2009JPO4026.1.

Marie, D., N. Simon, & D. Vaulot (2005), Phytoplankton cell counting by flow cytometry, in *Algal Culturing Techniques*, vol. 1, edited by R. A. Andersen, cap. 17, pp. 253–267, Academic Press, doi:10.1016/b978-012088426-1/50018-4.

Martin, A. P., & K. J. Richards (2001), Mechanisms for vertical nutrient transport within a North Atlantic mesoscale eddy, *Deep Sea Research Part II: Topical Studies in Oceanography*, *48*(4), 757–773, doi:10.1016/S0967-0645(00)00096-5.

Mascarenhas Jr., A. S., L. B. Miranda, & N. J. Rock (1971), A study of the oceanographic conditions in the region of Cabo Frio, in *Fertility of the Sea*, vol. 1, edited by J. D. Costlow Jr., pp. 285–308, Gordon and Breach.

Matsuura, Y. (1996), A probable cause of recruitment failure of the Brazilian sardine *Sardinella aurita* population during the 1974/75 spawning season, *South African Journal of Marine Science*, *17*(1), 29–35, doi:10.2989/025776196784158554.

McGillicuddy, D. J. (2016), Mechanisms of physical-biological-biogeochemical interaction at the oceanic mesoscale, *Annual Review of Marine Science*, *8*, 125–159, doi:10.1146/annurev-marine-010814-015606.

McGillicuddy, D. J., J. J. McCarthy, & A. R. Robinson (1995), Coupled physical and biological modeling of the spring bloom in the North Atlantic (I): Model formulation and one dimensional bloom processes, *Deep Sea Research Part I: Oceanographic Research Papers*, *42*(8), 1313–1357, doi:10.1016/0967-0637(95)00034-4.

McWilliams, J. C. (2021), Oceanic frontogenesis, *Annual Review of Marine Science*, *13*, 227–253, doi:10.1146/annurev-marine-032320-120725.

Meacham, S. P. (1991), Meander evolution on piecewise-uniform, quasi-geostrophic jets, *Journal of Physical Oceanography*, *21*(8), 1139–1170, doi:10.1175/1520-0485(1991)021%3C1139:MEOPUQ%3E2.0.CO;2.

Meeder, E., K. R. M. Mackey, A. Paytan, Y. Shaked, D. Iluz, N. Stambler, T. Rivlin, A. F. Post, & B. Lazar (2012), Nitrite dynamics in the open ocean clues from seasonal and diurnal variations, *Marine Ecology Progress Series*, *453*, 11–26, doi:10.3354/meps09525.

Mensa, J. A., Z. Garraffo, A. Griffa, T. M. Özgökmen, A. Haza, & M. Veneziani (2013), Seasonality of the submesoscale dynamics in the Gulf Stream region, *Ocean Dynamics*, *63*(8), 923–941, doi:10.1007/s10236-013-0633-1.

Mill, G. N., V. S. da Costa, N. D. Lima, M. Gabioux, L. A. A. Guerra, & A. M. Paiva (2015), Northward migration of Cape São Tomé rings, Brazil, *Continental Shelf Research*, *106*, 27–37, doi:10.1016/j.csr.2015.06.010.

Miranda, L. B. (1985), Forma da correlação TS de massas de água das regiões costeira e oceânica entre o Cabo de São Tomé (RJ) e a Ilha de São Sebastião (SP), Brasil, *Boletim do Instituto Oceanográfico*, *33*(2), 105–119.

Monterey, G. I., & S. Levitus (1997), Seasonal Variability of Mixed Layer Depth for the World Ocean, NOAA Atlas NESDIS 14, *National Oceanic and Atmospheric Administration*, *87*.

Moore, C. M., M. M. Mills, K. R. Arrigo, I. Berman-Frank, L. Bopp, P. W. Boyd, E. D. Galbraith, R. J. Geider, C. Guieu, S. L. Jaccard, et al. (2013), Processes and patterns of oceanic nutrient limitation, *Nature Geoscience*, *6*(9), 701, doi:10.1038/ngeo1765.

Munk, W. H. (1981), Internal waves and small-scale processes, in *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*, edited by B. Warren & C. Wunsch, cap. 9, pp. 264–291, MIT Press.

