UNIVERSIDADE FEDERAL DE PERNAMBUCO

CENTRO DE CIÊNCIAS E TECNOLOGIA

DEPARTAMENTO DE OCEANOGRAFIA

Tarsila Sousa Lima

UNDERSURFACE OCEAN CURRENT ENERGY IN THE SOUTHWESTERN TROPICAL ATLANTIC

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Trabalho de Conclusão de Curso apresentado ao Departamento de Oceanografia da Universidade Federal de Pernambuco como pré-requisito para a conclusão do curso de Bacharelado em Oceanografia.

Orientador(a): Marcus André Silva
Coorientador(a): Syumara Queiroz de Paiva e Silva

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BANCA EXAMINADORA

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Profº. Dr. Marcus Andre Silva (Orientador)
Universidade Federal de Pernambuco

____

Profº. Dr. Nadège Sophie Bouchonneau da Silva (Examinador Externo)
Universidade Federal de Pernambuco

____

Profº. Dr. Paulo Estevão Lemos de Oliveira (Examinador Externo)
Universidade Federal de Pernambuco

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RESUMO

As estratégias de mitigação das alterações climáticas incluem a redução da dependência dos combustíveis fósseis e o aumento da contribuição de fontes de energia renováveis na matriz energética. As fontes de energia renováveis oceânicas, como as correntes marinhas, surgem como uma alternativa promissora para diversificar a matriz energética. No Sudoeste do Atlântico Tropical, o potencial energético das correntes superficiais foi previamente investigado. Porém, a presença da Subcorrente Subsuperficial Norte do Brasil (NBUC) nesta região levou à investigação do potencial dessa corrente para a geração de energia. Dados climatológicos foram utilizados para avaliar a densidade de potência da corrente (CPD) em diferentes níveis verticais. Os resultados mostraram quatro *hotspots* para aproveitamento energético de correntes marinhas com CPD superior a 1000 Wm^{-2}. Os *hotspots* do Maranhão (MA) e Ceará (CE) na superfície foram relacionados à Corrente Norte do Brasil e os *hotspots* do Rio Grande do Norte (RN) e Paraíba (PB) foram relacionados à NBUC em profundidades entre 150 e 250 m. Todos os *hotspots* identificados foram consequência de interações de fluxo e topografia, em particular das mudanças na dinâmica das correntes devido às mudanças de direção da linha costeira e das isóbatas da quebra da plataforma. Uma comparação entre os *hotspots* foi feita em termos de proximidade da costa, proximidade de blocos de exploração de petróleo e gás, estabilidade do núcleo atual e ausência de sistema de recifes profundos na plataforma subjacente. Os resultados indicam que, apesar dos desafios na exploração devido ao núcleo atual estar em camadas mais profundas, a corrente subsuperficial fornece um CPD mais forte e sazonalmente mais estável do que as correntes superficiais. Em última instância, a investigação sobre a geração de energia a partir de correntes marinhas ainda está numa fase inicial e precisa de colmatar as lacunas de conhecimento, tais como os impactos ambientais, os desafios para as infraestruturas e os custos relacionados com a exploração energética das correntes marinhas.

Palavras-chave: Densidade de potência da corrente; Correntes de borda oeste; Margem Equatorial; Interações de fluxo e topografia; Corrente Norte do Brasil.

ABSTRACT

Climatic change mitigation strategies include the reduction of fossil fuels dependency and the increase of energy mix contribution from renewable sources. Oceanic renewable energy sources such as marine currents emerge as a promising alternative to diversify the energy mix. In the Southwestern Tropical Atlantic, shallow energy potential from surface currents were previously investigated. However, the presence of the subsurface North Brazil Undercurrent (NBUC) in this region lead to the investigation of the current energy related to this current. Climatologic data was used to evaluate the current power density (CPD) at different vertical levels. The results showed four hotspots for marine current energy exploitation with CPD higher than 1000 Wm^{-2}, the Maranhão (MA) and Ceará (CE) hotspots at the surface related to de North Brazil Current and the Rio Grande do Norte (RN) and Paraíba (PB) hotspots related to the NBUC at depths between 150 and 250 m. All the hotspots identified were a consequence of flow-topography interactions, in particular because of changes in current dynamics due to coastline and shelf-break isobaths direction changes. Comparison between the hotspots was made in terms of closeness to the coast, closeness to oil and gas exploration blocks, stability of current core and absence of deep reef system at the subjacent shelf. The results indicate that, despite the challenges in exploitation due to current core being in deeper layers, the undercurrent provides a stronger and seasonally stabler CPD than the surface currents. Furthermore, research on energy generation from marine currents is still in its early stages and need to address the knowledge gaps such as the environmental impacts, infrastructure challenges and costs related to marine currents energy exploitation.

Keywords: Current Power Density; Western Boundary System; Equatorial Margin; Flow-topography interactions; North Brazil Undercurrent.

SUMMARY

1 GENERAL INTRODUCTION AND FRAMEWORK

The present energy consumption model encompasses many variables, including energy sources (such as oil, natural gas, solar energy, etc.), energy carriers (electricity, biofuels), energy conversion devices (light bulbs, engines), and the services provided by energy (lighting, transportation) (Duarte, 2013). Renewable energy sources are essential to address environmental challenges and play a fundamental role in the sustainable transition of the global energy mix (Nations, 2023). The research for sustainable energy solutions is currently in the spotlight as they serve as alternatives to reduce greenhouse gases emissions related to the burning of fossil fuels (Bondarik *et al*., 2018). In this context, the transition from fossil fuels to renewable sources is crucial, not only to mitigate climate change but also to establish an energy mix aligned with global environmental objectives, promoting sustainability (Fleming, 2012; Gonçalves *et al*., 2018; IPCC, 2021; 2022a,b; 2023).

The increasing availability and economic competitiveness of renewable energies – which generates jobs and contribute to decarbonization – have driven their adoption in many countries (Matos *et al.*, 2022). In contrast to fossil fuels, energy sources such as sunlight, wind and oceans are constantly renewed, offering a cleaner and more sustainable alternative for energy generation (Bezerra Leite Neto *et al.*, 2011). In particular, renewable energy from oceanic sources can be driven by tides (tidal energy), waves (wave energy), salinity and temperature gradients (thermal energy) and marine currents (Pelc and Fujita, 2002; Bedard *et al.*, 2010; Ciampaglia, 2020).

Tidal energy is an effective mean of energy generation derived from the movement of tides, in operation since 1966 and expanding globally (Fleming, 2012; Gonçalves *et al.*, 2018). The efficiency, however, is most pronounced in regions characterized by a significant tidal range (Bezerra Leite Neto *et al*., 2011). Its generation is based on the periodic variation of sea level that creates a flow of water that can be efficiently harnessed for electricity production (Shetty and Priyam, 2022). Turbines are strategically installed in locations such as estuaries or bays, where the tidal height difference is enhanced and channel water to generate electricity, converting the kinetic or potential energy of water into electrical energy (Shetty and Priyam, 2022).

Unlike tidal energy, which relies on the periodic variation of sea level, wave energy is captured through the exploitation of the kinetic energy generated by the movement of waves (Barstow *et al.*, 2008). This form of renewable energy has gained prominence due to its constant and predictable nature, offering a reliable source of electricity. The global energy potential of wave energy is estimated at around 2 TW, equivalent to the annual average of global electricity consumption (Cruz and Sarmento, 2004; Gonçalves *et al.*, 2008). Particularly, Brazil presents a significant opportunity for the wave energy industry (~372 TWh/month) (Weiss *et al.*, 2018). However, despite representing a potentially advantageous opportunity, challenges associated with high costs, the significant influence of waves on equipment on a daily basis, dependence on weather and oceanic conditions, can pose considerable obstacles to effectiveness in energy generation, as well as complications in predicting energy production (Bastos *et al.*, 2023). Additionally, it is essential to highlight the potential visual impacts, interference with fishing activities, consequences for the coastal landscape and ecosystem, not to mention the interference with marine acoustics communication resulting from the operation of energy devices (Langhamer *et al.*, 2010; Frid *et al.*, 2012).

Marine thermal energy exploits the temperature difference between surface waters and deeper ocean waters (Khan *et al.*, 2022). The most notable system utilizing this thermal gradient is Ocean Thermal Energy Conversion (OTEC), in which warm surface water is used to evaporate a working fluid, thus driving a turbine for electricity generation (Ghilardi, 2021). Cold water from the depths is then used to condense the working fluid, completing the cycle. This form of energy proves particularly advantageous in tropical regions, where the oceanic thermal gradient remains more constant throughout the year (Ghilardi, 2021). The development and implementation of systems like OTEC on a commercial scale is recent, and realistic assessments of the costs and potential global environmental impacts of these systems are still pending (Cavrot, 1993; Vega, 2017; Langer *et al.*, 2020).

Marine currents can be harnessed for energy generation through marine current turbines (Fraenkel, 2002). These turbines are designed to capture the kinetic energy of moving ocean currents and convert it into electricity (Wei *et al.*, 2022). Analogous to wind turbines, turbine rotor for ocean currents converts the kinetic energy of moving the moving fluid into mechanical energy (Foley *et al.*, 2012). In general, ocean current velocities are smaller than wind averaged velocities, with the fastest current reaching maximum values of ~2m.s^{-1} (Gulf Stream) (Misra *et al.*, 2016) and most currents staying bellow this value. However, the potential of ocean current power generation is related to the density of water that is about 800 times denser than the air (Tsao *et al.*, 2017). This results in equivalence of the kinetic power density (of a 1 m.s^{-1} water flow to a wind at a speed of 9.3 m.s^{-1} (Tsao *et al.*, 2017).

