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Diatom accumulations on a tropical meso-tidal beach: Environmental drivers on phytoplankton biomass

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A B S T R A C T

Diatom accumulations are important phenomena that occur on many sandy beaches worldwide, but little is known about their seasonal occurrence and environmental drivers at lower latitudes. The results revealed that the diatom *Anaulus* cf. *australis* and *Asterionellopsis tropicalis* were accumulated on a tropical beach near the Equator (3°41′S; northeastern Brazil). The highest frequency of diatom accumulation (81%) occurred during the rainy season, when wind intensity was weak and waves had lower heights. The main environmental driver that control occurrence of the patches on this oligotrophic sandy beach is a rainfall that is associated with the availability of nutrients. Tides are a physical driver that affect the phytoplankton biomass at the surf zone, large tidal ranges were related to dispersal and biomass reduction of the diatom accumulations. In addition, there was an association between swell and patches, this kind of wave appear be an important physical driver, however this mechanism is not fully understood. These findings provide novel insights into the environmental drivers and general knowledge of diatom accumulations worldwide.

1. Introduction

In the surf zone of several sandy beaches around the world, diatom accumulations cause discolorations or viscous brown/yellow/green patches in the water. The diatoms are concentrated on the surface, especially in the foam of breaking waves (Campbell, 1996; Odebrecht et al., 2014). This phenomenon is seen in open or exposed sandy beaches with wide surf zones, moderate to high wave energy (dissipative and intermediate morphodynamic states; *sensu* Short and Wright, 1984), and well-developed rip currents. Nutrient enrichment is an important feature in these environments; aquifers may supply nutrients from groundwater stimulating the growth of surf diatoms (Campbell, 1996; Campbell and Bate, 1996).

Diatom accumulations are not blooms since they do not arise from exponential population growth associated with elevated nutrient levels and/or water temperature (Talbot and Bate, 1986; McLachlan and Brown, 2006). In contrast, the rapid daily increase in surf diatom numbers to millions and billions of cells per liter indicates the phenomenon is a physical accumulation (Talbot and Bate, 1986; McLachlan and Brown, 2006; Odebrecht et al., 2014).

Diatom accumulations in the surf zone of exposed sandy beaches usually begin with diatom stocks from the sediment being suspended and forming high-density patches. Part of the biomass is carried beyond the surf zone by rip currents and deposited behind the surf line where it contributes to the cell stock on the substrate. In the surf zone, diatom patches attached to foam are transported towards the coast and deposited on the beach sand by wave action and onshore winds (Talbot and Bate, 1988b; Rörig and Garcia, 2003; McLachlan and Brown, 2006; Odebrecht et al., 2014).

Diatoms patches are important food sources for suspension

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feeders in a dissipative beach (Bergamino et al., 2016) and may sustain transient, highly productive food webs (Odebrecht et al., 2014; Netto and Meneghel, 2014). In some sandy beaches, the mucilage (a form of dissolved organic carbon) produced by surf diatoms may be used by bacteria. Nevertheless, the precise role of diatom accumulation in surf zone microbial food webs is not completely understood (Odebrecht et al., 2014).

Most of the studies on surf zone diatom accumulations were conducted in subtropical and temperate micro-tidal beaches, such as those in South Africa (Talbot and Bate, 1986, 1988a, b), in Washington State (U.S. west coast) (Lewin et al., 1989), and in southern Brazil (Rörig and Garcia, 2003; Odebrecht et al., 2010; Netto and Meneghel, 2014). It was believed that tides influenced patches by shifting the supply of groundwater nutrients from dunes to the surf zone (Campbell and Bate, 1998). Yet an alternative hypothesis states that tides might also be a physical driver affecting diatom accumulations on meso-tidal beaches. Tides influence the hydrodynamic and morphodynamic processes of beaches subjected to meso- and macro-tidal regimes (Masselink and Short, 1993). Nevertheless, studies on diatom accumulations in tropical sandy beaches or shores with meso-tidal regimes only report on the occurrence of patches, surf diatom identification, and cell density (Van Heurck, 1896; Sournia and Plessis, 1974; Mishra et al., 2006). There is little information on the relationship between environmental drivers and the occurrence of diatom accumulations in these beaches (Villac and Noronha, 2008). Therefore, this study addresses the question: What are the main environmental factors influencing the formation of diatom accumulations in a tropical meso-tidal sandy beach (Futuro Beach, 3° 41’ S, northeastern Brazil)?

2. Material and methods

2.1. Study area

Futuro Beach (Fig. 1) is located in Fortaleza, the capital of the state of Ceará, in northeastern Brazil. The Fortaleza population has reached ~2.55 million in recent decades and exceeds 3.5 million in the overall metropolitan region (Garmany, 2011). This urban beach is 8 km long and is bordered by the Mucuripe harbor jetties (Titãzinho) to the north, and Cocó estuary to the south (Fig. 1).