Murphy, J., & J. P. Riley (1962), A modified single solution method for the determination of phosphate in natural waters, *Analytica Chimica Acta*, *27*, 31–36, doi:10.1016/S0003-2670(00)88444-5.

Namiki, C., M. Katsuragawa, D. C. Napolitano, M. L. Zani-Teixeira, R. A. Mattos, & I. C. A. d. Silveira (2017), Hydrodynamically-driven distribution of lanternfish larvae in the Southeast Brazilian Bight, *Journal of Marine Systems*, *170*, 115–133, doi:10.1016/j.jmarsys.2017.02.006.

Napolitano, D. C., C. B. Rocha, I. C. A. d. Silveira, I. T. Simoes-Sousa, & G. R. Flierl (2021), Can the Intermediate Western Boundary Current recirculation trigger the Vitória Eddy formation?, *Ocean Dynamics*, *71*(3), 281–292, doi:10.1007/s10236-020-01437-6.

Niiler, P. (1977), One-dimensional models of the seasonal thermocline, in *The Sea*, edited by E. D. Goldberg, I. N. McCave, J. J. O'Brien, & J. H. Steele, 6 ed., cap. 3, pp. 97–115, Wiley-Interscience, New York, United States.

O Progresso – Orgam dos Homens de Côr (24 August 1899), , Rare Books, National Library of Brazil, citation taken from Pinto, A. F. M. (2006), De pele escura e tinta preta: A imprensa negra do século XIX (1833–1899), Master's thesis, Department of History, University of Brasília, Brasília, Brazil, `https://repositorio.unb.br/handle/10482/6432`, 197 pp.

Oliveira, L. R., A. R. Piola, M. M. Mata, & I. D. Soares (2009), Brazil Current surface circulation and energetics observed from drifting buoys, *Journal of Geophysical Research: Oceans*, *114*(C10006), doi:10.1029/2008JC004900.

Olson, D. B., G. L. Hitchcock, A. J. Mariano, C. J. Ashjian, G. Peng, R. W. Nero, & G. P. Podestá (1994), Life on the edge: Marine life and fronts, *Oceanography*, *7*(2), 52–60.

Pacheco, M. M., P. S. Polito, O. T. Sato, & M. R. Rocha (2022), Evolution of physical and biological patterns along the Tropical and South Atlantic western boundary: A satellite perspective, *Journal of Geophysical Research: Oceans*, *127*(3), e2021JC017,714, doi:10.1029/2021JC017714.

Padman, L., M. Levine, T. Dillon, J. Morison, & R. Pinkel (1990), Hydrography and microstructure of an Arctic cyclonic eddy, *Journal of Geophysical Research: Oceans*, *95*(C6), 9411–9420, doi:10.1029/JC095iC06p09411.

Palóczy, A., I. C. A. d. Silveira, B. M. Castro, & L. Calado (2014), Coastal upwelling off Cape São Tomé (22°S, Brazil): The supporting role of deep ocean processes, *Continental Shelf Research*, *89*, 38–50, doi:10.1016/j.csr.2013.09.005.

Pereira, F., I. C. A. d. Silveira, G. R. Flierl, & A. Tandon (2019), NPZ response to eddy-induced upwelling in a Brazil Current ring: A theoretical approach, *Dynamics of Atmospheres and Oceans*, *87C*, 101,096, doi:10.1016/j.dynatmoce.2019.101096.

Peres, L. F., G. B. França, R. C. Paes, R. C. Sousa, & A. N. Oliveira (2017), Analyses of the positive bias of remotely sensed SST retrievals in the coastal waters of Rio de Janeiro, *IEEE Transactions on Geoscience and Remote Sensing*, *55*(11), 6344–6353, doi:10.1109/TGRS.2017.2726344.

Petrobras (2014), Bacia de Campos, `https://petrobras.com.br/pt/nossas-atividades/principais-operacoes/bacias/bacia-de-campos.htm`, accessed: 2022-08-15.

Pierrehumbert, R. T., & K. L. Swanson (1995), Baroclinic instability, *Annual Review of Fluid Mechanics*, *27*(1), 419–467, doi:10.1146/annurev.fl.27.010195.002223.

