SPATIO-TEMPORAL VARIABILITY OF OPTICAL WATER TYPES OVER THE BRAZILIAN OCEANIC EXCLUSIVE ECONOMIC ZONE BASED ON MULTI-SENSOR OCEAN COLOUR REMOTE SENSING

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ABSTRACT

This study aims to illustrate the interest in reflectance-based Optical Water Types (OWTs) classification for providing synthetical information on the spatio-temporal dynamics of the waters of the Brazilian Exclusive Economic Zone (EEZ). The 24-yr OWT time series provided by the multi-sensor OC-CCI data were used for describing the optical diversity of the whole Brazilian EEZ. Our results emphasize that the Brazilian EEZ corresponds to a mosaic of optically heterogeneous water masses reflecting modulations in terms of its biogeochemical quality. The impact of multiple oceanic and regional land-sea interaction processes controlling OWT distribution and temporal variability was further illustrated focusing especially on the seasonal modulations. Such optical classification could represent a valuable frame for monitoring the long-term modulation in the quality of Brazilian waters while this study further emphasizes the need to consider the optical heterogeneity of Brazilian waters for optimizing ocean color products at a regional scale.

Keywords — Ocean colour; Optical water types; Temporal variability, Blue Amazon.

1. INTRODUCTION

Optical classification roughly divides the water types into Case 1 and Case 2. Case 1 waters are those for which optical properties are determined primarily by phytoplankton pigments and where the other optically significant constituents (Coloured Dissolved Organic Matter, CDOM and Non-Algal Particles, NAP) covary with chlorophyll-*a* concentration (chl-a). On the other hand, Case 2 waters are the ones for which optical properties are not necessarily dominated by phytoplankton and where CDOM, NAP, and chl-a can present decoupled dynamics [1].

The water classification provides relevant information concerning the absorption of optical constituents at certain wavelengths. However, coastal waters can have a high level of spatio-temporal complexity. The optical water type (OWT) classification scheme can differentiate coastal waters into classes through the analysis of variables that modulate the colour of the ocean.

Several studies have moved toward the classification of OWTs based on cluster analysis [2], fuzzy logic [3], and weighted means [4], making use of the remote sensing reflectance (Rrs) spectra. An extensive list of OWTs classification on regional and global scales was presented by [5] and [6]. Among the cited studies, [2] generated 16 OWTs over global coastal waters using satellite-derived Rrs. Recently, global classification maps have been derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor with an increase to 21 OWTs [7].

OWTs classification proposed by [3] was adapted to be used for accuracy and uncertainty assignment for climate studies in satellite multi-sensor products derived by the Ocean Colour Climate Change Initiative (OC-CCI) [8]. This approach uses 14 OWTs to differentiate the colour of the ocean globally.

Up to now, previous optical classifications of the Brazilian waters were performed at a regional scale. 3 OWTs were defined in the inner continental shelf adjacent to Santos Bay [9]. 8 OWTs based on Rrs spectral shape and magnitude representing different limnological characteristics of Brazilian inland waters were defined by [10]. An OWT classification in the Lower Amazon region and its tributaries was conducted by [11], with an identification of 4 OWTs with their predominance to the hydrological dynamics of the Amazon waters (floods and droughts) and strong seasonal variability.

The objective of this study is to characterize the optical diversity of the Brazilian oceanic Exclusive Economic Zone (EEZ) based on a time series of multi-sensor remote sensing reflectance over a period of 24 years (1997-2021). We present a general description of the distribution of OWTs and discuss the temporal dynamics of optical characteristics, especially on the seasonal scale of variability.

2. MATERIAL AND METHODS

2.1. Study area

The Brazilian EEZ comprises the tropical and subtropical waters of the Western South Atlantic. The Brazilian coastline extends along ~8,000 km, from Cape Orange (4° N) to Chui (34° S). The largest shelf extensions (~160 km on average) are found in the North, Southeast, and South regions. The Northeastern and part of the Eastern shelf regions are narrow in width (~60 km on average) [12].