Futuro beach is under the influence of a semi-arid climate and a trade winds atmospheric system. The semi-diurnal meso-tidal regime has an unequal amplitude (maximum in spring tidal amplitude of 3.2 m) and a mean period of 12.4 h (Pinheiro et al., 2016). The height and direction of waves in Ceará are determined by wind speed and direction. Higher waves occur in the dry season (July to December) when the winds are more intense, while lower wave heights occur during the rainy period with weaker winds (January to June) (Silva et al., 2011; Pinheiro et al., 2016). Swell waves represent 20% of waves, occurring most often during the rainy season (Silva et al., 2011). The Futuro Beach sediment consists mainly of sand with a mean particle size (Mz) ranging from 0.8 to 1.4 ϕ (Albuquerque et al., 2009). The morphodynamic stage ranges from intermediary (low tidal current and tidal terrace) to ultradissipative and the beach presents well-developed rip currents (Albuquerque et al., 2009, 2010). Diatom accumulations can form anywhere along the 8 km of Futuro Beach (Fig. 2). These patches consist of *Anaulus* sp. (Odebrecht et al., 2014), *Asterionellopsis tropicalis* Franco, a species differentiated from other *Asterionellopsis* species by molecular biology (Franco et al., 2016) and *Aulacodiscus kittonii* Arnott ex Ralfs (Odebrecht et al., 2014).

The beach was sampled at two stations: S1 (03°43′27″ S; 38°27′34″ W) and S2 (03°45′19″ S; 38°26′37″ W) (Fig. 1). They differed in their morphodynamic states. S1 is near the Titãzinho (Mucuripe harbor jetties), is mainly dissipative to ultradissipative, and is of fine sand. S2 is near the Cocó estuary, has intermediate morphodynamic stages, and is of coarse and medium sand (Albuquerque et al., 2009) (Fig. 1).

Surface water was collected monthly and physical parameters were measured in the surf zone at Futuro beach at a local depth of ~85–125 cm at spring tide between July 2011 and June 2012 except in December, when sampling occurred at neap tide. To assess the influence of the tides, S1 and S2 were sampled at low tide (LT, around 10 a.m.) and high tide (HT, up to 4 p.m.) each day according to Mucuripe's harbor (03°42.9′ S; 38°28.6′ W) tide chart.

2.2. Sampling data

2.2.1. Physical and meteorological parameters

Salinity was measured *in situ* using a refractometer (ATAGO; ± 1) and water temperature with a sensor (Yellow Spring Instruments, model YSI550A12). The wave period (T) and breaker wave height (Hb) were visually estimated (Bascom, 1964). Waves were classified as sea waves if $T \leq 9$ s, while waves with $T > 9$ s were classified as swell waves (Pond and Pickard, 2009). The number of wave breaking lines was visually estimated in the field surveys. Tidal height was provided by the Brazilian Navy Agency (Diretoria de Hidrografia e Navegação, DHN). Tidal range (TR) was calculated by subtracting the height at the current tide (LT or HT) from that of the previous tide. The tidal movement direction (+or -) was not considered; only the magnitude of the change was recorded. Rainfall data (mm), wind direction, and wind speed ($m\ s^{-1}$) were provided by the Meteorological Station of the Federal University of Ceará (03°44′ S; 38°34’ W).

2.2.2. Biological parameters

Surface water was sampled (in triplicate) with a bucket in the surf zone. In the laboratory, the water samples were vacuum filtered (Whatman®, GF/C). The chlorophyll *a* concentration was determined by spectrophotometry (Strickland and Parsons, 1972) using the equation proposed by Jeffrey and Humphrey (1975). In addition, the absence or presence of diatom accumulations was recorded based on appearance, color intensity, and chlorophyll *a* concentration. When diatom accumulations were observed, surface phytoplankton samples were collected in a dark glass bottle immersed in the patches and fixed with acidic Lugol's iodine solution (1% v/v final concentration) for species identification and counting (Hasle and Syvertsen, 1996). Phytoplankton were quantified (cell L^{-1}) using the method of Utermöhl (Sournia, 1978). To ensure a precision of 20%, at least 100 individuals from the dominant species were counted (Wetzel and Likens, 2000). When necessary, owing to high cell numbers in the patches, the samples were diluted following the recommendations of Sournia (1978).