Piffer-Braga, A. (2019), Description and dynamics of the Santos Bifurcation, Master's thesis, Oceanographic Institute, University of São Paulo, São Paulo, Brazil, doi:10.11606/D.21.2020.tde-30012020-153237, 70 pp.

Pimentel, G. R., G. B. França, & L. F. Peres (2019), Removal of the MCSST MODIS SST Bias During Upwelling Events Along the Southeastern Coast of Brazil, *IEEE Transactions on Geoscience and Remote Sensing*, *57*(6), 3566–3573, doi:10.1109/TGRS.2018.2885759.

Polvani, L. M., N. J. Zabusky, & G. R. Flierl (1988), Applications of contour dynamics to two layer quasigeostrophic flows, *Fluid Dynamics Research*, *3*(1-4), 422, doi:10.1016/0169-5983(88)90103-7.

Pratt, L. J., & M. E. Stern (1986), Dynamics of potential vorticity fronts and eddy detachment, *Journal of Physical Oceanography*, *16*(6), 1101–1120, doi:10.1175/1520-0485(1986)016%3C1101:DOPVFA%3E2.0.CO;2.

Pullin, D. I. (1992), Contour dynamics methods, *Annual Review of Fluid Mechanics*, *24*(1), 89–115, doi:10.1146/annurev.fluid.24.1.89.

Ramachandran, S., A. Tandon, & A. Mahadevan (2014), Enhancement in vertical fluxes at a front by mesoscale-submesoscale coupling, *Journal of Geophysical Research: Oceans*, *119*(12), 8495–8511, doi:10.1002/2014JC010211.

Ramanantsoa, J. D., M. Krug, P. Penven, M. Rouault, & J. Gula (2018), Coastal upwelling south of Madagascar: Temporal and spatial variability, *Journal of Marine Systems*, *178*, 29–37, doi:10.1016/j.jmarsys.2017.10.005.

Rocha, C. B., & I. T. Simoes-Sousa (2022), Compact mesoscale eddies in the South Brazil Bight, *Remote Sensing*, *14*(22), 5781, doi:10.3390/rs14225781.

Rocha, C. B., I. C. A. d. Silveira, B. M. Castro, & J. A. M. Lima (2014), Vertical structure, energetics, and dynamics of the Brazil Current System at 22°S – 28°S, *Journal of Geophysical Research: Oceans*, *119*(1), 52–69, doi:10.1002/2013JC009143.

Rodrigues, L. (2021), Painel da produção de petróleo mostra recorde da Bacia de Santos, `https://agenciabrasil.ebc.com.br/economia/noticia/2021-07/painel-da-producao-de-petroleo-mostra-recorde-da-bacia-de-santos`, accessed: 2022-08-16.

Rodrigues, S. V., M. M. Marinho, C. C. A. C. Jonck, R. M. Correa, A. C. L. Oliveira, E. S. Gonçalves, M. C. Santos, V. F. Brant, & F. P. Brandão (2017), Composição do fitoplâncton a partir da avaliação de pigmentos marcadores (carotenoides e clorofilas), in *Ambiente Pelágico: Caracterização Ambiental Regional da Bacia de Campos, Atlântico Sudoeste*, vol. 5, edited by A. P. C. Falcão & D. L. Moreira, cap. 6, pp. 89–125, Elsevier, Rio de Janeiro, Brazil, doi:10.1016/B978-85-352-7276-5.50013-0.

Rodriguez, J., J. Tintoré, J. T. Allen, J. M. Blanco, D. Gomis, A. Reul, J. Ruiz, V. Rodríguez, F. Echevarría, & F. Jiménez-Gómez (2001), Mesoscale vertical motion and the size structure of phytoplankton in the ocean, *Nature*, *410*(6826), 360–363, doi:10.1038/35066560.

Roy, S., D. S. Broomhead, T. Platt, S. Sathyendranath, & S. Ciavatta (2012), Sequential variations of phytoplankton growth and mortality in an NPZ model: A remote-sensing-based assessment, *Journal of Marine Systems*, *92*(1), 16–29, doi:10.1016/j.jmarsys.2011.10.001.