The generation of energy from marine currents has been the subject of detailed studies aimed at identifying the primary drivers of its energy potential (Dudhgaonkar *et al.*, 2017; Chen *et al.*, 2018; Morales and Segura, 2023). These include forces resulting from the gravitational interaction between the Earth, the Moon, and the Sun, as well as submarine topography directing the flow of water, along with precise resource assessments to estimate energy potential and determine optimal installation conditions (Bahaj, 2013).

Harnessing energy from marine currents presents several significant advantages, such as the stability and reliability of the energy source due to its more predictable and seasonal nature, making it valuable when compared to energy generated from fossil fuel combustion (Shadman *et al.*, 2019). Additionally, marine current turbines are smaller compared to other types of renewable technology, allowing for the construction of plants close to each other, resulting in cost savings on cables and installation (Fraenkel, 2002).

However, despite increasing attention towards exploration as a potential green energy source, research on energy generation from marine currents is still in its early stages and faces significant challenges (Bahaj and Myers, 2003; Zhou *et al.*, 2017; Taveira-Pinto *et al.*, 2020). The main challenges include the costs, and technological complexity associated with the installation and maintenance of marine current energy infrastructures (Bahaj and Myers, 2003; Bahaj, 2013). In addition, the knowledge gaps include potential long-term environmental, and fisheries impacts beyond specific challenges and potential solutions related to energy generation through marine currents. Identifying and addressing these research gaps is essential for developing effective strategies that can maximize the potential of this renewable and stable energy source in the future. Including technological and regulatory obstacles associated with large-scale development and implementation (Boehlert and Gill, 2010; Halamay *et al.*, 2011).

When considering the marine current turbines, water in motion is directed onto the rotor, which generates torque, and consequently, electrical energy is produced from the lift forces generated (Fraenkel, 2002; Tsao *et al.*, 2024). The capacity to generate energy from turbines varies from 500 kW to 2 MW (Zhou *et al.*, 2014). Some turbines, such as the Seagen S, adopt a design similar to primary wind turbines, with pitch control and gearboxes, while others, like the GE-Alstom, feature a floating turbine design with direct-drive generators and non-adjustable blades (Douglas *et al.*, 2008). The OpenHydro and Sabella turbines are examples of technologies specific to marine current turbines, with direct-drive generators and fixed blades (Zhou *et al.*, 2014; Gotelli *et al.*, 2019). Additionally, the Voith turbines, developed by Voith Hydro, are designed to efficiently harness energy from marine currents (Hogan *et al.*, 2014). These diverse technologies reflect the ongoing evolution and specialization in the field of marine current energy harnessing, aiming to provide effective and sustainable solutions for renewable energy generation from marine resources (Batten *et al.*, 2008).

Innovative cost-effective systems such as the Cross-stream Active Mooring (CSAM) system – idealized by academics Che-Chih Tsao, Chia-Che Yang, and Zhi-Xiang Chen from the National Tsing Hua University in Taiwan – are being developed to increase generation capacity and energy efficiency solving some challenges in power plant implementation (Tsao *et al.*, 2017; 2018; 2023; 2024; Tsao and Feng, 2019).

The functioning of CSAM is based on a system composed of multiple energy-generating turbines, anchored in series on a common cable and stabilized by actively adjusted hydraulic sails (Tsao et al., 2018). In this manner the system can be anchored in shallow bottom – instead of the deep bottom under the velocity cores – at a more favorable type of substrate and outside biological sensitive areas such as deep-sea coral. Additionally, it allows for precise adaptation to the dynamics of the currents, including vertical movement and meandering ensuring efficient capture of the kinetic energy of ocean flows (Tsao and Feng, 2019). The automated control of hydraulic sails, in response to the real-time flow velocity field, provides the system with the ability to maintain the linear line close to neutral buoyancy, even under variable current conditions (Tsao and Feng, 2019)

The development of CSAM technology presents significant strategic advantages. Firstly, the reduction in submarine engineering costs, resulting from the series arrangement of turbines and anchoring at a single point, economically enables the implementation of large-scale systems. Additionally, the possibility of active depth adjustment of the system, coupled with the ability to evade adverse maritime conditions during storms, confers operational robustness to the system in challenging oceanic environments. Utilizing onboard sensors, upstream deployed sensors, and high-frequency land-based radars would allow for precise monitoring of current velocity fields, facilitating dynamic adjustment of hydraulic sails to optimize energy capture (Tsao *et al.*, 2017; 2018; 2023).

In terms of locations for implementation of current energy power plants, while some studies have highlighted the potential of marine current energy generation in specific locations such as Ireland and China, knowledge gaps persist, necessitating further investigation (Rourke *et al.*, 2010; Zhang *et al.*, 2014). Potential features for marine current energy production are the currents along the western margins of oceanic basins, known as Western Boundary Currents (WBC). Indeed, the CSAM system that was initially designed to operate in unidirectional currents such as the Kuroshio, Florida Current and the Gulf current, all of them are WBCs.

Western boundary currents (WBCs) are swift, narrow oceanic currents found in the western side of all major oceanic gyres. Their counterparts are the slower and wider Eastern Boundary Currents (EBS) at the opposite sides of the oceanic gyres. This asymmetry in the large-scale circulation in the ocean basins occurs is known as westward intensification of the circulation. Due to the Earth’s rotation, the trade winds blow westward in the tropics and the westerlies blow eastward at mid-latitudes. This applies a stress to the ocean surface with a curl in north and south hemispheres, causing Sverdrup transport equatorward (EBCs). Due to conservation of mass and of potential vorticity, the transport is balanced by a narrow, intense poleward current (WBCs), which flows along the western coast. Western boundary currents are divided into sub-tropical or low-latitude western boundary currents. Sub-tropical western boundary currents carry warm water from the tropics poleward (e.g. Gulf Stream, Agulhas Current, and Kuroshio Current) while low-latitude western boundary currents carry waters from the subtropics equatorward (e.g Mindanao Current and the North Brazil Current) (Talley *et al.*, 2011).

Particularly for the Brazilian waters, among energy sources, marine currents are the least explored, with few studies assessing their potential and most of the research focusing on the southern region of the country (Fischer *et al.*, 2013; Kirinus and Marques, 2015; Kirinus *et al.*, 2018; 2022). However, at the Southwestern Tropical Atlantic (SWAT), along the North and Northeast Brazil, WBCs flow along the continental margin, represented by the surface Brazil Current (BC) and North Brazil Current (NBC) and subsurface NBUC (North Brazil Undercurrent). In a review by Shadman *et al.*, (2019), the potential of renewable energy sources, including waves, tides, and thermal and salinity gradient, along the Brazilian coast was evaluated. The results showed considerable ocean current energies for the North and Northeast regions, with the maximum annual average of surface currents reaching 1.52 $m.s^{-1}$ (approximate power density of 500 $W.m^{-2}$) near the equatorial margin of Brazil. However, this investigation considered only the shallow currents (down until 50m), which disregard the potential of currents such as the subsurface NBUC.

Systems like the CSAM holds promising attributes that make it a viable candidate for application in the context of the SWTA currents. Given the capabilities offered by technologies like CSAM, which enable energy capture at greater depths (Tsao *et al.*, 2023), there is a need to consider not only surface levels but also subsurface layers, significantly expanding the scope of application and energy utilization potential.

Subsurface currents play a vital role in global ocean circulation, transporting heat, nutrients, and energy over vast oceanic expanses (Stramma *et al.*, 1995). For example, NBUC exhibits average speeds of up to 1 $m.s^{-1}$ and variable depths between 100 and 500 meters (Damasceno *et al.*, 2022). Include subsurface currents in the assessment of ocean energy generation potential offers considerable advantages in terms of optimizing the location and design of current energy devices. By considering not only surface currents but also deeper and more constant currents like NBUC, energy generation projects can be more precisely tailored to local conditions, maximizing the utilization of available energy sources. Furthermore, the interaction between NBUC and platform morphology is essential for understanding sedimentary and ecological differences between the northern and eastern margins of the Brazilian Continental Margin (Stramma and Peterson, 1990; Stramma *et al.*, 1995; Schott *et al.*, 2005; Damasceno *et al.*, 2022), further highlighting the importance of subsurface currents in the analysis of ocean energy generation potential.

It is important to note that subsurface currents not only complement surface currents in terms of energy availability but also offer a more stable and consistent source of kinetic energy. Subsurface currents, unlike surface currents, demonstrate greater stability over time, as they are less susceptible to seasonal and climatic variations (Fonseca *et al.*, 2004). This stability is attributed to the lesser influence of wind and solar radiation (Barnier *et al.*, 2001; Fonseca *et al.*, 2004). These characteristics provide a solid foundation for renewable energy generation in a continuous and reliable manner.

Therefore, it is essential to focus significant attention on Brazil, given the presence of notably robust marine currents, particularly the Brazil Current and the North Brazil Current. Due to the singular intensity of these currents, they can become substantial sources of oceanic energy, justifying specific attention to the development of appropriate energy generation technologies. Additionally, it is crucial to highlight the need for a comprehensive focus that encompasses not only surface currents but also subsurface currents. Emphasizing the understanding and harnessing of these currents in deeper layers is fundamental to maximizing the potential for energy generation from ocean currents. In this context, the objective of the present work is to explore and evaluate the potential of surface and subsurface currents in the Southwestern Tropical Atlantic. This comprehensive and strategic approach will significantly contribute to the expansion of knowledge and practical possibilities in the field of renewable energies.

2 JUSTIFICATIONS

The decarbonization of energy production, essential for reducing reliance on polluting energy sources, is aligned with the Sustainable Development Goals (SDGs) outlined in the United Nations' 2030 Agenda. Ensuring universal, reliable, modern, and affordable access to energy services (SDG 7.1) is imperative, necessitating a transition to sustainable and clean energy sources. Establishing energy systems incorporating a significant share of renewable energies in the global energy matrix (SDG 7.2) is a priority, not only for reducing greenhouse gas emissions but also for diversifying energy supply and ensuring long-term energy security. Doubling the global rate of improvement in energy efficiency by 2030 (SDG 7.3) is crucial and achievable through technological advancements, effective policies, and behavioral changes. Moreover, strengthening international cooperation to facilitate access to clean energy research and technologies, such as renewable energies and energy efficiency (SDG 7.a), is fundamental. Investments in energy infrastructure and clean technologies (SDG 7.b) are essential for driving the transition to a more sustainable and accessible energy system, particularly for developing countries.