2.2.3. Statistical analysis

The normality of the data was verified by the Shapiro–Wilk test. Differences between the proportion of patches present and absent were evaluated using chi-square tests. Differences between means were compared with a *t*-test or a Mann-Whitney *U* test for normally- or non-normally distributed data, respectively (Zar, 2010). The relationships between sampling day tide height and tidal range, patch chlorophyll *a* content and cell density, chlorophyll *a* content and tidal range were evaluated using the Spearman correlation coefficient (Zar, 2010). Principal component analysis (PCA) was used to examine the relationships between phytoplankton biomass and the environmental drivers TR (tidal range), Hb (wave height in the breakers), P (rainfall), T (wave period), and W (wind speed). PCA assumptions were verified with the Kaiser–Meyer–Olkin (KMO) test. The Bartlett's sphericity test was

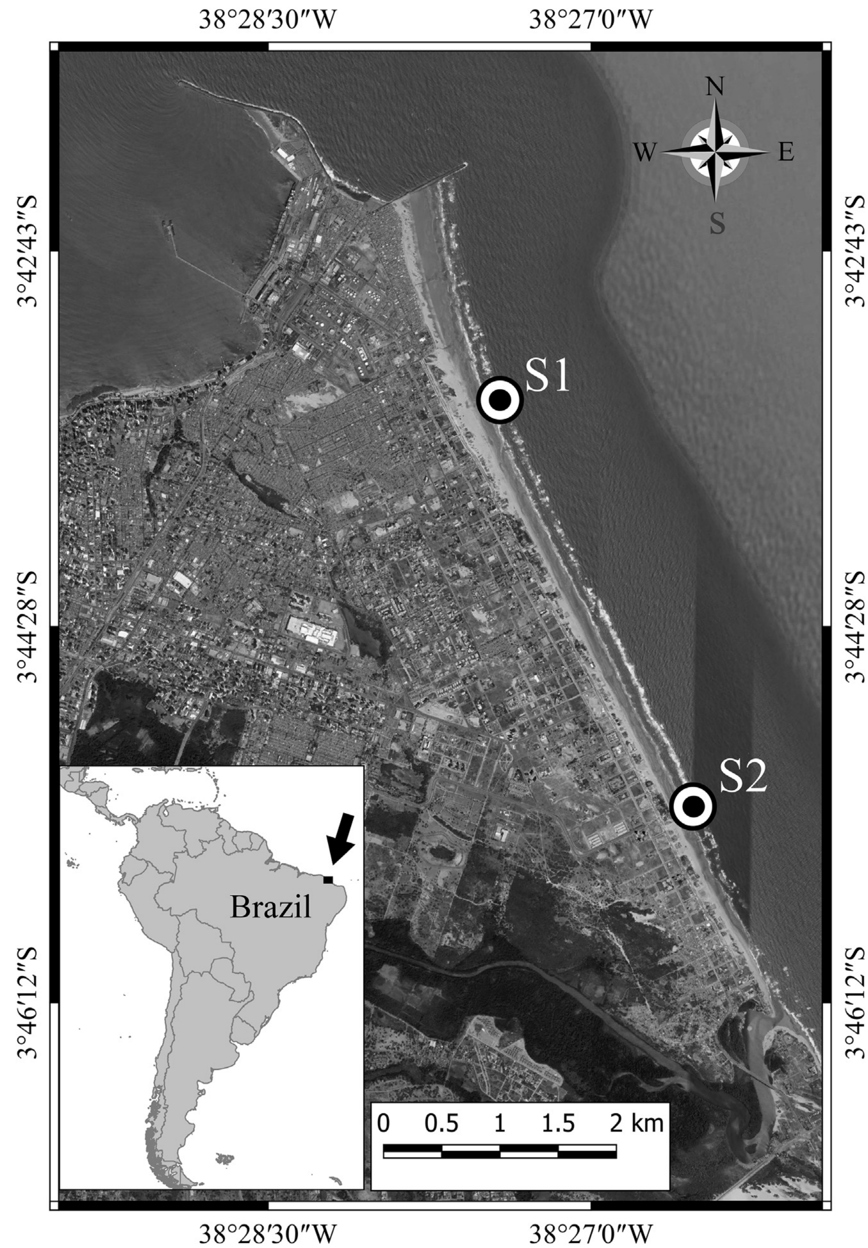

Fig. 1. Map of Futuro Beach (Fortaleza - Ceará - Brazil) showing the locations of the sampling stations: S1 (03°43′27″ S; 38°27′34″ W) and S2 (03°45′19″ S; 38°26′37″ W).

used to determine whether the correlation matrix was an identity. The statistical analyses were conducted using PAST (Hammer et al., 2001) and R (R Development Core Team, 2014).

3. Results

3.1. Environmental factors

During the study period, 86% of the annual accumulated rainfall (1531.4 mm) occurred in the rainy season between January and June (Fig. 3A). Precipitation was <1 mm on 75% of the sampling days, and never exceeded 7 mm. Water temperature (average 28.2 °C) did not show seasonal variation (*t*-test; $p > 0.05$) and had minima in August (26.7 °C), and maxima in September (29.9 °C). Salinity (average 36) variation was larger and ranged between 33 (March) and 40 (November and December). Salinity was higher in the dry season than in the rainy season (*t*-test; $p < 0.01$), and was significantly correlated with precipitation (Fig. 3A and C).

