ASSESSING THE EFFECTS OF THE PASSAGE OF COLD FRONTS ON SATELLITE-DERIVED CHLOROPHYILL IN THE SOUTH BRAZIL BIGHT

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ABSTRACT

The South Brazil Bight (SBB) is oceanographically characterized by a strong vertical stratification during the austral summer and a more mixed water column during winter. Atmospheric mesoscale dynamics and circulation are highly dominated by the passage of cold fronts. Cold front passages cause wind intensification and a shift in its main quadrant direction, impacting on the dynamics of the water column and ocean circulation. However, the effects on biological processes are still poorly understood. In the present study, daily MODIS-Aqua chlorophyll-*a* concentration (chl) estimates were analyzed before and after the passage of cold fronts in the SBB region, between 01/2004-12/2008. The frontal systems were more frequent during spring, winter and fall, with 157 cold fronts identified in Cabo Frio and 192 in Santos, with mean frequencies of 2-4 events per month. The Wilcoxon-signed rank test showed that the increase in chl after the cold front passages were significant (p-value < 0.05) within 3 days in Cabo Frio and 8 days in Santos. Cloud cover was a limitation for obtaining daily MODIS data. Future work should test the use of different orbital sensors, complemented by *in situ* biophysical data and numerical simulations for better understanding the role of cold front passages on water column and phytoplankton dynamics.

Key words — Chlorophyll-*a* concentration, cold fronts, South Brazil Bight, MODIS.

1. INTRODUCTION

The ocean is a dynamic environment governed by physical, chemical, geological and biological processes constantly interacting. Understanding how these factors regulate biological production in this environment is a key subject that challenges researchers. In the large scale, physical processes are responsible for structuring biological communities, where plankton, due to its low mobility, is the most affected group [1]. Phytoplankton's photosynthesis accounts for over 95% of total marine primary production [2], relying on sunlight, nutrients and temperature which act as limiting factors to phytoplankton growth [3].

The thick layer above ocean and below atmosphere determines the boundary between these two fluids (air and water) where momentum, heat and mass exchanges occur [4]. The wind is one of the major disturbances driving forces in the air-sea interface, responsible to generate turbulence and currents resulting in water column mixing and, in some conditions, upwelling. Owing to the stratified structure of the water column, vertical friction effects (governed by wind stress) may cause convergence or divergence leading to circulation in deep zones (Ekman pumping effect) — this effect can play an important role in the primary production dynamics, by mixing up nutrients from below [4].

The effect of wind stress on phytoplankton primary production and biomass, the later usually indexed as chlorophyll-*a* concentration (chl), has been investigated by other authors, in different regions [5, 6, 7]. Considering extreme wind events, such as tropical cyclones, nearshore blooms might be associated with rainwater discharges, while more offshore blooms can be related to nutrient increase from mixing and upwelling [5]. In temperate and high latitudes, seasonal winds play an important role in controlling the spring and fall blooms [6]. Winds can also disturb coastal marine ecosystems by inducing changes in the phytoplankton community, reducing the abundance of some phytoplankton groups and increasing the abundance of other groups [7].

On the seasonal cycle are superimposed the effects of sporadic mixing events in response to passing storms and cold fronts. The short-term increases in primary production and chl associated with these sporadic events are often missed by sampling schemes designed to record the seasonal cycle [5].

Although strong cyclonic surface winds of hurricanes and typhoons are most likely to promote phytoplankton growth that is observable as in increase in chl [8], other episodic atmospheric disturbances such as storms and cold fronts also have the capacity to generate similar processes [9]. Cold fronts are characterized as atmospheric disturbances produced by the collision of a cold air mass and a warm air mass [10].