These measures are intrinsically linked to other objectives established in the 2030 Agenda. For instance, they significantly contribute to SDG 13, which aims to combat climate change and its impacts by reducing greenhouse gas emissions through energy decarbonization. Similarly, the pursuit of renewable energy sources and the promotion of energy efficiency align with SDG 12, ensuring sustainable production and consumption patterns. This reduces the carbon footprint of energy production, promoting sustainable and efficient management of natural resources and reducing energy waste.

Lastly, SDG 14, focusing on the conservation and sustainable use of oceans, can also benefit from a transition to clean energy sources. The reduction of greenhouse gas emissions from energy production helps minimize the adverse impacts of ocean acidification, protecting marine and coastal ecosystems. By adopting approaches aligned with the SDGs, efforts to decarbonize energy production can be effectively integrated into a global agenda for sustainable development, simultaneously promoting climate change mitigation and equitable access to energy.

The expansion of renewable energy technologies for use in marine environments offers a relevant opportunity for transitioning towards a cleaner and more sustainable energy matrix (Ruddy, 2023). This approach contributes to reducing greenhouse gas emissions and promotes greater energy security by increasing the diversity of energy sources and reducing dependence on fossil fuels (Leporini *et al.*, 2019). Additionally, integrating offshore energy production with already-installed platforms, such as oil and gas platforms, can leverage existing infrastructure and expertise at these sites, thus reducing costs and resources (Tiong *et al.*, 2015; Klabučar *et al.*, 2020).

However, it is imperative to address the challenges and opportunities inherent in this transition, including the necessary technical feasibility to sustain renewable energy equipment, as well as the logistical and operational challenges associated with their installation and maintenance (Leporini *et al.*, 2019). Furthermore, conducting a comprehensive life cycle assessment of these equipment on platforms is crucial, as well as considering the integration and stabilization of the electrical grid in conjunction with other energy sources (Crivellari *et al.*, 2019; Leporini *et al.*, 2019). It is worth noting that maximizing the benefits arising from the energy transition can be achieved through the diversification of renewable energy sources on a single platform (Roussanaly *et al.*, 2019).

Lastly, the identification of potential sites to current energy production close to the existing exploration blocks may be a promising approach to advance regarding the coupling of sustainable energy production on offshore platforms.

3 MAIN GOALS AND HYPOTESIS

Present work aims to investigate the potential for energy generation through currents in the SWAT at different vertical levels from a climatological dataset. Our hypothesis is that subsurface western boundary currents, such as the NBUC represent as much potential as surface currents as a source of renewable energy.

O PRESENTE TRABALHO ESTÁ APRESENTADO NO FORMATO DE ARTIGO REQUERIDO PELA REVISTA **JOURNAL OF MARINE SYSTEMS**, CUJAS NORMAS PARA SUBMISSÃO DE ARTIGOS SE ENCONTRAM NO ANEXO A.

4 UNDERSURFACE OCEAN CURRENT ENERGY IN THE SOUTHWESTERN TROPICAL ATLANTIC

Tarsila Sousa Lima[1]; Syumara Queiroz[1]; Marcus André Silva[1]; Moacyr Araujo[1,2].

[1]Laboratório de Oceanografia Física Estuarina e Costeira (LOFEC), Department of Oceanography, Universidade Federal de Pernambuco, Av. Arquitetura, 50740-550, Recife, Pernambuco, Brazil.

[2]Brazilian Research Network on Global Climate Change – Rede CLIMA, 12227-010, São José dos Campos, São Paulo, Brazil.

Corresponding author: Tarsila Sousa Lima (tarsilalimass@gmail.com)

Abstract

Climatic change mitigation strategies include the reduction of fossil fuels dependency and the increase of energy mix contribution from renewable sources. Oceanic renewable energy sources such as marine currents emerge as a promising alternative to diversify the energy mix. In the Southwestern Tropical Atlantic, shallow energy potential from surface currents were previously investigated. However, the presence of the subsurface North Brazil Undercurrent (NBUC) in this region lead to the investigation of the potential related to this current. We used climatologic data to evaluate the current power density (CPD) at different vertical levels. The results showed four hotspots for marine current energy exploitation with CPD higher than 1000 $W.m^{-2}$; two of them related to the NBUC at depths between 150 and 250 m. All the hotspots identified were a consequence of flow-topography interactions, in particular because of changes in current dynamics due to coastline and shelf-break isobaths direction changes. We compared the hotspots in terms of closeness to the coast, closeness to oil and gas exploration blocks, stability of current core and absence of deep reef system at the subjacent shelf. Our results indicate that, besides the challenges of current core being in deeper layers, the undercurrent provides a stronger and seasonally stabler CPD than the surface currents. Furthermore, research on energy generation from marine currents is still in its early stages and need to address the knowledge gaps such as the environmental impacts, infrastructure and costs related to marine currents energy exploitation.

Keywords: Marine Current Energy. Current Power Density. Western Boundary System. Equatorial Margin. North Brazil Undercurrent.

INTRODUCTION

The research for sustainable energy solutions is currently in the spotlight as they serve as alternatives to reduce greenhouse gases emissions related to the burning of fossil fuels (Bondarik *et al.*, 2018). Renewable energy sources are essential to address environmental challenges and play a fundamental role in the sustainable transition of the global energy mix (Nations, 2023). Among them, the energy derived from the oceans has emerged as a protagonist in the search for a cleaner and more efficient energy matrix (Shadman *et al.*, 2019). Globally, the transition from fossil fuels to renewable sources has become crucial due to the environmental challenges generated by climate change (Dong *et al.*, 2022; IPCC, 2021; 2022a,b; 2023). Despite the technological advances in renewable energy technologies, the dominant use of fossil fuels persists, driven by increasing availability and demand, even in face of environmental impacts and the risk of catastrophic events, such as oil spills in the oceans (Da Silva *et al.*, 1997; Martins *et al.*, 2015).

The increasing availability and economic competitiveness of renewable energies – which generates jobs and contribute to decarbonization – have driven their adoption in many countries (Matos *et al.*, 2022). In contrast to fossil fuels, energy sources such as sunlight, wind and oceans are constantly renewed, offering a cleaner and more sustainable alternative for energy generation (Bezerra Leite Neto *et al.*, 2011). Renewable energy from oceanic sources can be driven by tides (tidal energy), waves (wave energy), salinity and temperature gradients (thermal energy) and marine currents (Pelc and Fujita, 2002; Bedard *et al.*, 2010; Ciampaglia, 2020).

Brazil government recognizes the critical need to diversify its energy mix in face of the global climatic changes and the increase of energy demand (Bondarik, 2018; Aguiar *et al.*, 2023). In his context, the harvesting of energy from oceanic currents emerges as a promising and fascinating alternative as ocean currents can provide a constant supply of energy (Rourke *et al.*, 2010). Marine currents can travel long distances of thousands of kilometers and include both surface and deep currents (Tsao *et al.*, 2017). Beyond their important role in global climate regulation, currents are responsible for the transport of heat and nutrients around the world (Schott *et al.*, 1998; Dudhgaonkar *et al.*, 2017).

In general, ocean current velocities are smaller than wind averaged velocities, with the fastest current reaching maximum values of ~2$m.s^{-1}$ (Gulf Stream) (Misra *et al.*, 2016) and most currents staying bellow this value. Tsao *et al.* (2017) relate the ocean current power generation potential to the density of water (~800 times denser than the air) which results in equivalence between the kinetic power density of a 1 $m.s^{-1}$ water flow and wind at a speed of 9.3 $m.s^{-1}$.

The generation of energy from marine currents has been the subject of detailed studies aimed at identifying the primary drivers of its energy potential (Dudhgaonkar *et al.*, 2017; Chen *et al.*, 2018; Morales and Segura, 2023). These include forces resulting from the gravitational interaction between the Earth, the Moon, and the Sun, as well as submarine topography directing the flow of water, along with precise resource assessments to estimate energy potential and determine optimal installation conditions (Bahaj, 2013).

Harnessing energy from marine currents presents several significant advantages, such as the stability and reliability of the energy source due to its more predictable and seasonal nature, making it valuable when compared to energy generated from fossil fuel combustion (Shadman *et al.*, 2019). Marine currents can be harnessed for energy generation through submerged marine current energy devices (MCEDs) designed to capture the kinetic energy of moving ocean currents and convert it into electricity (Fraenkel, 2002; Rourke *et al.*; 2010; Wei *et al.*, 2022). Then, the electricity can be used locally or transmitted to the power grid (Hidayati *et al.*, 2016; Dudhgaonkar *et al.*, 2017; Tsao *et al.*, 2017). Additionally, marine current turbines are smaller compared to other types of renewable technology, allowing for the construction of plants close to each other, resulting in cost savings on cables and installation (Fraenkel, 2002).

In terms of locations for implementation of current energy power plants, while some studies have highlighted the potential of marine current energy generation in specific locations such as Ireland and China, knowledge gaps persist, necessitating further investigation (Rourke *et al.*, 2010; Zhang *et al.*, 2014). Potential features for marine current energy production are the currents along the western margins of oceanic basins, known as Western Boundary Currents (WBC). WBCs are powerful ocean currents that flow along the western margins of ocean basins. These currents are narrower and deeper than the eastern edge currents (Hogg and Johns, 1995; Tsao *et al.*, 2017) and play a crucial role in transferring heat from the equator to higher latitudes, influencing regional and global climate patterns (Schott *et al.*, 1998; Silveira *et al.*, 2000; Todd et al., 2019). Beyond that, they are the fastest oceanic currents on the planet, which implicates their potential for marine current power generation.