The average wind speed during the study period was 3.85 ± 1.40 m s^{-1}. Despite its high standard deviation in monthly average wind speed, seasonality was observed, and wind speeds were higher in the dry season (July to December; average 4.16 ± 1.47 m s^{-1}) than the rainy season (January to June; average 3.53 ± 1.23 m s^{-1}) (Mann-Whitney *U* test, $p < 0.01$). The average dry season wind speeds were similar in both LT and HT (Mann-Whitney *U* test, $p > 0.05$), but lower during the rainy season at LT (Mann-Whitney *U* test, $p < 0.01$) (Fig. 3B). On sampling days, however, wind speed seasonality was not readily apparent even though during the rainy season it was more frequently lower (≤3 m s^{-1} on 67% of days) than it was in the dry season (>3 m s^{-1} on 58% of days). The frequency of the prevailing eastern (46.9%) and southeastern (43.4%) winds was similar in both seasons. Together, the SE and E winds prevailed 92% and 89% of the time during the dry and rainy seasons, respectively.

Fig. 2. Aerial photograph with several diatom accumulations along the tropical meso-tidal beach (Futuro beach, Fortaleza, NE Brazil). On the left side, the main species in diatom patches are shown: *Anaulus* cf. *australis* with bar = 10 μm (above) and *Asterionellopsis tropicalis* with bar = 20 μm (below).

The height of waves in the breakers (Hb) was greater in the dry season than in the rainy season (Mann-Whitney *U* test, $p < 0.01$). The minimum Hb was observed in June (0.90 ± 0.25 m) and the maximum (1.07 ± 0.45 m) in October. Both occurred at S2 LT (Fig. 3D). There were no significant differences between S1 and S2 in Hb (Mann-Whitney *U* test, paired; $p > 0.05$; average 0.96 m at each station). The wave period (T) varied between 4 s (S1 HT, October 2011) and 17 s (S2 HT, January 2012). Swell waves (T > 9) occurred on 68% of the sampling days (n = 44). Nevertheless, swell waves occurred on 92% of the collection days during the rainy season, whereas they appeared on only 40% of the sampling days during the dry season (Fig. 3E). Swell waves (T > 9) occurred in 50% of the samplings at LT and 90% of the collections at HT.

The mean number of wave breaking lines was not different statistically between S1 (3.1 ± 1.2) and S2 (2.7 ± 1.2) (*t*-test, $p > 0.05$), as well as, the mean number of wave breaking lines during rainy season (3.2 ± 1.2) and dry season (2.7 ± 1.0) was not different statistically (Mann-Whitney *U* test, $p > 0.05$). The tidal range on the sampling days (average: 2.75 m) varied from 2.1 m (LT, December 2011) to 3.2 m (HT, September 2011). There were no significant differences between LT (average: 2.7 m) and HT (average: 2.8 m) (*t*-test, $p > 0.05$). Therefore, the largest tidal ranges did not occur mainly at HT and the smallest tidal ranges did not predominate at LT. The correlation between tidal range and tide level height on the sampling days was not significant (Spearman $r = 0.02$, $p > 0.05$), so these factors are independent of each other.

3.2. Diatom accumulations in the surf zone

The chlorophyll *a* concentration varied between 1.4 ± 0.6 μg L^{-1} (S1 HT; August 2011) and 2082.4 ± 554 μg L^{-1} (S1 LT; December 2011) (Fig. 4). Average chlorophyll *a* concentrations were higher during the rainy season (mean: 150.5 ± 201 μg L^{-1}; median: 68.8 μg L^{-1}) than the dry season (mean: 123.9 ± 449 μg L^{-1}; median: 3 μg L^{-1}) (Mann-Whitney *U* test; $p < 0.01$). Phytoplankton biomass was higher during the rainy season and coincided with the main period of patch occurrence.

Brown/yellow diatom patches were observed all year around (43%; 21/48 samplings) in the surf zone of Futuro Beach. They were more frequent during the rainy season (81%) and mainly associated with S1 (67%). A significantly higher patch frequency was found at LT (57%) than at HT (43%) (chi-square test, $p < 0.05$). On two occasions (August and November, S1 LT), yellowish foam was observed but the patches dissipated quickly. In these cases, patches collection was prevented, chlorophyll *a* concentration was measured, but phytoplankton was not counted.

When patches were observed during the dry season, about half of them formed foams ranging in color from light brown to yellowish, which dissipated quickly after the waves were breaking, being less intense (cell density and reduced biomass) and with lower visibility. The average dry season chlorophyll *a* concentration increased due to two large patches in December. Exceptionally, these samples were taken during neap tide.

Overall, the phytoplankton biomass showed spatial patterns during HT with higher chlorophyll *a* levels observed in S1, except in August 2011 and January, February 2012, when higher levels were measured in S2. During LT, there was no spatial pattern to chlorophyll *a* (Fig. 4).