In southern-southeastern Brazil, atmospheric mesoscale dynamics and circulation are highly dominated by the passage of cold fronts, with an annual mean of 5-6 per month and a higher frequency and intensity in the austral winter [11, 12]. The cold fronts propagate from SW to NE over the South Brazil Bight (SBB; Fig. 1) at an average speed of 500 $km.d^{-1}$ [11]. In the region that precedes the front (the warm sector), NE winds have mean velocities of 5 $m.s^{-1}$ [11]. With the approach of the front, the wind rotates counterclockwise to NW. Just after the passage of the front, SW winds (in the cold sector) have mean velocities of 8 m.s^{-1}. After ~1 day, the winds return to the prevailing NE direction [11]. The frontal systems are expected to impact on the dynamics of the water column and oceanic circulation, potentially affecting the pelagic structure. Although these effects on biological processes are still poorly understood, recent studies have shown the importance of the passage of cold fronts in regulating larval supplies and settlement dynamics [13], and on interactions between atmospheric, pelagic and benthic systems in the SBB region [14].

Seasonally, the South Brazil Bight is oceanographically characterized by a strong vertical stratification in the water column during the summer and a more mixed water column during the winter [15], except in areas where upwelling occur [16]. In this context, the passage of cold fronts would increase the mixture of the water column mainly during the winter and spring, when they are more frequent [17] and the water column is weakly stratified [15].

Satellite-derived chl are used in a variety of applications, e.g. for estimating primary production [17], phytoplankton biomass, algal blooms timing, intensity and duration [18], among others. Chlorophyll-*a* concentration estimates based on MODerate resolution Imaging Spectroradiometer (MODIS) data onboard NASA-Aqua satellite has been largely studied and validated in Brazilian waters [19].

Considering what was mentioned above, our hypothesis is that the passage of cold fronts in the SBB region causes a measurable alteration on surface chlorophyll concentrations. To test this hypothesis, daily MODIS-Aqua chl are statistically analyzed in relation to the passage of cold fronts in the study region between 2004-2008.

2. MATERIAL AND METHODS

2.1. Study area

The South Brazil Bight comprises the region of the southeastern Brazilian continental shelf from Cabo São Tomé (22°S-41°W) to Cabo Santa Marta (28°S-48°49'W) [20]. The shelf break along the SBB occurs at depths of 100 m near Cabo Frio (23°S-42°W), and 120-180 m towards the south. The shelf width ranges between 50 km in Cabo Frio and 230 km in front of Santos (~24°S) [15] (Figure 1).

In the SBB, the offshore circulation is dominated by the Brazil Current (BC), which flows southward (limited to the upper 500 m), advecting tropical water (TW, $S > 36$, $T > 20$ °C) [20] and influencing the shelf water masses during summer [21]. Also, during austral summer, northerly winds favor an upwelling process and advection toward the shore of the South Atlantic Central Water (SACW, S 34.6–36.2, T 8.7–20°C), which occupies the bottom layer and reaches the surface in some areas. The contribution of local freshwater produces coastal water (CW, $S < 35$, T varying seasonally) [21].

To study the impact of cold front passages on the chlorophyll concentration, two rectangular boxes of equal dimensions (1.25° in longitude, 0.75° in latitude), were defined approximately in front of Cabo Frio and Santos (Figure 1b), covering an area of 10645 and 10502 km², respectively.

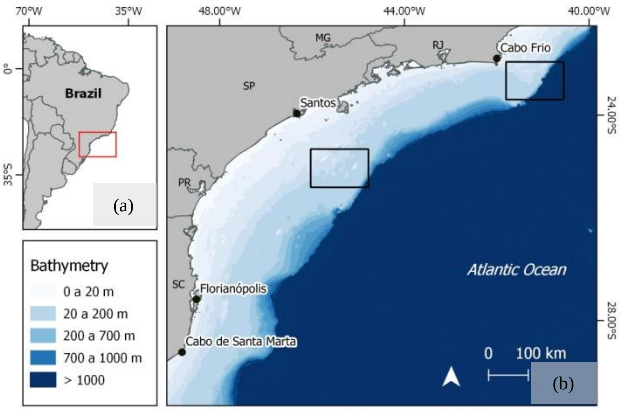


Figure 1. (a) Overview of the study area location; (b) South Brazil Bight and adjacent areas. The black rectangles represent the MODIS-Aqua daily chlorophyll-*a* concentration sampled areas.

2.2. Ocean color data and cold front passage dates

MODIS-Aqua Level 3 daily chl data for the study area were obtained from the NASA Goddard Space Flight Center through the Google Earth Engine platform. The average daily chl were calculated for the defined rectangles (Figure 1b), to compensate for the lack of data due to cloud coverage. Chl time-series were obtained from January 1, 2004 to December 31, 2008.