Particularly for the Brazilian waters, among energy sources, marine currents are the least explored, with few studies assessing their potential and most of the research focusing on the southern region of the country (Fischer *et al.*, 2013; Kirinus and Marques, 2015; Kirinus *et al.*, 2018; 2022). However, at the Southwestern Tropical

Atlantic (SWAT), adjacent to Northeastern Brazil (NEB), three important Western Boundary Current are found: the Brazil Current (BC), the North Brazil Current (NBC) and the North Brazil Undercurrent (NBUC) (Stramma *et al.*, 1995; Schott *et al.*, 2002, 2005; Veleda *et al.*, 2012; Dossa *et al.*, 2021). The NBUC flows northward in the subsurface while the BC flows southward on the surface, both arising from the bifurcation of the southern branch of the South Equatorial Current (sSEC; **Figure 1**) (Pereira *et al.*, 2014). As the NBUC flows toward the equator, it becomes shallower until it connects with the central branch of the South Equatorial Current (cSEC; **Figure 1**). This encounter gives rise to the NBC, which, in turn, flows along the northernmost Northeast coast at the surface (Dossa *et al.*, 2021)

In a review by Shadman *et al.* (2019), the potential of renewable energy sources, including waves, tides, and thermal and salinity gradient, along the Brazilian coast was evaluated. The results showed considerable ocean current energies for the North and Northeast regions, with the maximum annual average of surface currents reaching 1.52 $m.s^{-1}$ (approximate power density of 500 $W.m^{-2}$) in the region known as Equatorial Margin. However, this investigation considered only the shallow currents (down until 50m), which disregard the potential of currents such as the subsurface NBUC. Taking this into account, the present work aims to investigate the potential for energy generation through currents in the SWTA at different vertical levels from a climatological dataset. Our hypothesis is that subsurface western boundary currents in the SWTA represent as much potential as surface currents as a source of renewable energy.

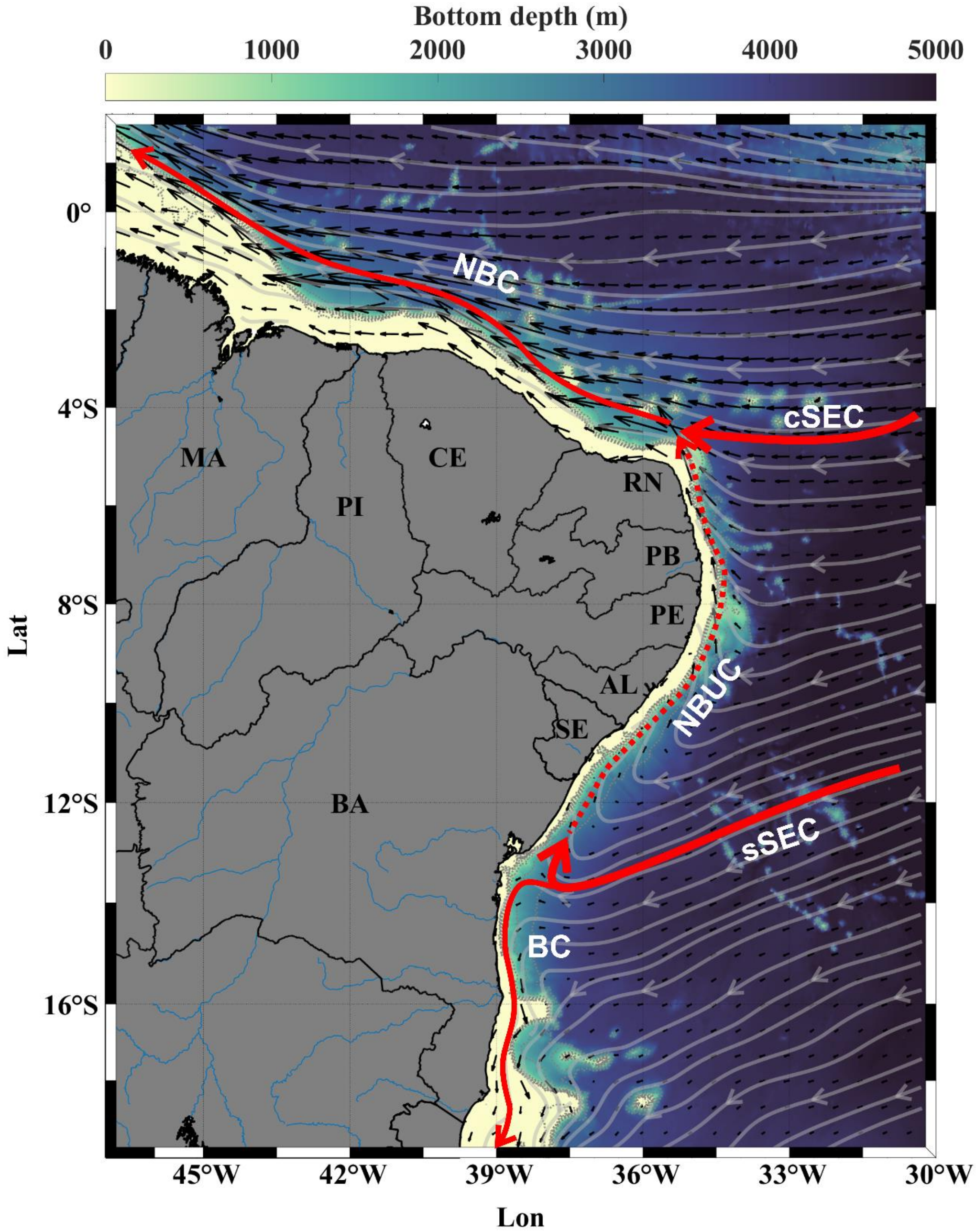

Figure 1. Study region showing bottom depth (colormap), current vectors (black arrows) and streamlines in the Southwestern Tropical Atlantic (SWAT). Schematic red arrows demonstrate the direction of the zonal flows for the central and southern branches of the South Equatorial Current (cSEC and sSEC, respectively) and the Western Boundary Currents: North Brazil Current (NBC), North Brazil Undercurrent (NBUC, dashed) and Brazil Current (BC). Northeast Brazil states: Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE) and Bahia (BA).

MATERIAL AND METHODS

For our analysis we used climatological data comprised by the monthly mean of 23 years (1993 to 2016) of current velocity, salinity, and temperature in our study region. The data was extracted from Global Ocean Physics Reanalysis product (https://doi.org/10.48670/moi-00021) provided by Copernicus Marine Service. The product has the NEMO platform as the model component, forced at the surface by the ECMWF ERA-Interim and ERA5 reanalysis. Remote measurements of sea level anomaly, sea surface temperature, sea ice concentration and *in situ* temperature and salinity vertical profiles are the assimilated to the model to increase model accuracies. This product has horizontal resolution of 1/12° (~8 km) and 50 vertical levels, however, we restricted our analysis to the first 35 vertical levels from surface to 902m, considering that bellow this depth, only slow currents (<0.5m.s^{-2}) can be observed in our study region (not shown).

Ocean current energy can be estimated as the amount of marine-hydrokinetic energy that flows through a unit cross-sectional area oriented perpendicular to the current direction per unit time (Lowcher *et al.*, 2017) expressed in Eq. (1) as the current power density (P) in W.m^{-2}. In this equation, S is the flow speed (in m.s^{-1}) and ρ is the density of seawater in kg.m^{-3}. It should be noted that Shadman *et al.,* (2019) used the same Copernicus product, for different years, for their estimative. However, they considered ρ in the as a constant density of 1025 kg.m^{-3}. We decided instead to use the density of seawater in kg.m^{-3} as a function of temperature, salinity depth and latitude given by the *gsw_p_from_z* function from the GSW package (https://www.teos-10.org/software.htm)

$$P = \frac{1}{2}\rho S^3 \qquad (1)$$

We obtained current power density (CPD) for each level evaluated in terms of the annual mean from the climatology. We summarized our results in terms of the vertical maximum current power density (MCPD) and the associated depth to identify hotspots of CPD along depths and geographic location. Additionally, we present the monthly data to provide a seasonal context for the hotspots identified.

RESULTS AND DISCUSSION

We present our results for the only where the current power density was higher than 300 W.m^{-2}. We restrict our findings to latitudes bellow than 12°S, since low values for all level depths evaluated were found at latitudes higher than 12°S.

As expected, the results for the first 50m, showing considerable ocean currents energy in restricted to the Northern Northeast region (**Figure 2a**), were coherent with the estimates by Shadman *et al.* (2019). However, the presence of an undercurrent (NBUC) in the region led us to interesting findings.

Intermediary values, between 250 and 500 $W.m^{-2}$, were observed on the surface associated with intermediary values of the NBC (**Figure 2a,b**) and bellow 100m associated with the shallowing NBUC (**Figure 2c,d**). Highest values (>500 $W.m^{-2}$), were also associated with NBC at the surface (**Figure 2a,b**) and NBUC core depth – that decreases from 222m at 10°S to 156m (**Figure 2e,f**) at 4°S – while only low values (< 300 $W.m^{-2}$) were observed in the BC region (not shown). Slower (<0.6 $m.s^{-1}$) currents bellow 500m lead to low CPD (<250 $W.m^{-2}$) for the whole region (**Figure 2g,h**).

The vertical Maximum Current Power Density (**Figure 3a**) was used to summarize annual mean results and highlight hotspots of CPD in different depths, while MCPD depth (**Figure 3b**) was used to identify at which depth these hotspots are found. Locations with MCPD higher than 1000 $W.m^{-2}$ (>1.25 $m.s^{-1}$) (Blue line in **Figure 3a,b**) were found along the shelf-break at the surface offshore of Maranhão (MA hotspot; red arrow) and Ceará (CE hotspot; yellow arrow) coasts, and off-shore of Rio Grande do Norte (RN hotspot; green arrow) and Paraíba (PB hotspot; blue arrow) at 156 and 222m, respectively (**Figure 3a,b**). The maximum values were observed at the RN hotspot, were MCPD reached annual mean of 2000 $W.m^{-2}$ at the center of the hotspot.