Total phytoplankton patch cell densities ranged from 0.07×10^8 cells L^{-1} (S1 HT, April 2012) to 6.98×10^8 cells L^{-1} (S2 HT, February 2012) and showed a significant correlation with chlorophyll *a* levels (Spearman $r = 0.9$; $p = 0.0001$). The diatoms present in all patches were *Anaulus* cf. *australis* G. Drebes & D. Schulz and *Asterionellopsis tropicalis*. *Aulacodiscus* cf. *kittonii* was present in half of the patches observed with <1% of the relative abundance (Fig. 2). *Anaulus* cf. *australis* dominated most patches, its density ranged from 0.48×10^6 cells L^{-1} (S1 HT, May 2012) to 670.16×10^6 cells L^{-1} (S2 HT February 2012). *Anaulus* cf. *australis* relative abundance ranged from 1% (S1 HT, May 2012) to 99.9% (S2 LT, January 2012).

A. tropicalis dominated the patches only in May and density ranged from 0.07×10^6 cells L^{-1} (S2 HT, January 2012) to 29.65×10^6 cells L^{-1} (S2 LT, May 2012), with minimum relative abundance of 0.04% (S2 LT, January 2012) and maximum of 96.08% (S1 HT, May 2012).

The PCA ordination met the required assumptions (KMO > 0.5; correlation matrices were not identity matrices based on Bartlett's sphericity test; $p < 0.05$). The two principal components accounted for 65% of the environmental variation (Fig. 5). PCA ordination