Offshore, the Brazilian water masses are influenced by the South Equatorial Current (SEC), which reaches the Brazilian shelf between 11-15° S [13]. Part of the SEC flows northward being renamed as North Brazil Current (NBC). The NBC continues flowing to the west with exception periods when the North Atlantic Gyre interacts with the NBC changing its offshore waters to the east [14].

The remaining part of SEC flows southward as the Brazil Current (BC) [15]. Along the BC path, eddies and vortices are generated by moving towards the shelf break creating an upwelling of nutrient-rich South Atlantic Central Water (SACW). Seasonal events such as wind-driven coastal upwelling [15-16] and continental runoff in coastal waters are intensified in austral summer. The Southern region is influenced by the Patos Lagoon and La Plata river plumes mainly during winter with the weakening of the BC and the increase of cold front passages [17].

2.2. Satellite data

The ocean colour merged Ocean Colour Climate Change Initiative, version 5.0 (OC-CCI, [18]) data set covering the last 24 years (09/04/1997-12/31/2021) was considered in the frame of this study.

The OC-CCI OWTs are multi-sensor products based on medium spatial resolution satellites atmospheric corrected using the POLYMER algorithm and SeaDAS v7.3 processor [18]. The OC-CCI dataset was cropped using the Brazilian EEZ borders as a mask (https://www.marinha.mil.br/dhn/?q=node/169).

Specifically, monthly composites of water class products (henceforth only OWTs) at a spatial resolution of ~4 km were used to characterize the optical diversity of the Brazilian waters. These OWTs were defined from a classification scheme applied to normalized multispectral remote sensing reflectance (Rrs) spectra (standard MERIS wavelengths = 412, 443, 490, 510, 560, 665 nm) (Figure 1). Such normalized Rrs based classification aimed to focus on variation of the Rrs spectral shape providing better insights into the characterization of qualitative changes in the water optical properties [19].

The OC-CCI OWT considered here encompasses 14 classes, which numbers follow turbidity levels. OWTs 1 and 2 correspond to ultra-oligotrophic waters, while OWTs between 3 to 8 correspond to clear water with a gradual decrease in the blue band. OWTs 9 to 11 are characterized by an increasing signal in the green band (560 nm). OWTs from 12 to 14 correspond to turbid waters with an increase in the green and red bands (665 nm).

In order to facilitate the description of the Brazilian waters optical diversity, the latitudinal partition proposed by [12], dividing the Brazilian domain into 5 regions, was considered in the frame of this study. This approach was based on ecological criteria for the differentiation of ecosystems and is organized into bathymetry, hydrography, productivity, and trophic relationships.

From the OC-CCI data set, the monthly climatology for the 14 OWTs products was computed, considering the OWT dominance and the OWT relative contribution at a pixel-level. The temporal optical diversity of the Brazilian waters was further characterized by assessing for each pixel the number of dominant OWTs along the year (number of occurrences of different dominant classes over monthly climatological data).

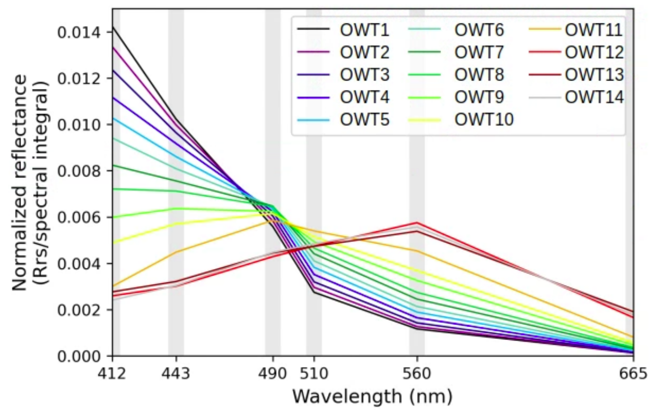

Figure 1. OWT average normalized Rrs spectra. Vertical gray lines represent the MERIS bands.