We used the standard mean deviation of the monthly data at the depth of the Maximum Current Power Density as a measure of the seasonal variability (**Figure 3c**). This variability was higher at the MA and CE hotspots (in the surface) and lower at RN and PB hotspots **(Figure 3c)**. We also defined one vertical cross-section for each hotspot identified and, the locations are presented in **Figure 3c**.

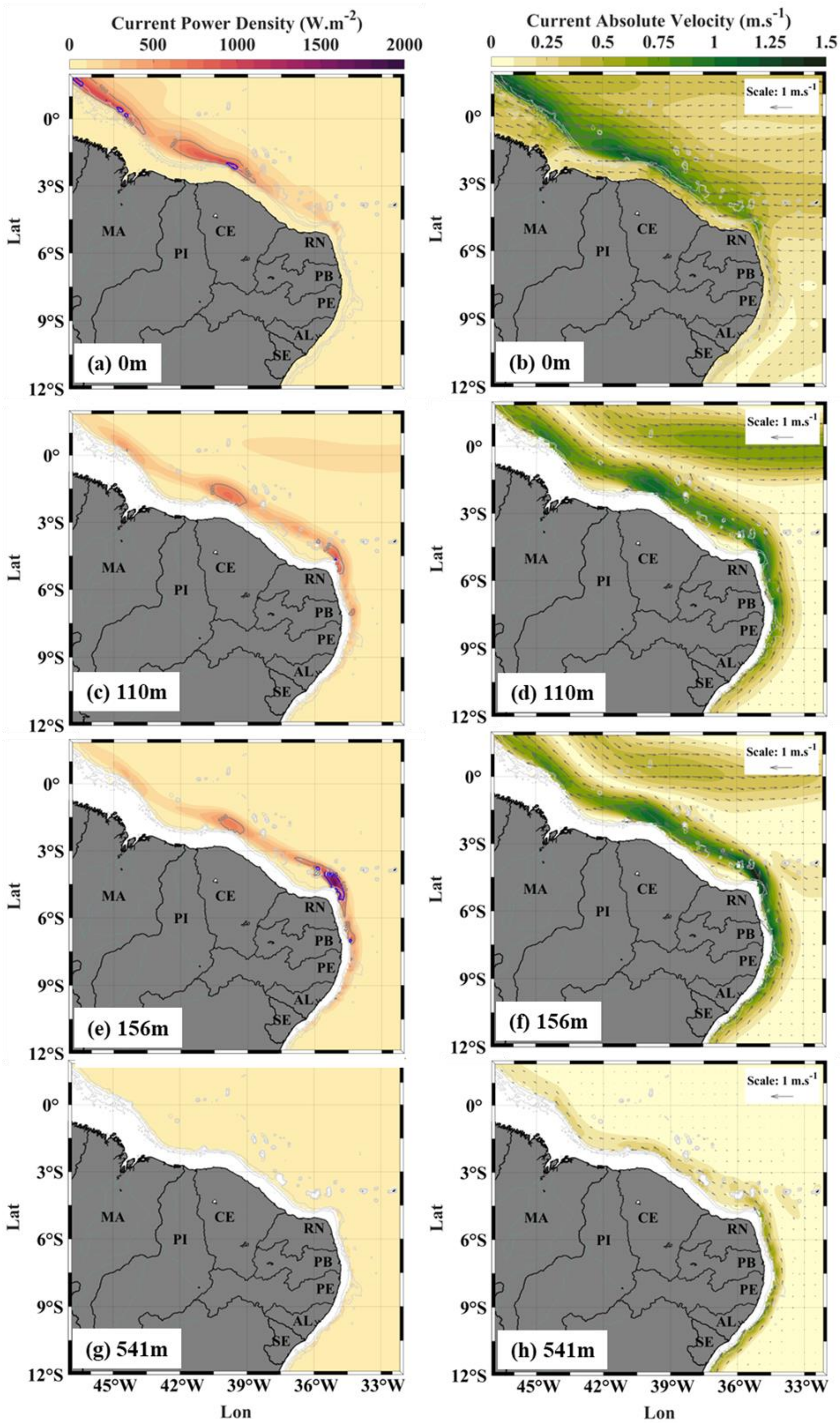

Figure 2. Annual mean of Current Power Density (a,c) and current velocity (b,d) at the surface (a,b) and 110m (c,d).

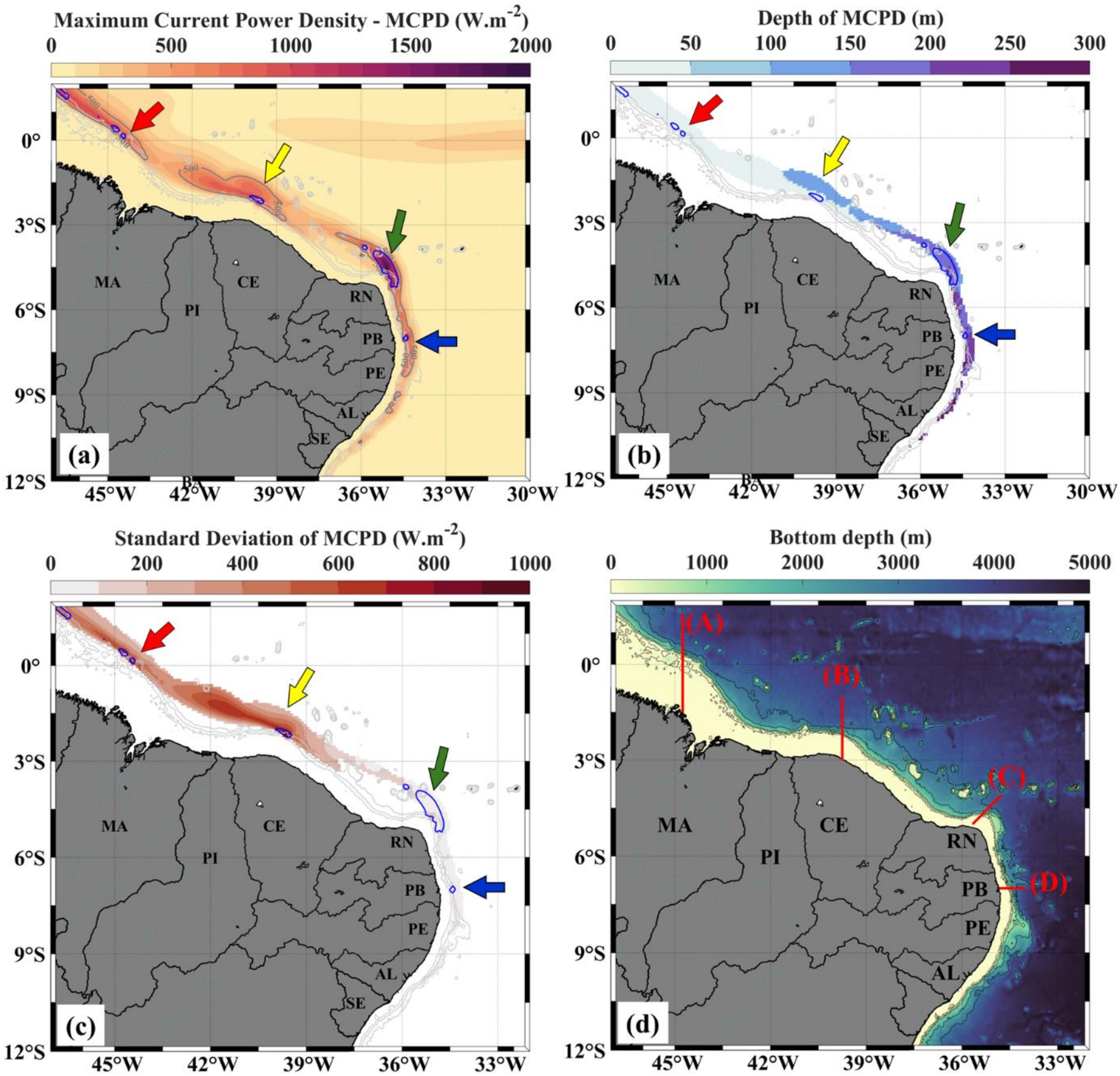

Figure 3. Colormap shows (a) annual mean of maximum current power density (MCPD) and (b) depth of MCPD. We show only depths for MCPD higher than 300 W.m^{-2}. Hotspots for current power density higher than 1000 W.m^{-2} are highlighted by blue contour line. Standard deviation of CPD is shown to demonstrate seasonal variability of Current Power Density at the depth of the MCPD. Hotspots vertical cross-sections are represented in (c) as the red lines (A to D).

Figure 4 shows the annual mean configuration of CPD along the cross-sections (left panels) and the standard deviation (right panels) shows that the highest variability for all hotspot is in the upper 100 m, which affects MA and CE but not the RN and PB hotspots cores. Current velocity climatology at the surface for the northern portion of the study region (**Figure 5**) explains the high standard deviation found for MA and CE hotspots. The seasonal pattern stronger along-shelf currents (>1.2 m.s^{-1}) between May and August (**Figure 5e-h**) and weaker currents for the remainder of the year. This is coherent with the positive coastal northwestward alongshore wind stress that onsets in May and peaks in austral winter, related to the annual migration of the ITCZ in the western equatorial region (Johns *et al.*, 1998). In contrast, at the eastern portion (**Figure 6**), the undersurface currents do not show the marked seasonality and the relatively stable current core provides a high CPD all year along for RN an MA hotspots. Subsurface currents, when compared with their surface counterparts demonstrate greater stability over time, as they are less susceptible to seasonal and climatic variations (Fonseca *et al.*, 2004) due to the lesser influence of wind and solar radiation (Barnier *et al.*, 2001; Fonseca *et al.*, 2004). This stability should make the energy provided by undercurrents more reliable throughout the year.