The atmospheric frontal systems were identified through the analyzes of daily surface synoptic charts, in average levels of 500 hPa and 250 hPa, at 00:00 and 12:00 GMT [22]. The analysis of the positioning and displacement of the cold front systems was obtained from INPE's Weather Forecast and Climate Studies Center [22].

2.3. Data analysis

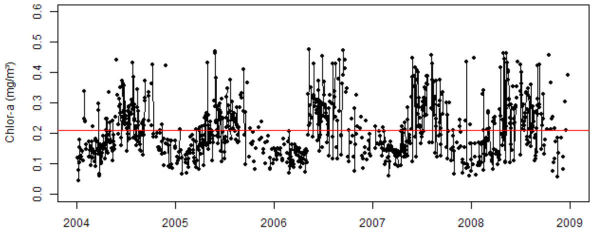
The differences between MODIS-Aqua chl values before and after the cold front passage were calculated for both rectangles located in Cabo Frio and Santos (see Fig.1b). Chl median values were calculated for three pre-defined days intervals (3, 5 and 8 days) before and after the cold front passages. The non-parametric Wilcoxon-signed rank test was applied to verify the significance of the differences between the two-paired set of chl data before and after the cold front passage, with the significance of 0.05. R language and packages were used for data processing and statistical tests.

3. RESULTS AND DISCUSSION

In Cabo Frio, mean chlorophyll-*a* concentration was 0.209 mg/m³, varying between 0.046 to 0.475 mg/m³, with a standard deviation of 0.089 mg/m³ (Figure 2a), and the percentage of valid data was 51%. In Santos, the mean value was 0.194 mg/m³, varying between 0.057 to 0.386 mg/m³, with a standard deviation of 0.062 mg/m³ (Figure 2b), and the percentage of valid data was 45%.

Ciotti et al. [23] obtained a clear annual chl cycle in different regions along the Brazilian continental shelf, also observing minimum values during the summer. In our work, a strong seasonal variability is also observed (Figures 2 and 3), with lower chl values during summer (Dec-Mar) and higher concentrations during winter (Jun-Sep).

(a) Cabo Frio - RJ



(b) Santos - SP

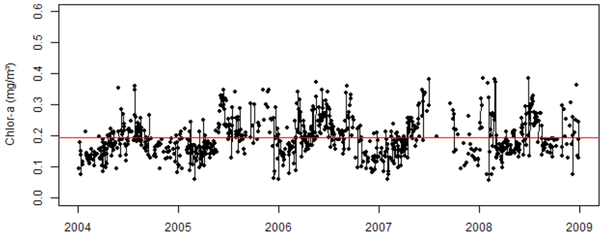
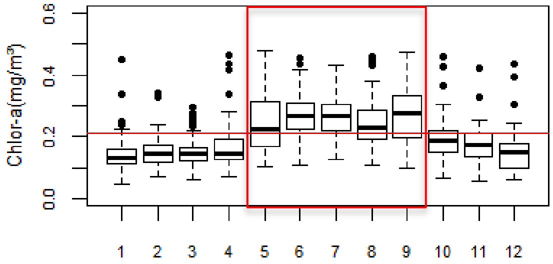


Figure 2. Time series of the MODIS-Aqua derived daily mean chlorophyll-*a* concentration (chl) for (a) Cabo Frio and (b) Santos rectangles (see Fig. 1b). The red lines correspond to the mean chl of the corresponding time series.

It is remarkable that Cabo Frio presented higher mean values during fall and winter, even though the upwelling takes place mainly during summer and spring (Figure 3a). Kampel & Freitas [24] also observed this pattern, the growth of chl concentrations starting at the end of the fall (May) reaching the peak in the middle of the winter (Jul and Aug), in the continental shelf and slope at Campos basin. In Santos the same pattern was detected, i.e. growth of chl at the end of fall and higher values in the winter. Kampel et al. [25] attributed this pattern to mixing in the water column, fertilization of the euphotic zone by nutrients with potential effects of the intrusion of colder and richer waters coming from south during the winter.