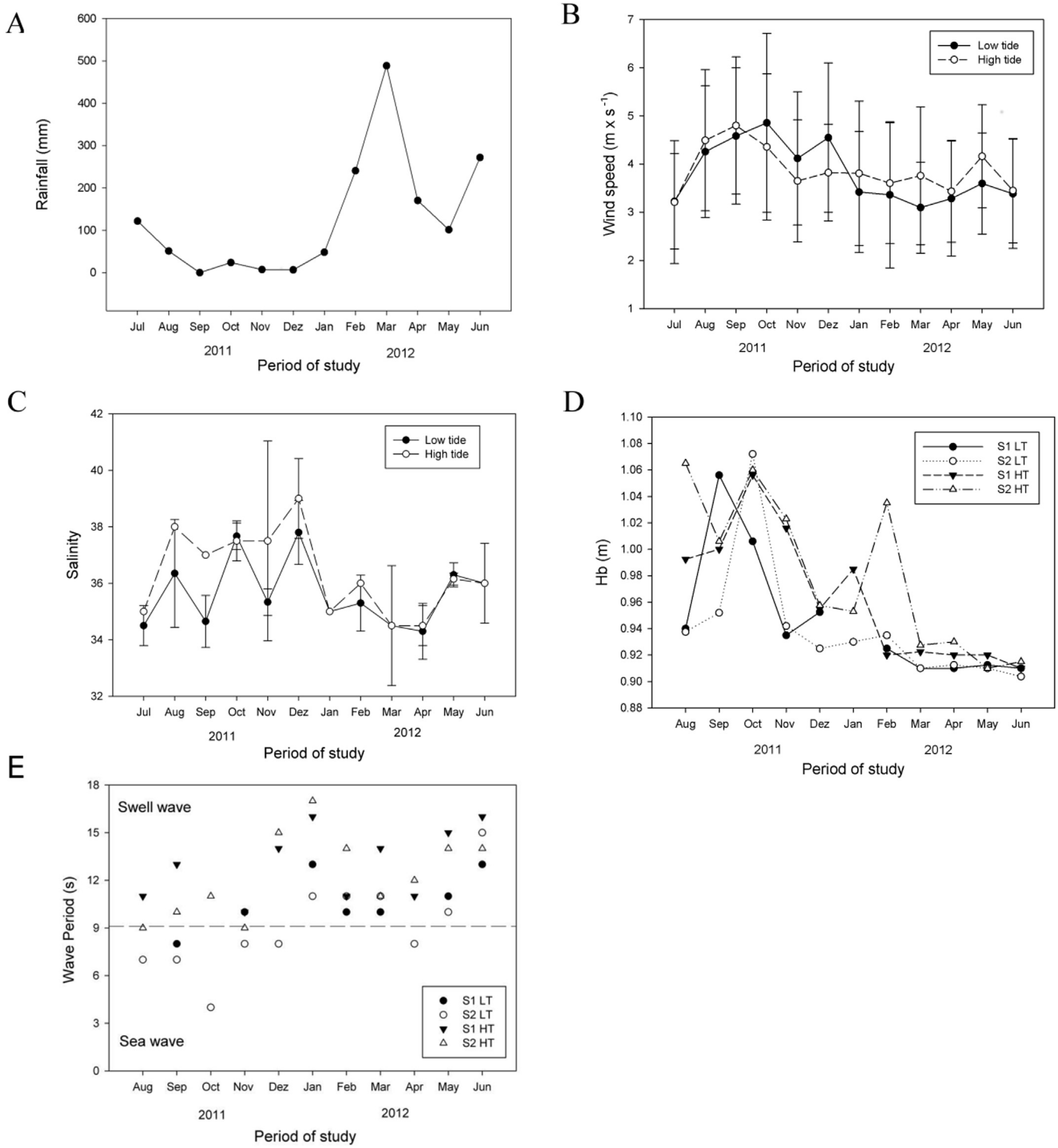

Fig. 3. Environmental factors during the study period (July 2011 to June 2012): A) Total monthly rainfall (mm); B) Monthly values (mean ± standard deviation) of wind speed (m s^{-1}) calculated separately for morning and afternoon sampling, corresponding to the time of low tide and high tide, respectively; C) Monthly values (mean ± standard deviation) of salinity at two tide levels (LT and HT); D) Wave height in the breakers (Hb) during sampling at collection stations (S1 and S2) and two tide levels (LT and HT); E) Wave period and wave type (Sea, $T < 9$ s or Swell, $T > 9$ s) during sampling at collection stations (S1 and S2) and two tide levels (LT and HT).

revealed seasonal separations between dry- and rainy season samples. The dry season samples were closely correlated with wind speed (W) and breaker wave height (Hb), whereas the rainy season samples and patches were correlated with increases in wave period (T) and rainfall (P) (Fig. 5). All diatom accumulation samples ($N = 19$) appeared in the negative region of PC1 and wind speed in the positive PC1 region. Therefore, relative to PC1, patches are correlated more with wave period (T) and rainfall (P) and less with wind speed and Hb (Fig. 5). Chlorophyll *a* concentration was negatively correlated with PC1 and PC2 whereas the tidal range was

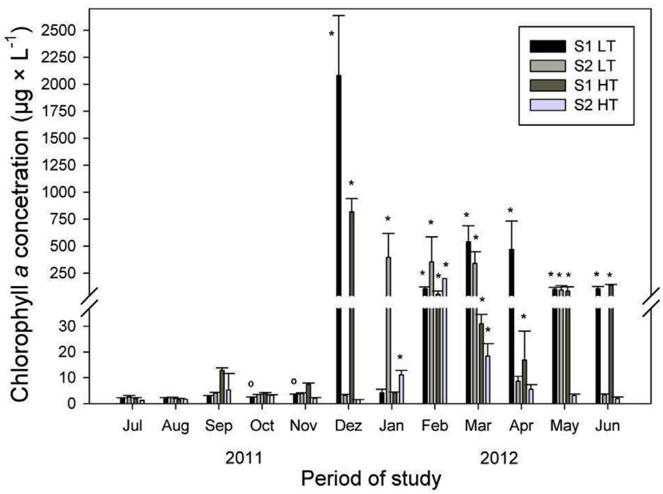

Fig. 4. Monthly variation in chlorophyll *a* concentration (µg L^{-1}) at stations S1 and S2 at low tide (LT) and high tide (HT) during the study period (July 2011 to June 2012). (*) Diatom accumulation; (°) Diatom accumulation was observed, but the patches dissipated quickly, preventing sample collection.

positively correlated with them. No correlation was found between chlorophyll *a* and tidal range overall (Spearman r = −0.2, p > 0.05, n = 48) or in samples without visible patches (Spearman r = 0.2, p > 0.05, n = 27). Nevertheless, the chlorophyll *a* measured in diatom accumulations was moderately negatively correlated with the tidal range (Spearman r = −0.5, p < 0.05, n = 19).

4. Discussion

Unlike the subtropical and temperate micro-tide beaches from South Africa and southern Brazil (Talbot and Bate, 1988b; Rörig and Garcia, 2003; Odebrecht et al., 2014), the diatom patches in this meso-tidal tropical beach were not associated with wind direction, increased wind velocity, or wave height. The highest frequency (81%) of surf zone diatom accumulations occurred during the rainy season when wind velocity and wave height (Hb) were low (Fig. 2B and D). There was probably no influence of wind direction since the prevailing directions (E, SE) did not show seasonal variations at Futuro Beach.

Variations in wind direction, wind velocity, and wave height (Fig. 3B and D) were consistent with the seasonal pattern previously described for this region (Silva et al., 2011; Pinheiro et al., 2016). Generally, winds are more intense and create higher waves during the dry season. The weaker winds of the rainy seasons generate smaller waves (Silva et al., 2011). Wind speed measured on the sampling days during the rainy season were lower than those measured during the dry season.

The highest rainy season patch frequency is correlated with increases in rainfall and swell wave frequency (Fig. 5). Swell waves occurred during most of the sampling occasions during the rainy season (Fig. 3E). In addition, PCA revealed a strong association between samples of the rainy season and the wave period. Therefore, swell waves appear be a physical driver that promotes the turbulence required to suspend and accumulate surf diatoms. Incoming swell or storm waves are hydrodynamic factors involved in the formation of diatom accumulations elsewhere (Rörig and Garcia, 2003; McLachlan and Brown, 2006).