Santana, R., F. B. Costa, D. Mignac, A. N. Santana, V. F. d. S. Vidal, J. Zhu, & C. A. S. Tanajura (2020), Model sensitivity experiments on data assimilation, downscaling and tides for the representation of the Cape São Tomé Eddies, *Ocean Dynamics*, *70*(1), 77–94, doi:10.1007/s10236-019-01307-w.

Schlosser, T. L., A. J. Lucas, N. L. Jones, J. D. Nash, & G. N. Ivey (2022), Local winds and encroaching currents drive summertime subsurface blooms over a narrow shelf, *Limnology and Oceanography*, *67*(4), 888–902, doi:10.1002/lno.12043.

Schmid, C., & S. Majumder (2018), Transport variability of the Brazil Current from observations and a data assimilation model, *Ocean Science*, *14*(3), 417–436, doi:10.5194/os-14-417-2018.

Schmid, C., H. Schäfer, W. Zenk, & G. Podestá (1995), The Vitória Eddy and its relation to the Brazil Current, *Journal of Physical Oceanography*, *25*(11), 2532–2546, doi:10.1175/1520-0485(1995)025%3C2532:TVEAIR%3E2.0.CO;2.

Schmidtko, S., G. C. Johnson, & J. M. Lyman (2013), MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers, *Journal of Geophysical Research: Oceans*, *118*(4), 1658–1672, doi:10.1002/jgrc.20122.

Shcherbina, A. Y., E. A. D'Asaro, C. M. Lee, J. M. Klymak, M. J. Molemaker, & J. C. McWilliams (2013), Statistics of vertical vorticity, divergence, and strain in a developed submesoscale turbulence field, *Geophysical Research Letters*, *40*(17), 4706–4711, doi:10.1002/grl.50919.

Siegelman, L., P. Klein, A. F. Thompson, H. S. Torres, & D. Menemenlis (2020), Altimetry-based diagnosis of deep-reaching sub-mesoscale ocean fronts, *Fluids*, *5*(3), 145, doi:10.3390/fluids5030145.

Signorini, S. R., B. A. Franz, & C. R. McClain (2015), Chlorophyll variability in the oligotrophic gyres: Mechanisms, seasonality and trends, *Frontiers in Marine Science*, *2*, 1, doi:10.3389/fmars.2015.00001.

Silva, G. L., M. S. Dourado, & R. N. Candella (2006), Estudo preliminar da ressurgência na região de Cabo Frio, in *Proceedings of the XIV Congresso Brasileiro de Meteorologia*, Organized by *Sociedade Brasileira de Meteorologia*, Florianópolis, Brazil.

Silva, P. C. M. d. (1957), Oceanografia do triângulo Cabo Frio-Trindade-Salvador, *Anais Hydrográficos*, *16*, 213–308.

Silveira, I. C. A. d., & G. R. Flierl (2002), Eddy formation in 2 1/2-layer, quasigeostrophic jets, *Journal of Physical Oceanography*, *32*(3), 729–745, doi:10.1175/1520-0485(2002)032%3C0729:EFILQJ%3E2.0.CO;2.

Silveira, I. C. A. d., G. R. Flierl, & W. S. Brown (1999), Dynamics of separating western boundary currents, *Journal of Physical Oceanography*, *29*(2), 119–144, doi:10.1175/1520-0485(1999)029<0119:DOSWBC>2.0.CO;2.

Silveira, I. C. A. d., A. C. K. Schmidt, E. J. D. Campos, S. S. Godoi, & Y. Ikeda (2000), The Brazil Current off the Eastern Brazilian Coast, *Revista Brasileira de Oceanografia*, *48*(2), 171–183, doi:10.1590/S1413-77392000000200008.

Silveira, I. C. A. d., L. Calado, B. M. Castro, M. Cirano, J. A. M. Lima, & A. S. Mascarenhas Jr. (2004), On the baroclinic structure of the Brazil Current–Intermediate Western Boundary Current system at 22°S–23°S, *Geophysical Research Letters*, *31*(14), doi:10.1029/2004GL020036.

Silveira, I. C. A. d., J. A. M. Lima, A. C. K. Schmidt, W. Ceccopieri, A. Sartori, C. P. F. Franscisco, & R. F. C. Fontes (2008), Is the meander growth in the Brazil Current system off Southeast Brazil due to baroclinic instability?, *Dynamics of Atmospheres and Oceans*, *45*(3), 187–207, doi:10.1016/j.dynatmoce.2008.01.002.