3. RESULTS AND DISCUSSION

Among the 14 OC-CCI OWTs, 12 are globally found over the Brazilian EEZ (OWTs from 3 to 14). The OWTs 1 and 2 characterize ultra oligotrophic waters present in oceanic gyres areas and were not observed in a significant proportion, only appearing in some months in the eastern boundary of the EEZ for a restricted number of pixels (Figure 2). The inner shelf waters are mainly characterized by the presence of OWTs 8 to 13, with OWT 14 being present only at very located areas corresponding to the ultra-turbid waters under the influence of the Amazon River waters or at other specific coastal environments (e.g. Patos Lagoon).

Focusing on each individual region, the North region (from the north to 5°S) presents a high optical diversity and dynamics, emphasizing the impact of the high dynamical regime on the mixing of OWTs in the corresponding area. The proximal part of the Amazon plume is characterized by the permanent presence of ultra-turbid waters here defined as OWT 14 (Figure 2). Conversely, the highest variability along the seasons is found in more offshore waters mainly due: 1) to modulations of the NBC intensity driving the extension of the Amazon River waters northwestards [13]; 2) to modulations in the Amazon River discharge [11,14].

The Northeast and East regions (5°S to 13°S and 13°S to 22°S, respectively) are mainly dominated by OWTs 3 and 5, presenting a lower optical diversity when compared to the other regions (Figure 3). A seasonal variation of the

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extension of OWTs towards the coast is observed in the NE and E region underlining seasonal variation in the influence of the SEC on the water masses distribution.

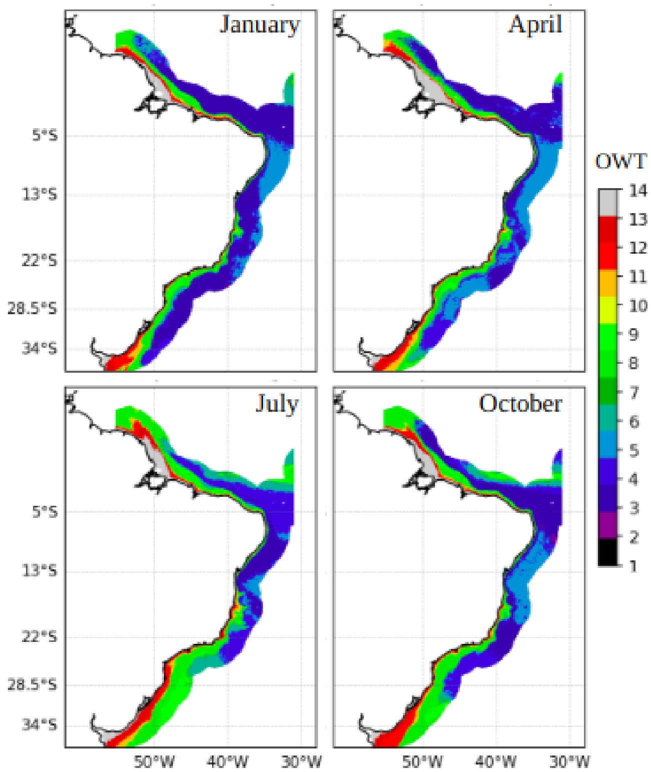

Figure 2. OWT predominance in monthly climatological composites computed over the 24 years of the OC-CCI data. The latitudinal grids represent the coastal zone division used to guide the analysis based on 5 regions [12].

Closer to the coast and up to the shelf break, water masses in these areas are classified as OWTs 8 and 9. Some OWTs corresponding to highly turbid waters (OWTs 13) can however be observed in some restricted areas (~18°S coastal zone) impacted by continental inputs of dissolved and particulate matter and also by wind-driven sedimentation forced by cold fronts passages (not shown) [19,20].