However, the influence of wind as a physical driver of diatom accumulation formation during rainy season should be considered given that southerly winds between 3.0 and 4.0 m s^{-1} are sufficient to form diatom accumulations in micro-tidal beaches (Rörig and Garcia, 2003) and the average wind speed during the rainy season at Futuro Beach is 3.53 ± 1.23 m s^{-1}. Therefore, it is not accurate to affirm what is the main physical driver (swell waves or winds) that promotes the turbulence required to suspend and accumulate surf diatoms in rainy season. The main environmental driver that

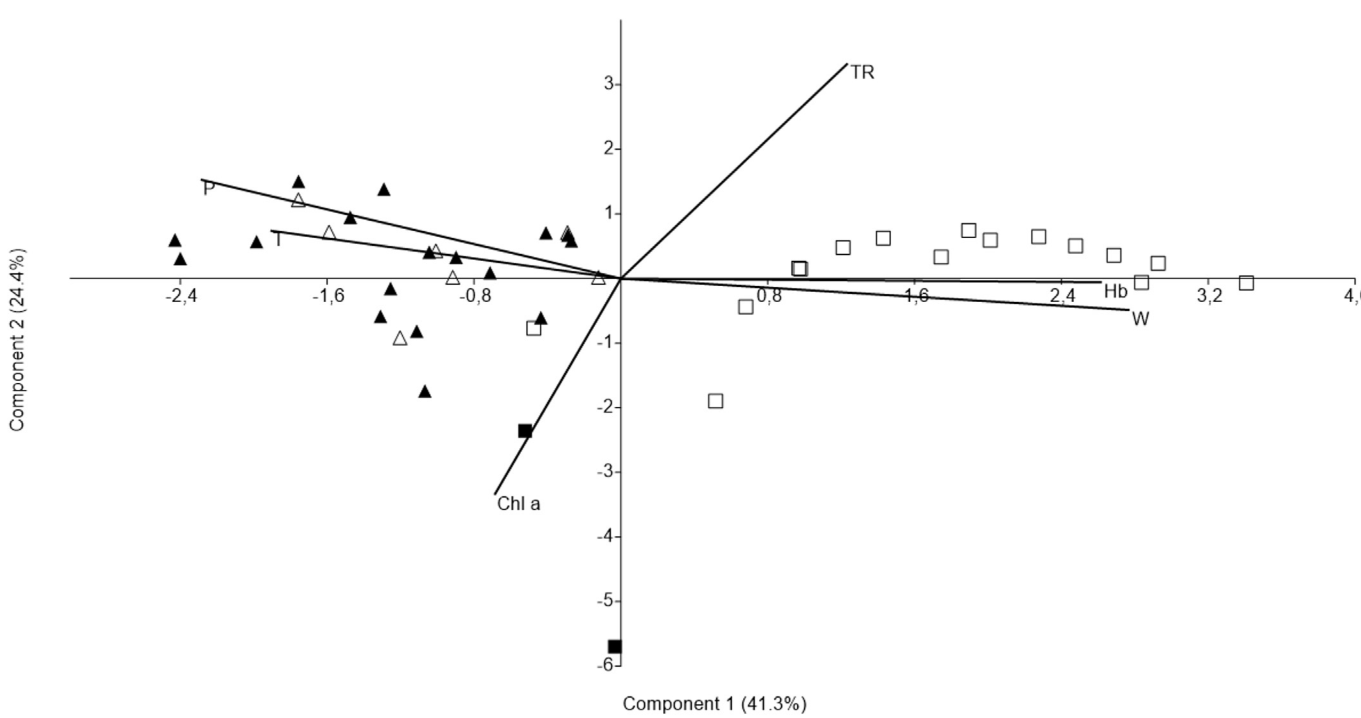

Fig. 5. Results of PCA ordination (white square: dry season without accumulation; black square: dry season with accumulation; white triangle: rainy season without accumulation; black triangle: rainy season with accumulation). Variables: chlorophyll *a* (Chl *a*), TR (tidal range), Hb (breaker wave height), P (rainfall), T (wave period), and W (wind speed).

controls the patch occurrence on this oligotrophic tropical sandy beach is a rainfall that is associated with the availability of nutrients. Once, in the dry season, the lower frequency of diatom patches may be correlated with the very low nutrient concentrations at Futuro Beach (nitrite: not detected to 0.03 mg L^{-1}; nitrate: not detected to 0.50 mg L^{-1}; phosphate: not detected to 0.04 mg L^{-1}; Magini et al., 2007) despite favorable hydrodynamic conditions (higher waves and stronger winds).