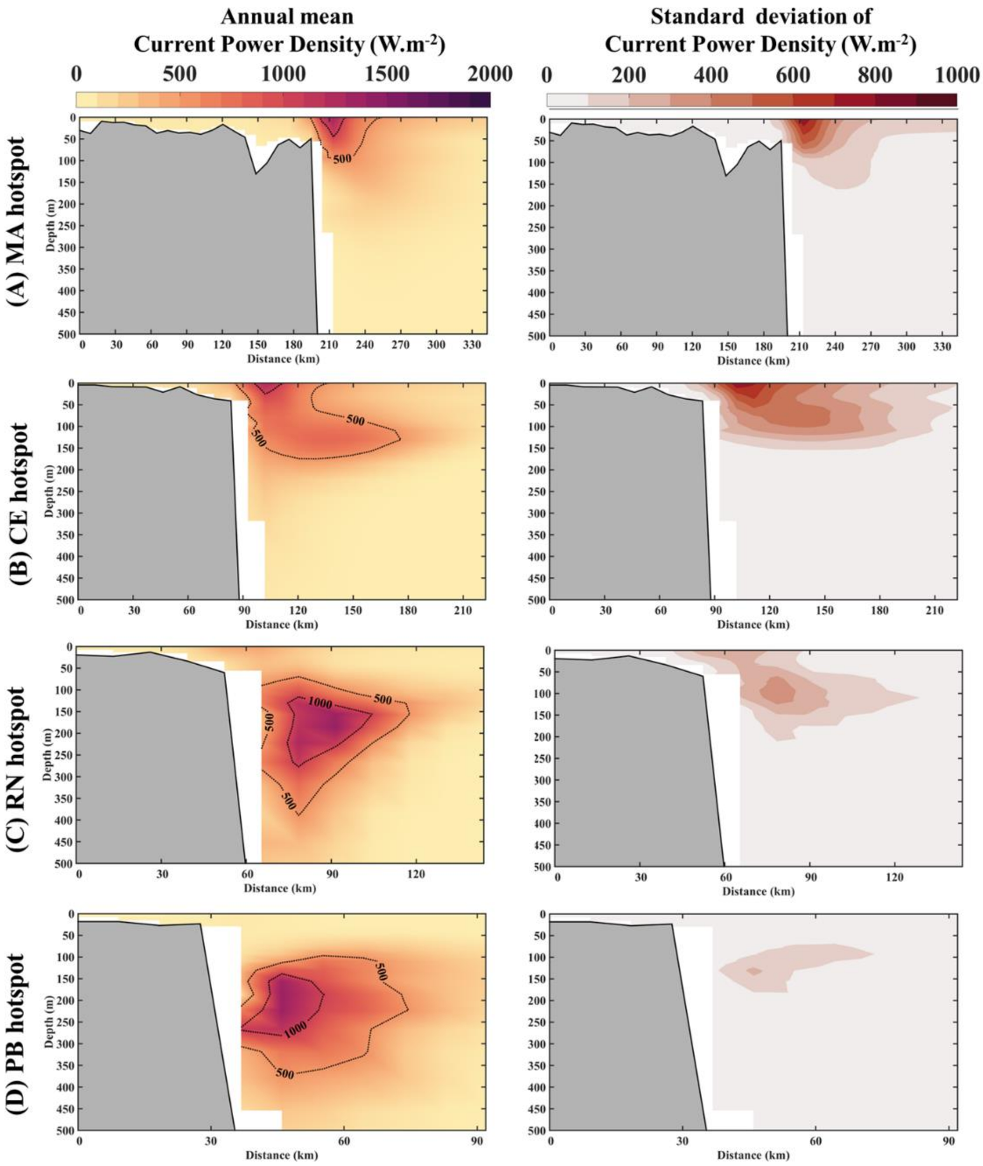

Figure 4. Vertical cross-sections of current power density annual mean (left panels) and standard deviation (right panels) for the Maranhão (A), Ceará (B), Rio Grande do Norte (C) and Paraíba (D) hotspots. The locations of the cross-sections are presented in **Figure 3d**.

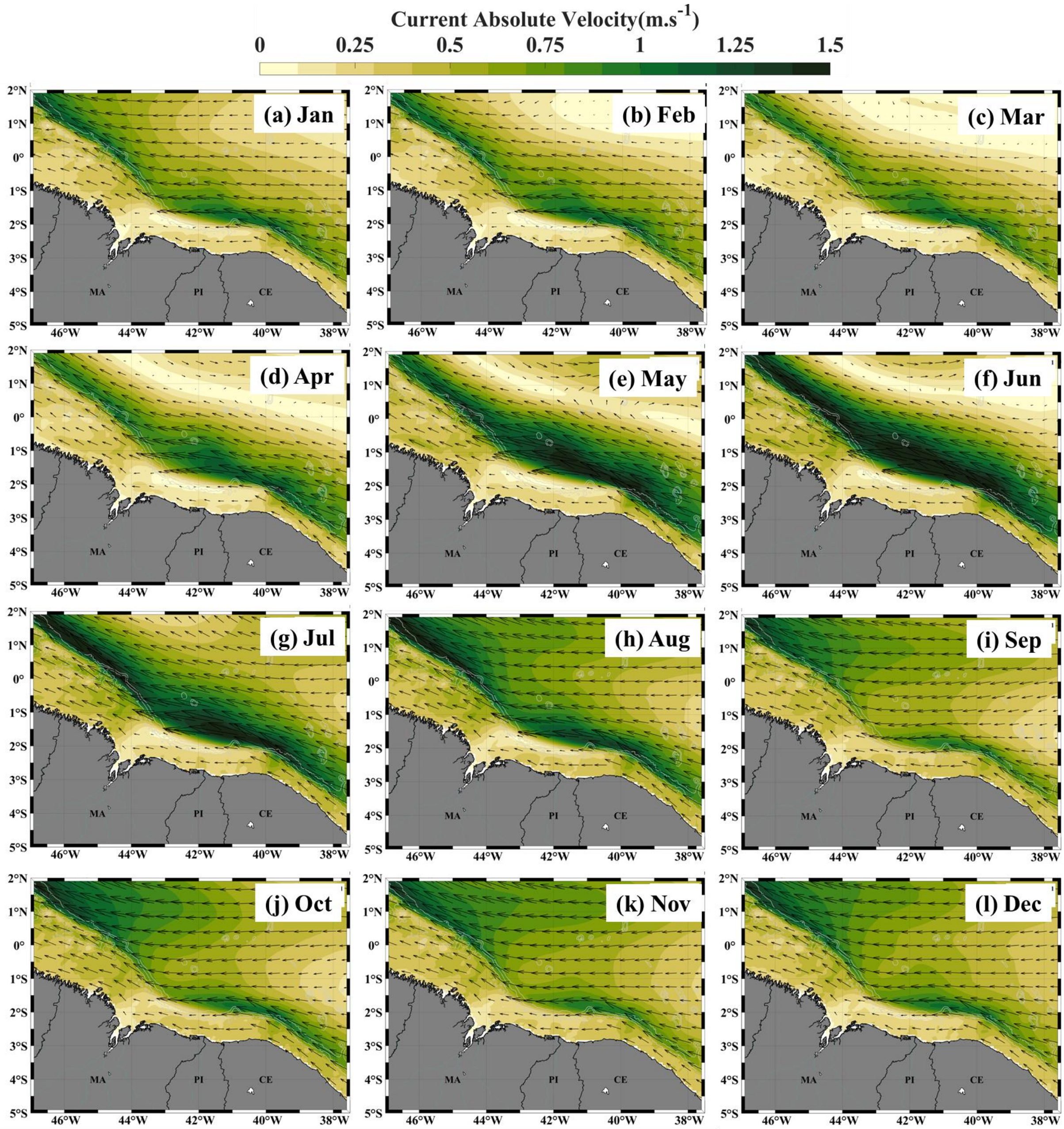

Figure 5. Absolute Current velocity (m.s^{-1}) climatology (monthly mean) at the surface for the Northern portion of the study region.