In the Southeast (22°S to 28.5°S) and South (from 28.5°S to south) regions, the OWT classification shows the highest optical dynamics (Figure 3) with the presence of up to 6 OWTs over one year for larger areas. The SE and S waters also show the largest extension in the more offshore area, with the presence of OWTs 8-9 contrasting with the NE and E regions. The latter features are related to the area's morphology (e.g. coastline geometry [16]), and meteo-oceanographic processes (e.g. NE winds and cold front intrusions [13,15-17]) driving the regional dynamics of the water masses, the latter being highly variable in time.

More precisely, the coastal zone in the SE and S regions shows a lower optical diversity related to the predominant contribution of the Tropical Water in the inner and middle shelves [21], explaining the presence of OWTs 8 and 9. This feature can be however seasonally modulated by the intrusion during winter of the La Plata River plume bringing more turbid waters (OWT 13). Offshore waters in the S and SE regions show the highest optical diversity in these areas as a consequence of the alternation of heterogeneous OWTs (Figure 4). This can be explained by seasonal variation of the intensity of the BC carrying oligotrophic waters during the summer (OWTs 3-5; Figure 4) while during the winter, there is a weakening of this current allowing the intrusion of more turbid water coming from the south (OWT 8-9; Figure 4) [17].

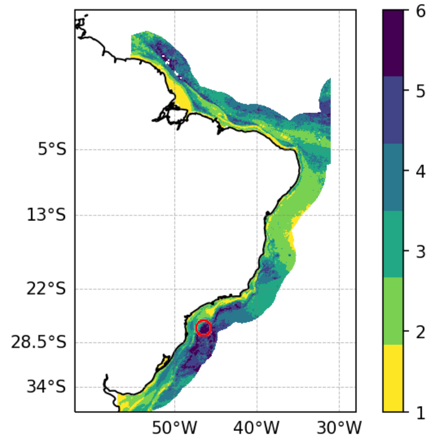

Figure 3. Number of OWTs on a pixel-by-pixel basis over one year (monthly climatology). The red circle at 27°S-46°W indicates a succession of 6 OWTs over one year.

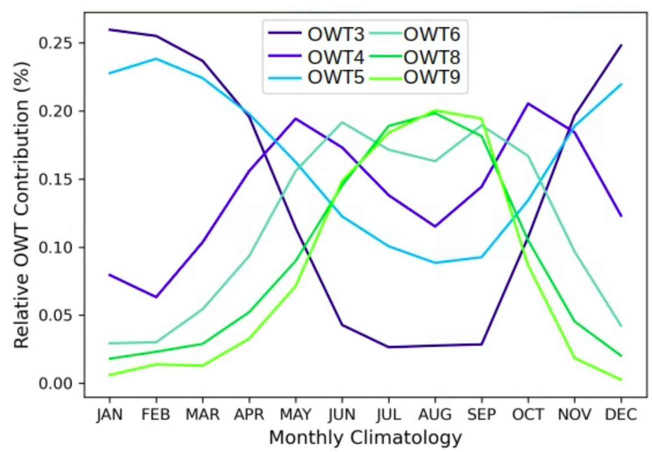

Figure 4. Principal OWTs monthly contribution at 27°S-46°W.

4. CONCLUSIONS

This study shows the spatio-temporal variability of water masses optically differentiable along the Brazilian EEZ. The dynamical characterization of the optical properties might represent a concise summary of the water's bio-optical and biogeochemical properties representing a promising proxy for monitoring the potential changes in the water masses through a synthetical descriptor.

Also, OWTs can be useful for evaluating the performance of ocean colour remote sensing algorithms considering the optical characteristics of the water masses. It is also potentially useful to combine the most adapted ocean colour remote sensing algorithms for different optical water types [22].

The OWT approach classified the Brazilian waters as expected showing the areas with low and high diversity. Further studies may combine OWTs which show the same variability on time or the necessity to create a new class for a specific region.

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