Nutrient concentrations were not measured in the field surveys, but the seasonal variations in nutrients concentration may occur at Futuro Beach, as evidenced by the bathing water quality declines in the rainy season, due to leaching, organic pollution from storm sewers with illegal connections, and flow from urban estuaries (Magini et al., 2007; Silva et al., 2009). Futuro Beach has sources of organic pollution with higher concentration of nutrients: storm sewers (Magini et al., 2007) and Cocó Estuary (Barroso et al., 2016). Isotope studies at Main Beach (Australia) showed that *Anaulus australis* is likely to use significant quantities of nitrogen from anthropogenic sources (Hewson et al., 2001).

Increases in nutrient loading during the rainy season are well-known on tropical urban beaches (Ferreira et al., 2010) and on the inner continental shelf of northeastern Brazil (Bastos et al., 2011; Otsuka et al., 2016; Ferreira et al., 2015). It is possible that increase in nutrient concentrations during the rainy season is needed to maintain the metabolic activity of accumulated cells in the patches at Futuro Beach. Diatom accumulations are formed by hydrodynamic processes, but they might require a minimum nutrient concentration to ensure diatom survival and sustain high cell concentrations.

Inadequate sewage control is the main source of organic pollution at the urban beaches of Fortaleza (Silva et al., 2009). Nevertheless, diatom accumulations occur only in Futuro Beach (Odebrecht et al., 2014). Patch formation is determined by moderate to high energy morphodynamic stages (dissipative and intermediate) and surf zone width (Campbell, 1996; Odebrecht et al., 2014). Other beaches near Fortaleza are in bays with low wave energy (Morais, 1980) and no diatom accumulations. Therefore, these patches do not serve as water quality indicators. Nevertheless, the role of nutrients as environmental drivers in tropical meso-tidal beaches (e.g., Futuro beach) needs further investigation.

The occurrence of diatom accumulations in this tropical meso-tidal beach depends simultaneously on chemical drivers (availability of nutrients to sustain high biomass), physical drivers (force to accumulate cells) and biological drivers (surf diatoms), as observed by Odebrecht et al. (2014) on other beaches. Few species are enabled to form accumulation on sandy beaches in the world (Odebrecht et al., 2014; Franco et al., 2016). The accumulations of cells are not all passive, surf diatoms have biological adaptations to undertake vertical diel migration and to accumulate in the foam by adhering to air bubbles from breaking waves (Talbot and Bate, 1986, 1988a). These abilities appear be associated with production and changing in composition of the mucilage excreted by diatoms (Maria et al., 2016). However, there is little information on the physiological triggers for changes in surf diatoms buoyancy and forming patches.

Previous studies have shown that changes in tide height influenced diatom accumulation by promoting nutrient flux from underground aquifers to the surf zone (Campbell and Bate, 1998). Chlorophyll *a* concentrations were generally higher at LT than at HT at the same collection point (S1 or S2). The 6-h time gap between tidal stages, however, may not suffice to allow significant phytoplankton growth and biomass increase. It is possible that during LT, wave breaking suspended more microalgae whereas during HT, since the surf zone migrates towards the coast and waves break near the swash zone during HT.

The chlorophyll *a* from diatom accumulations was negatively correlated with tidal range and there was no correlation with samples lacking accumulations. Larger tidal amplitude was not associated with greater tide height. The tidal range and tide height (LT or HT) varied independently. Therefore, with a larger tidal range, there is greater sea level movement between the current tide (LT or HT) and previous tide, which promotes more patch dispersion since diatoms have already accumulated on the surface. Further study is necessary in order to understand this process better. Phytoplankton biomass reduction may be associated with tidal currents since their speed is directly proportional to the tidal range (Knauss, 2005). The largest patches were observed in December. These patches were collected at that time during neap tide, whose smaller range can promote a higher diatom concentration.

5. Conclusions

Diatom accumulations at Futuro Beach consisted mainly of *Anaulus* cf. *australis* and *Asterionellopsis tropicalis*. Unlike the other exposed beaches studied, the diatom accumulations at Futuro Beach were not associated with increases in wind velocity or wave height. The results of this study suggest that diatom patches is correlated with the higher rainfall. Probably, rainfall increase the supply of nutrients available to surf zone phytoplankton from this oligotrophic beach. In addition, there were association between swell and patches, this kind of wave may be a physical driver to form diatom accumulation, however this mechanism is not understood. Futhermore, the influence of wind velocity on patch formation in this tropical meso-tidal sandy beach must also be considered. Tides are a physical driver that affect the phytoplankton biomass at the surf zone of meso-tidal beaches and information on tidal range and stage (LT or HT) must be included in future studies in such environments. Aspects surf diatom physiological trigger to form patches (changes in cell buoyancy), nutrients requirements to grow and maintenance of high biomass, and the role of swell as hydrodynamic driver to form patches on the surf zone require further investigation. The current research provides a better understanding of the baseline functioning of warm high-energy coastal systems.

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