Silveira*, I. C. A. d., F. Pereira*, G. R. Flierl, I. T. Simoes-Sousa, A. Palóczy, M. Borges-Silva, & C. B. Rocha (2023), The Brazil Current quasi-stationary unstable meanders at 22°S–23°S, *Progress in Oceanography*, *210*, 102,925, doi:10.1016/j.pocean.2022.102925, * denotes joint first authors with equal contribution.

Souza, B. C. P., & P. M. L. Menezes (2011), A cartografia histórica e os nomes geográficos: Uma análise dos geônimos de Cabo Frio - RJ, in *Proceedings of the 1º Simpósio Brasileiro de Cartografia Histórica*, Organized by *Centro de Referência em Cartografia Histórica, Universidade Federal de Minas Gerais*, Paraty, Brazil.

Souza, L. S. d., & G. N. C. Sgarbi (2019), Bacia de Santos no Brasil: Geologia, exploração e produção de petróleo e gás natural, *Boletín de Geología*, *41*(1), 175–195, doi:10.18273/revbol.v41n1-2019009.

Spiro Jaeger, G., J. A. MacKinnon, A. J. Lucas, E. Shroyer, J. Nash, A. Tandon, J. T. Farrar, & A. Mahadevan (2020), How spice is stirred in the Bay of Bengal, *Journal of Physical Oceanography*, *50*(9), 2669–2688, doi:10.1175/JPO-D-19-0077.1.

Stech, J. L., & J. A. Lorenzzetti (1992), The response of the South Brazil Bight to the passage of wintertime cold fronts, *Journal of Geophysical Research: Oceans*, *97*(C6), 9507–9520, doi:10.1029/92JC00486.

Stewart, K. D., A. M. Hogg, S. M. Griffies, A. P. Heerdegen, M. L. Ward, P. Spence, & M. H. England (2017), Vertical resolution of baroclinic modes in global ocean models, *Ocean Modelling*, *113*, 50–65, doi:10.1016/j.ocemod.2017.03.012.

Stramma, L., & M. England (1999), On the water masses and mean circulation of the South Atlantic Ocean, *Journal of Geophysical Research: Oceans*, *104*(C9), 20,863–20,883, doi:10.1029/1999JC900139.

Strass, V. H. (1992), Chlorophyll patchiness caused by mesoscale upwelling at fronts, *Deep Sea Research Part A. Oceanographic Research Papers*, *39*(1), 75–96, doi:10.1016/0198-0149(92)90021-K.

Suga, T., & L. D. Talley (1995), Antarctic Intermediate Water circulation in the Tropical and Subtropical South Atlantic, *Journal of Geophysical Research: Oceans*, *100*(C7), 13,441–13,453, doi:10.1029/95JC00858.

Talley, L. D., G. L. Pickard, W. J. Emery, & J. H. Swift (2011), *Descriptive Physical Oceanography: An Introduction*, 6 ed., Academic Press.

Thomas, L. N., A. Tandon, & A. Mahadevan (2008), Submesoscale processes and dynamics, in *Ocean Modeling in an Eddying Regime*, vol. 177, edited by M. W. Hecht & H. Hasumi, cap. 3, pp. 17–38, American Geophysical Union, Washington, United States, doi:10.1016/B978-85-352-6208-7.50008-8, Geophysical Monograph Series.

Tura, P. M., C. H. Pilskaln, & F. P. Brandini (2021), A first assessment of particle flux over the South Brazil Bight continental slope, *Deep Sea Research Part I: Oceanographic Research Papers*, *178*, 103,643, doi:10.1016/j.dsr.2021.103643.

Uchoa, I., I. T. Simoes-Sousa, & I. C. A. d. Silveira (2023), The Brazil Current mesoscale eddies: Altimetry-based characterization and tracking, *Deep Sea Research Part I: Oceanographic Research Papers*, *192*, 103,947, doi:10.1016/j.dsr.2022.103947.