The passages of cold fronts in the SBB region were more frequent during spring, winter and fall during the studied period (01/2004-12/2008). The same temporal variability was also observed by Cardozo et al. [26]. In Cabo Frio, 157 cold fronts were reported in the present work. Jan, Feb, Mar and Jun had less than two cold front passages per month, while other months presented 3 to 4 frontal systems (Figure 3a). In Santos, 192 cold fronts were reported. March presented the lowest frequency (< 2), and all the other months presented more than 3 cold front passages per month (Figure 3b).

(a) Cabo Frio -RJ



(b) Santos - SP

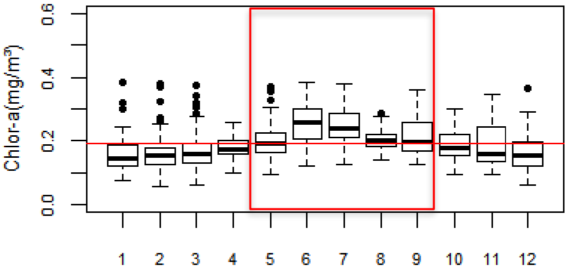
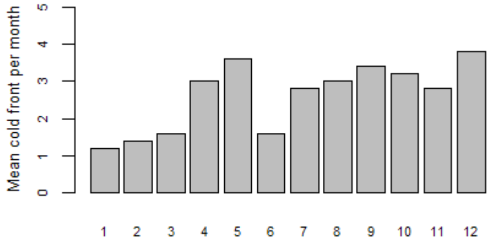


Figure 3. Boxplot of MODIS-Aqua chlorophyll-*a* concentrations during 2004-2008 for (a) Cabo Frio and (b) Santos. Months are represented as 1-12 numbers. The red lines correspond to the mean chl value of each area. The red rectangle highlights the months above mean chl.

(a) Cabo Frio - RJ



(b) Santos - SP

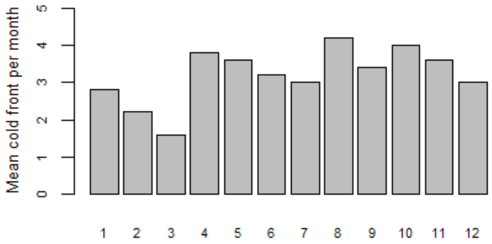


Figure 4. Mean cold front passages per month, between 01/2004-12/2008.

The Wilcoxon-signed rank test showed that the increase in chl after the cold front passage was significant ($p\text{-value} < 0.05$) within 3 days in Cabo Frio and 8 days in Santos (Table 1). For Cabo Frio, p-values for 5 and 8 days (0.06

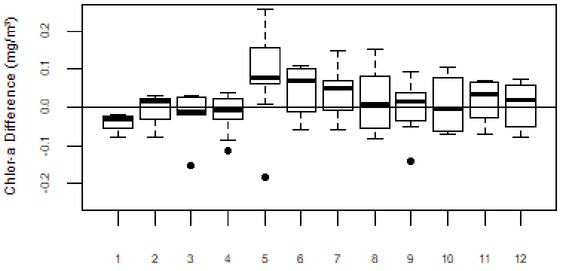
and 0.07) are also very low and close to the significance level (0.05). Higher chl increases were observed in fall (May, Jun), winter (Jul, Aug, Sep) and spring (Nov, Dec) (Figure 5a).

Table 1. Wilcoxon-signed rank test results considering the increase in chl within 3, 5 and 8 days after the cold front passage; n is the number of observations; p-values < 0.05 are highlighted.

Latitude	**3 days** **p-value (n)**	**5 days** **p-value (n)**	**8 days** **p-value (n)**
Cabo Frio	**0.02** (90)	0.06 (126)	0.07 (145)
Santos	0.79 (99)	0.31 (139)	**0.04** (166)

The increase in chl in a relatively longer number of days observed for Santos (8 days) can be related to a delay in the mixing effect on biological productivity considering relatively deeper waters. However, the transport of coastal waters associated with the increase in river runoff after the increase of rainfall due to the cold front passage should not be neglected. Chl differences were observed mainly during fall (Apr, May, jun), winter (Jul, Aug), and spring (Oct, Nov, Dec), but in general, values are lower than the differences observed in Cabo Frio (Figure 5b).