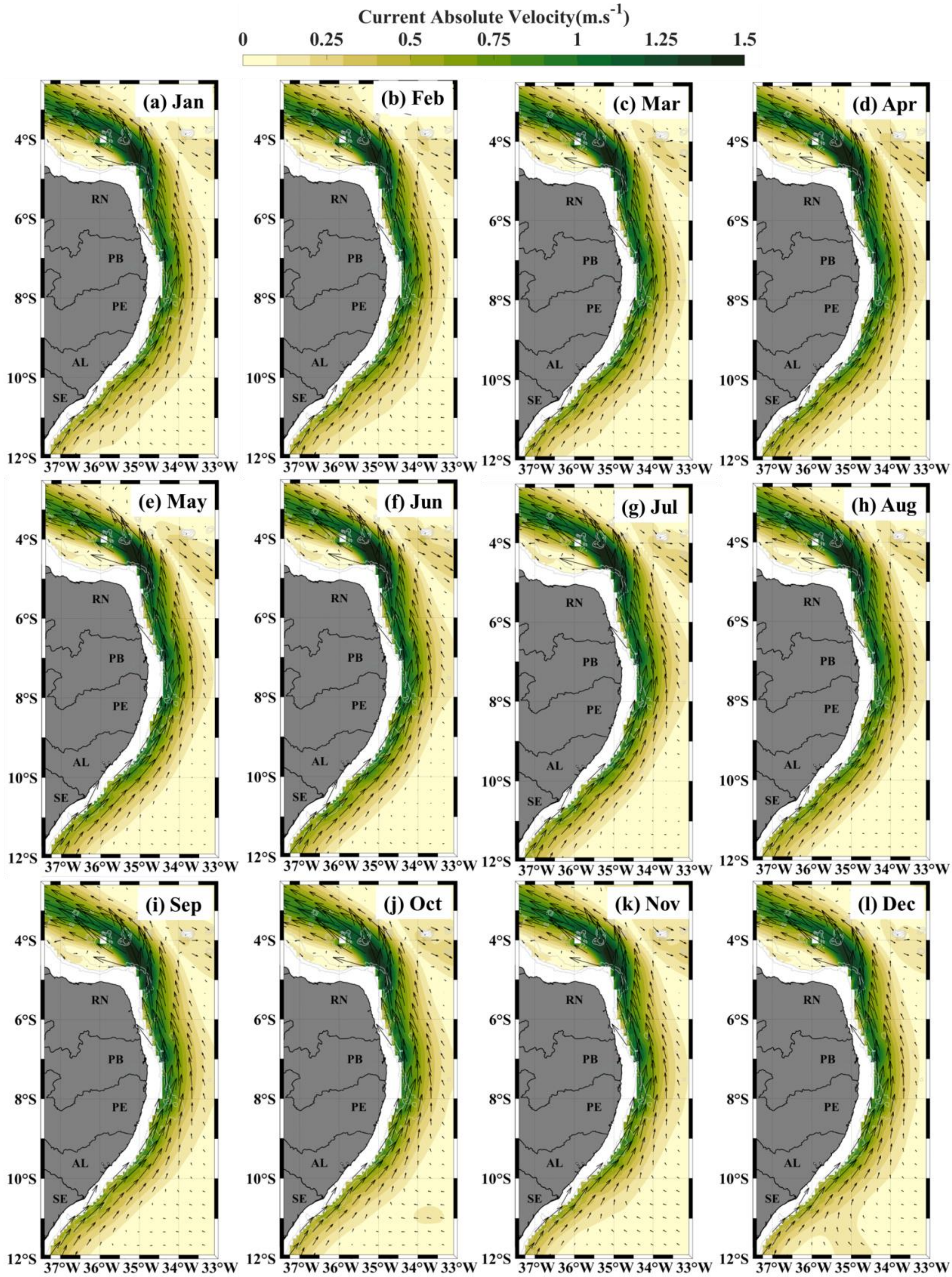

Figure 6. Absolute Current velocity ($m.s^{-1}$) climatology (monthly mean) at the surface for the eastern portion of the study region.

Physical mechanisms related to the hotspots

MA and CE hotspots are most likely related to increase of velocity due to flow interactions of the NBC with the adjacent continental shelf. NBC flows northwestward along the continental slope, that constrains the current flow accelerating the velocity (Johns *et al.*, 1998; Prestes *et al.*, 2018). However, when the isobaths change the direction from NW/SE to W/E around 41°W/2.25°N the NBC expands, flowing into the shelf, and the velocity decreases until the isobaths changes again tom NW/SE and velocity starts to increase again (**Figure 2b**). Some observations by Johns *et al*. (1998) and Prestes *et al.* (2018) corroborate this these findings.

The RN hotspot (~150m) is located at the transition zone where the NBUC is shallowest and encounters the central branch of the South Equatorial Current to originate the NBC (Dossa *et al.,* 2021). However, the high velocities (>1.0 $m.s^{-1}$) observed in this work are linked to the offshore (northwestward) core of the Potiguar Eddy, that extends vertically from 120 to 160 m (Krelling *et al.*, 2020). The genesis of this eddy is related to the NBUC dynamics separating from the continental margin north of Cape Calcanhar, and subsequently reattaching to it and recirculating (Krelling *et al.*, 2020). The feature of quasi-stationary of this Eddy, might be responsible for the sustained stability of this hotspot along the seasons.

Values above 500 $W.m^{-2}$ along the slope offshore of Pernambuco (PE) and Paraíba (PB) states were related to the shallowing and strengthening of the NBUC core (~1.25 $m.s^{-1}$ between 150 and 250 m) with decrease in latitude, associated with higher density waters from uplift related to flow-topography interaction process previously reported by Silva *et al.* (2022). The peak at 7°S (PB hotspot) is mostly likely related to the change in coastline (and isobaths) direction (Krelling *et al.*, 2020) and the observed velocity values agree with the observation data between 8°S and 7°S (Dossa *et al.*, 2021).

For all hotspots evaluated, some level of Flow-Topography Interactions (FTI) has a play in the strong current flows. FTIs can increasing flow velocities and kinetic energy in marine currents along the continental margin or canyons (Oke and Middleton, 2000; Allen and Hickey, 2010; Schaeffer and Roughan, 2015; Girton *et al.*, 2019). The identification of FTI hotspots should, therefore, contribute to finding locations economically viable for extracting energy from marine currents, especially where flows exceed may exceed 1 m.s^{-1}.

Challenges and opportunities for current power generation

FTI hotspots, beyond increasing current kinetic energy as pointed in the previous section, are also known to increase primary productivity and aggregate of marine organisms in many regions around the world (Huthnance, 1995; Acha *et al.*, 2004; Genin, 2004). The evaluation of current marine potential for energy production should consider the possible environmental impacts of the related infrastructure. However, there is a significative knowledge gap regarding the potential impacts of the current turbines and mooring. Rourke *et al*. (2010) raised some potential issues that should be investigated in the deployment of marine current energy devices (MCEDs) that include impacts on marine mammals, fish and fisheries, local effects, underwater archaeology and recreational activities. They also highlighted that the major known impact of MCEDs is the pollution due to oil leakage from hydraulic systems which could affect the surrounding environment. The impacts of the MCEDs are beyond the scope of the present work and should be investigated in future works. Here we are interested in specific challenges for the implementation of systems such as the Cross-stream Active Mooring (CSAM) that will be discussed further ahead.

Considering the stability of the quasi-permanent flow of the North Brazil Undercurrent, the RN and PB hotspots should be the more attractive for current power generation. However, one of the major challenges to current energy exploitation is related to the depth of these hotspots (bellow 150m). Most of the existing MCEDs are not applicable to harness deep current structure since most of them are moored on the bottom or fixed to a floating structure (Rourke *et al*., 2010). The latter should be viable for MA and CE hotspots. For the undersurface current an innovative cost-effective system such as the Cross-stream Active Mooring (CSAM) may increase generation capacity and energy efficiency solving some challenges in power plant implementation (Tsao *et al.,* 2017; 2018; 2023;2024; Tsao and Feng, 2019).

The functioning of CSAM is based on a system composed of multiple energy-generating turbines, anchored in series on a common cable and stabilized by actively adjusted hydraulic sails (Tsao *et al.,* 2018). In this manner the system can be anchored in shallow bottom – instead of the deep bottom under the velocity cores – at a more favorable type of substrate and outside biological sensitive areas. Additionally, it allows for precise adaptation to the dynamics of the currents, including vertical movement and meandering ensuring efficient capture of the kinetic energy of ocean flows (Tsao and Feng, 2019). The automated control of hydraulic sails, in response to the real-time flow velocity field, provides the system with the ability to maintain the linear line close to neutral buoyancy, even under variable current conditions (Tsao e Feng, 2019). The reduction in submarine engineering costs, resulting from the serial disposition of turbines anchored at a single point, economically enables the implementation of large-scale systems (Tsao *et al.,* 2017; 2018; 2023). For our study region, to keep the turbines at the observed depths for the undercurrents on the RN and PB hotspots, the system could be moored at the continental shelf-break or slope while the hydraulic sails should be adjusted for greater depths (150 to 250m).

The presence of benthic ecosystems such as the Brazilian reef systems may present as a major challenge for mooring along the continental shelf-break and/or slope. The MA hotspot is situated within the Amazon Reef System and the RN and PB within the Eastern Brazilian Reef System. The Amazon Reef System is characterized by a wide depth range, potentially extending down to 220 meters (Carneiro *et al.*, 2022). The reefs within this system play a significant role as an ecological bridge between the Southwest Atlantic and the Caribbean (Soares *et al*., 2019; Carneiro *et al.*, 2022). The Eastern Brazilian Reef System is characterized by the presence of shallow (<30m) and mesophotic (30-150 m) reefs along the continental shelf (Carneiro *et al.*, 2022). The reefs in this area harbor a vast diversity of marine species, promoting local biodiversity and contributing to the resilience of marine ecosystems in the region (Leão *et al.*, 2016). Among all hotspots, only the CE Hotspot lies outside the influence area of the reef systems. However, this distinction does not eliminate the need for conducting environmental impact assessments, adopting low-impact technologies, and implementing rigorous environmental monitoring practices. In this context, a high-resolution mapping of the shelf-break reef ecosystems is needed to evaluate the possibility of mooring outside these biological sensitive areas.

In terms of the substrate for mooring current energy systems, outside the reef ecosystems, the calcareous composition of the substrate and sparse coverage of gravel in the sedimentary basins of Pará-Maranhão (Soares *et al.*, 2007), Ceará

(Condé *et al.*, 2007), Potiguar (Neto *et al.*, 2007) and Pernambuco-Paraíba basins (Córdoba *et al.*, 2007), should not represent a major challenge.

Beyond the challenges presented above, distance from the coast may hamper the viability of current power generation. Average distance between the center of the hotspot and the closest coastal cities reached 190 km, 90 km, 65 km and 40km in relation to MA, CE, RN and PB hotspots, respectively. From a commercial point of view, the PB hotspot becomes the most attractive since the continental shelf is the narrowest compared to the other states. On the other hand, the distance of the other hotspots from the coast should significantly increase the costs in infrastructure for commercial purposes.