Valentin, J. L. (2001), The Cabo Frio Upwelling System, Brazil, in *Coastal Marine Ecosystems of Latin America*, edited by U. Seeliger & B. Kjerfve, 1 ed., cap. 7, pp. 97–105, Springer-Verlag Berlin Heidelberg, New York, United States, doi:10.1007/978-3-662-04482-7_8.

Valentin, J. L., D. L. Andre, & S. A. Jacob (1987), Hydrobiology in the Cabo Frio (Brazil) upwelling: Two-dimensional structure and variability during a wind cycle, *Continental Shelf Research*, *7*(1), 77–88, doi:10.1016/0278-4343(87)90065-3.

Vallis, G. K. (2017), *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation*, 2 ed., 875 pp., Cambridge University Press, doi:10.1017/9781107588417.

Vazquez-Cuervo, J., B. Dewitte, T. M. Chin, E. M. Armstrong, S. Purca, & E. Alburqueque (2013), An analysis of SST gradients off the Peruvian Coast: The impact of going to higher resolution, *Remote Sensing of Environment*, *131*, 76–84, doi:10.1016/j.rse.2012.12.010.

Visbeck, M. (2002), Deep velocity profiling using Lowered Acoustic Doppler Current profilers: Bottom track and inverse solutions, *Journal of atmospheric and oceanic technology*, *19*(5), 794–807, doi:10.1175/1520-0426(2002)019<0794:DVPULA>2.0.CO;2.

Wang, L., J. Gula, J. Collin, & L. Mémery (2022), Effects of mesoscale dynamics on the path of fast-sinking particles to the deep ocean: A modeling study, *Journal of Geophysical Research: Oceans*, *127*(7), e2022JC018,799, doi:10.1029/2022JC018799.

Ward, B. B. (2008), Nitrification in marine systems, in *Nitrogen in the Marine Environment*, edited by D. G. Capone, D. A. Bronk, M. R. Mulholland, & E. J. Carpenter, 2 ed., cap. 5, pp. 199–262, Academic Press, Burlington, United States.

Welschmeyer, N. A. (1994), Fluorometric analysis of chlorophyll a in the presence of chlorophyll b and pheopigments, *Limnology and Oceanography*, *39*(8), 1985–1992, doi:10.4319/lo.1994.39.8.1985.

Wiafe, G., & E. S. Nyadjro (2015), Satellite observations of upwelling in the Gulf of Guinea, *IEEE Geoscience and Remote Sensing Letters*, *12*(5), 1066–1070, doi:10.1109/LGRS.2014.2379474.

Woodson, C. B., & M. A. McManus (2007), Foraging behavior can influence dispersal of marine organisms, *Limnology and Oceanography*, *52*(6), 2701–2709, doi:10.4319/lo.2007.52.6.2701.

Yoshinaga, M. Y., P. Y. G. Sumida, I. C. A. d. Silveira, A. M. Ciotti, S. A. Gaeta, L. F. C. M. Pacheco, & A. G. Koettker (2010), Vertical distribution of benthic invertebrate larvae during an upwelling event along a transect off the tropical Brazilian continental margin, *Journal of Marine Systems*, *79*(1), 124–133, doi:10.1016/j.jmarsys.2009.07.007.

Zacharias, D. C., & A. Fornaro (2020), Brazilian offshore oil exploration areas: An overview of hydrocarbon pollution, *Revista Ambiente & Água*, *15*, doi:10.4136/ambi-agua.2569.

Zhang, W. G., P. Alatalo, T. Crockford, A. J. Hirzel, M. G. Meyer, H. Oliver, E. Peacock, C. M. Petitpas, Z. Sandwith, W. O. Smith, H. M. Sosik, R. H. R. Stanley, B. L. F. Stevens, J. T. Turner, & D. J. McGillicuddy (2023), Cross-shelf exchange associated with a shelf-water streamer at the Mid-Atlantic Bight shelf edge, *Progress in Oceanography*, *210*, 102,931, doi:10.1016/j.pocean.2022.102931.

Zweng, M. M., J. R. Reagan, D. Seidov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, A. V. Mishonov, O. K. Baranova, K. Weathers, C. R. Paver, & I. V. Smolyar (2018), World Ocean Atlas 2018, Volume 2: Salinity. A. V. Mishonov, Technical Editor, *NOAA Atlas NESDIS 82, 50 pp.*