(a) Cabo Frio - RJ



(b) Santos - SP

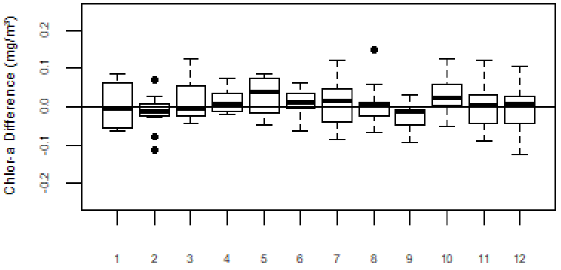


Figure 5. Boxplot of chl differences per month after cold front passages during 2004-2008, considering the significant interval of 3 days for Cabo Frio (a) and 8 days for Santos (b).

The results indicate a temporal variability in the effects of cold front passages, suggesting that the season of the year and the geographical location are essential factors to be considered for future analyzes.

4. CONCLUSIONS

Cold front passages showed a significant effect on satellite-derived chlorophyll-*a* concentration in the South Brazil Bight region. Even though we could not characterize those events in a regular or predictable mode, we could observe that chl increase was more frequent in winter, fall and spring when the water column stratification is not so strong as it is in the summer. Cloud coverage was a limitation for obtaining MODIS-Aqua imagery, as the passage of cold fronts is usually associated with an increase in cloud coverage and rain. We decided to work with the rectangular-boxes approach and calculating the median chl values to minimize the effect of that limitation. However, future studies should apply different approaches, also testing different orbital sensors and the use of numerical simulations to model the main oceanographic processes involved in the increase of chl. We also encourage the analyzes of biophysical *in situ* data for better understanding the role of cold front passages on water column and phytoplankton dynamics.

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6. REFERENCES

[1] Daly, K.L; Smith Jr., W. O. “Physical-biological interactions influencing marine plankton production”. *Annu. Rev. Ecol. Syst.* 24, 555–85, 1993.

[2] Schlesinger, W. H.; Bernhardt, E. *Biogeochemistry : an analysis of global change*,Elsevier, Oxford, ed.3rd, 688p., 2013.

[3] Sathyendranath, S.; Platt, T., Primary Production Distribution, in Reference Module in Earth Systems and Environmental Sciences, 2013, doi: 10.1016/B978-0-12-409548-9.04304-9.

[4] Pond, S.; Pickard, G.L. *Introductory dynamical oceanography*, 2nd edition, Pergamon Press, 349p, 1983. https://doi.org/10.1016/B978-0-08-057054-9.50002-X

[5] Zheng, G. M.; Tang, D. “Offshore and nearshore chlorophyll increases induced by typhoon winds and subsequent terrestrial rainwater runoff”. *Mar Ecol Prog Ser*. 333, 61–74 2007.

[6] Kim, H.; Yoo, S.; Oh I.S. “Relationship between phytoplankton bloom and wind stress in the sub-polar frontal area of the Japan/East Sea”. *J Mar Syst*. 67(3–4):205–16. 2007.

[7] Chang, J.; Chung, C. C.; Gong, G. C. “Influences of cyclones on chlorophyll-a concentration and *Synechococcus* abundance in a subtropical western Pacific coastal ecosystem”. *Mar. Ecol. Prog. Ser*. 140, 199–205, 1996.

[8] Shropshire, T., Y. Li, and R. He. “Storm impact on sea surface temperature and chlorophyll a in the Gulf of Mexico and Sargasso Sea based on daily cloud-free satellite data reconstructions”, *Geophys. Res. Lett*., 43, 12,199–12, 207, 2016. doi:10.1002/2016GL071178.

[9] Fujii, M.; Yamanaka, Y. “Effects of storms on primary productivity and air-sea CO2 exchange in the subarctic western North Pacific: a modeling study”, *Biogeosciences*, 5, 1189-1197, 2008, doi: 10.5194/bg-5-1189-2008.

[10] Thompson, R. *Atmospheric Processes and Systems*, London,

Routledge, 1998.