Figure 7 present the MCPD hotspots in relation to the sedimentary basins and oil and gas (O&G) exploratory blocks (ANP, 2023) of the Brazilian Equatorial Margin – considered as a new frontier in terms of oil and gas exploration and exploitation (Krelling *et al.*, 2020). Offshore exploratory blocks of Potiguar and Pará-Maranhão basins are located within the RN and MA hotspots, which reveals the opportunity of integrating offshore current energy production with already-installed O&G platforms. The need to decrease carbon footprint to mitigate climatic change impacts stimulate research concerning the use of renewable sources such as wind, solar and wave energy at off-shore oil rigs (Kumar *et al*., 2015; Oliveira-Pinto *et al*., 2019; 2020; Gu *et al.*, 2021; Zereshkian and Mansoury, 2021; Zheng *et al*., 2022). The use of the existing offshore infrastructure for renewable energy generation is also considered as an option for decommissioning oil and gas platforms (Bernstein, 2015; Henrion et al., 2015; Leporini et al., 2019; Sommer et al., 2019). However, to our knowledge it was never considered for current energy. In particular, the stability of the RN hotspot can be advantageous due to the need for continuous energy supply at those structures. In addition, the existing infrastructure and expertise at these sites can reduce costs and resources (Jefferys, 2012; Tiong *et al.*, 2015; Klabučar *et al.,* 2020) this includes the technology for deep "pré-sal" exploitation that already exists in Brazil. Whether active or inactive offshore platforms for production and exploration of oil and gas have infrastructure that may facilitate the installation and use of energy plants in the region. However, marine current energy technology is still not economically viable on a large scale due to its current stage of development (Rourke *et al.*, 2009).

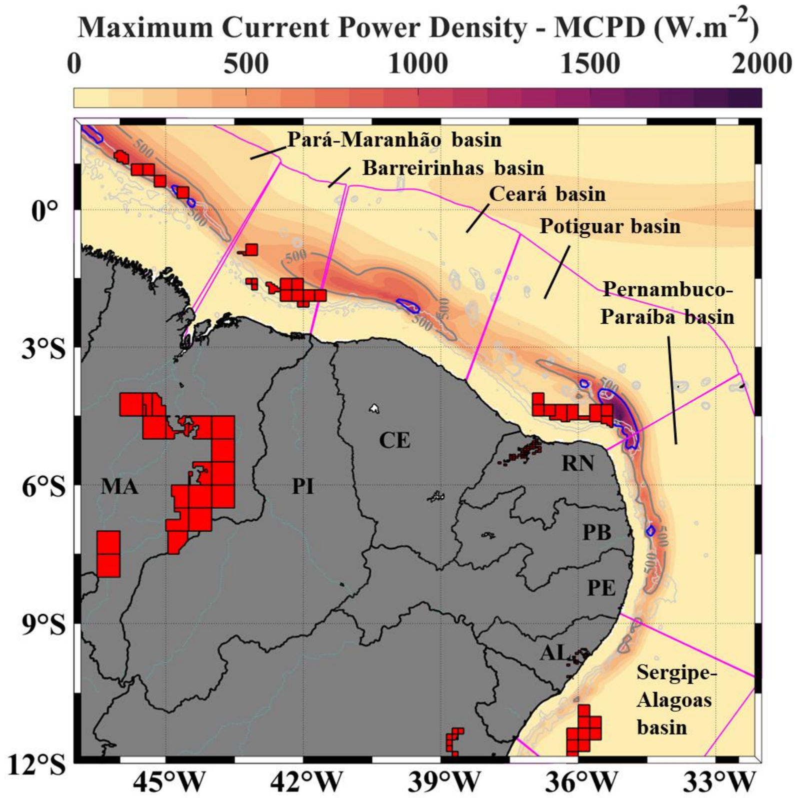

Figure 7. Location of the Explorations Blocks (red boxes) and sedimentary basins in relation to the Maximum Current Power Density in the study region.

Lastly, it should be notice that we used climatology in this work, which correspond to an idealization of expected seasonal patterns. But several processes from large scale (interannual variability, climate signals) to local and mesoscale (meandering, eddies) factors can change current dynamics. For the region under NBC influence, for example, the climatology does not consider the tides, that have primordial importance for the dynamics (Prestes *et al.,* 2018) and should therefore, affect current dynamics at the MA hotspot.

The inference of interannual variability for the eastern margin of our study region (between 10°S and 4°S) is impaired by the lack of long-term current measurements along the continental margin shelf. In particular, the lack of in-situ long-term marine current measurements, leads to a dependence of global models and climatology that may not represent today's configuration of the current dynamics. For the Northeast Brazil, the oldest monitoring system in the region are the mooring lines at 11°S (Schott *et al.*, 2005; Hummels *et al.*, 2015). For this reason, we included here as a challenge the implementation of monitoring systems in the NBUC low latitude (<10°S). These systems are important not only for the identification of patterns and variability for marine current energy purposes, but also in the context of climate change (see Todd *et al.*, 2019). The NBUC is a part of the Atlantic Meridional Overturning Circulation (AMOC), that is responsible for interhemispheric heat exchanges in the Atlantic and has a role in global climate. Recent works investigate the AMOC collapse due to climatic changes (Ditlevsen and Ditlevsen, 2023; Nian *et al.*, 2023) and although the impacts are still under investigation, the need for long term observation of current flows and early-warning signals of AMOC collapse is of critical importance (Ditlevsen and Ditlevsen, 2023). Indeed, our investigation of the climate patterns do not consider the projected changes in the Southwestern Tropical Atlantic boundary currents.

SUMMARY AND FINAL CONSIDERATIONS

IPCC (2023) report show the need to reduce greenhouse gas emissions and energy dependence on fossil fuels. However, oil and gas exploration in the Equatorial Margin remains prominent in Brazil. The need to migrate the energy mix to more sustainable energy sources is one of the main requirements towards mitigation of climatic change. Energy harnessed from marine currents presents as a cleaner and more sustainable option as an energy renewable source. Previous work evaluated the potential of energy generation from marine currents in the Southwestern Tropical Atlantic (SWTA), however, only from surface currents.

Subsurface currents play a vital role in global ocean circulation, transporting heat, nutrients, and energy over vast oceanic expanses (Stramma *et al.,* 1995). Including subsurface currents in the assessment of ocean energy generation potential offers considerable advantages in terms of optimizing the location and design of current energy devices. By considering not only surface currents but also deeper and more constant currents, the design of MCEDs can be more precisely tailored to local conditions, maximizing the utilization of available energy sources.

We investigated current energy potential of surface and subsurface currents through the current power density calculations for the SWTA. Our results revealed four hotspots for current energy production, all of them trace back to flow topography interactions and two of them (RN and PB hotspots) linked to the subsurface North Brazil Undercurrent. The potential for current energy from subsurface current was higher (annual average >1000 $W.m^{-2}$; ~2000 $W.m^{-2}$ at RN hotspot) than from surface current, resulting mostly from the stability along season of this current. NBUC exhibited maximum values above 1.25 $m.s^{-1}$ at the hotspots between 150 and 250 meters. We highlighted some challenges and opportunities for each of the hotspots comparatively, which included depth of current core (RN and PB hotspots), closeness to the coast (PB hotspot), closeness to oil and gas exploration blocks (MA and RN hotspot), and absence of deep reef system at the subjacent shelf (CE hotspot).

It is important to note that undersurface currents in this work not only complemented surface currents in terms of energy availability but also offer a more stable and consistent source of kinetic energy. These characteristics provide a solid foundation for renewable energy generation in a continuous and reliable manner. Additionally, with some adaptations, systems such as the Cross-stream Active Mooring – that allows the harnessing of current energy in subsurface waters – can be used to harness energy from the NBUC core. However, research on energy generation from marine currents is still in its early stages and, to our knowledge, this system is still in the development phase and was not implemented anywhere in the world.

Many gaps in general knowledge of the environmental impact of marine turbines can hamper the future development and implementation of marine current plants. Therefore, the previous assessment of marine ecosystems state along the SWTA is required prior to the implementation of current energy systems. Additionally, to complete the investigation of current energy potential in the region, further research and observational long-term timeseries analysis needs to be considered, since the role of interannual variability of the NBUC (between 4°S and 11°S) is obscured by the lack of significative long term in-situ measurements. The hotspots for both, flow-topography interactions and marine current energy potential makes their locations good for the implementation of mooring arrays.

Lastly, considering the increasing need for the energy renewable resources, we recommend that future works in the development of turbine systems and mooring for marine current energy production consider not only the surface, but also the undersurface current systems.

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ANEXO A – NORMAS DE PUBLICAÇÃO DA REVISTA JOURNAL OF MARINE SYSTEMS

NEW SUBMISSIONS

Submission to this journal proceeds totally online and you will be guided stepwise through the creation and uploading of your files. The system automatically converts your files to a single PDF file, which is used in the peer-review process.
As part of the Your Paper Your Way service, you may choose to submit your manuscript as a single file to be used in the refereeing process. This can be a PDF file or a Word document, in any format or lay-out that can be used by referees to evaluate your manuscript. It should contain high enough quality figures for refereeing. If you prefer to do so, you may still provide all or some of the source files at the initial submission. Please note that individual figure files larger than 10 MB must be uploaded separately.

References

There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/ book title, chapter title/article title, year of publication, volume number/book chapter and the article number or pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct.

Formatting requirements

There are no strict formatting requirements but all manuscripts must contain the essential elements needed to convey your manuscript, for example Abstract, Keywords, Introduction, Materials and Methods, Results, Conclusions, Artwork and Tables with Captions.
If your article includes any Videos and/or other Supplementary material, this should be included in your initial submission for peer review purposes.
Divide the article into clearly defined sections.

Please ensure your paper has consecutive line numbering this is an essential peer review requirement.

Figures and tables embedded in text

Please ensure the figures and the tables included in the single file are placed next to the relevant text in the manuscript, rather than at the bottom or the top of the file. The corresponding caption should be placed directly below the figure or table.