[11] Stech, J. L.; Lorenzzetti, J. A. "The response of the South Brazil bight to the passage of Wintertime Cold Fronts", *J. Geophys. Res.* 97, 9507–20, 1992.

[12] Amorim, F. N.; Cirano, M. ; Soares, I. D. ; Campos, E. J. D.; Middleton, J. F. "The influence of large-scale circulation , transient and local processes on the seasonal circulation of the Eastern Brazilian Shelf, 13°S". *Cont. Shelf Res.* 32, 47–61, 2012.

[13] Mazzuco, A. C. A.; Christofoletti, R. A. ; Coutinho, R. ; Ciotti, A. M. "The influence of atmospheric cold fronts on larval supply and settlement of intertidal invertebrates: Case studies in the Cabo Frio coastal upwelling system (SE Brazil)". *J. Sea Res.* 137, 47–56, 2018.

[14] Galluci, F.; Netto, S.A. "Effects of the passage of cold fronts over a coastal site: an ecosystem approach". *Mar Ecol Prog ser*, 281:79-92, 2004.

[15] Miranda, L.B. *Análise de massas de água da plataforma continental e da região oceânica adjacente: Cabo de São Tomé (RJ) à Ilha de São Sebastião (SP)*. Universidade de São Paulo, Thesis, 123p.,1982.

[16] Ciotti, A. M.; Mahiques, M.; Möller, O. O. "The meridional gradients of the S-SE Brazilian continental shelf: Introduction to the special volume". *Cont. Shelf Res.* 89, 1–4, 2014.

[17] Lee, Z.; Marra, J.; Perry, M. J.; Kahru, M. "Estimating oceanic primary productivity from ocean color remote sensing: A strategic assessment". *J. Mar. Syst.* 149, 50–59, 2015.

[18] Binding, C. E.; Greenberg, T. A.; McCullough, G.; Watson, S. B.; Page, E. "An analysis of satellite-derived chlorophyll and algal bloom indices on Lake Winnipeg". *J. Great Lakes Res.* 44, 436–446, 2018.

[19] M. Kampel et al., Bio-Optical Variability in Coastal Waters of Southeast Brazil. Coast. Ocean Remote Sens. 6680, 1–8 (2007).

[20] Castro Filho, B. M., *Subtidal response to wind forcing in the South Brazil Bight during winter*, Ph.D. thesis, 211 pp., Rosenstiel Sch. of Mar. and Atmo. Sci. Univ. of Miami, Miami, Fl., 1985.

[21] Castro, B.M; Miranda, L.B. "Physical oceanography of the western Atlantic Continental Shelf located between 4o N and 34o S". In: ROBINSON AR, BRINK KH, editors. *The sea*. Inc., John Wiley & Sons; p. 209–251 p. 1998.

[22] CPTEC/INPE. "Climanálise – Boletim de monitoramento e análise climática". http://climanalise.cptec.inpe.br/~rclimanl/boletim/., jan/2004-dez/2008.

[23] Ciotti, A. M.; Garcia, C. E.; Jorge, D. S. F. "Temporal and meridional variability of Satellite-estimates of surface chlorophyll concentration over the Brazilian continental shelf". *Panam. J. Aquat. Sci.* 5, 236–253, 2010.

[24] Kampel, M.; Freitas, L. B. "Caracterização espaço-temporal de campos superficiais estimados por satélite na Bacia de Campos" in *Ambiente Pelágico*, A. P. F. Falcão, D. L. Moreira, Eds. Elsevier, Rio de Janeiro, 43–68, 2017.

[25] Kampel, M.; Freitas, L. B.; Delcourt, F. ; Cortivo, F. D. "Caracterização e análise ambiental da Bacia de Santos com base no processamento de campos oceânicos superficiais estimados por satélites", in *Anais XVII Simpósio Brasileiro de Sensoriamento Remoto – SBSR*, João Pessoal, 3596–3603, 2015.

[26] Cardozo, A.B.; Custódio, I.S.; Reboita, M.S.; Garcia, S.R. "Climatologia de frentes frias na América do Sul e sua relação com o modo anular Sul". *Rev Bras Climatol*. 17(July 2017). 2015.