



Spatial and temporal variability of hydrodynamics on the Amazon Continental Shelf: an observational approach

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ABSTRACT

Amazon Continental Shelf (ACS) presents highly energetic hydrodynamics, modulated by multiple forcing mechanisms, and significant socio-economic and climate importance. This study characterizes the spatial-temporal variability of hydrodynamics on the ACS between 2°S and 4°N based on in situ data of 6 coastal sea level stations provided by IBGE, BNDO and SiMCosta, velocity measurements from 201 drifters of NOAA Global Drifter Program and 3 moorings of the AMANDES III project, and 127 CTD profiles from AMANDES and REVIZEE projects. The analysis of the coastal sea level shows that the tidal band contributes for 95 % (Santana, Amapá shelf) to 99 % (Turiaçu and Ribamar, Maranhão shelf) of the temporal variability of the sea level. Moreover, it shows that characteristics typical of a macrotidal regime occur up to 75 % and 41 % of the time at Turiaçu and Salinópolis, the eastern and central regions of the ACS, respectively. Velocity time series from drifters and moorings reveal a northwestward flow pattern along the ACS, which is associated with wind-driven circulation. The semidiurnal tides play a crucial role in the temporal variability of the cross-shelf velocity component, reaching a maximum percentage importance of 90 % on the central region of the ACS. Residual currents (without tides) are more pronounced in the alongshelf component. Their percentage importance increases towards the western shelf, from 68 % (73 %) and 20 % (10 %) in the upper (lower) water column at the eastern shelf, to 95 % (90 %) and 54 % (46 %) in the alongshelf and cross-shelf components, respectively. The wavelet analysis of the residual currents reveals high energy in two distinct period bands between 4 and 20 days and longer than 20 days at all moorings. The first period band is associated with wind modulations, while the second band indicates influence of the North Brazil Current (NBC) fluctuations. The time series of Richardson numbers show that the central and western shelves are stable for most of the time (>70 %). The stratification (N2) and vertical velocity shear (S2) parameters increase toward MAM4 (western shelf) associated with the spreading of the Amazon River plume and the increased influence of the NBC on the speed and direction of currents in the outer shelf. The TS diagrams show the presence of three distinct water masses on the ACS: coastal water influenced by river discharge, mixed water, and oceanic water.

1. Introduction

The Amazon Continental Shelf (ACS) is a highly energetic region with hydrodynamics modulated by: i) trade winds, ii) tides, iii) fluvial discharge, and iv) the North Brazil Current (NBC) mesoscale activity (Geyer et al., 1996; Aguiar et al., 2022). The ACS is located between 2°S

and 4°N (Fig. 1) and extends for approximately 2600 km comprising the continental shelves of the Brazilian states of Amapá, Pará, and Maranhão, referred to throughout the text as the AP (western) shelf, PA (central) shelf, and MA (eastern) shelf. It receives the largest river discharge worldwide and presents a shelf break at approximately the 100 m isobath (Nittrouer and DeMaster, 1986) located up to 290 km

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from the coast. The spatial variability of morphological (width and orientation of the isobaths) and sedimentological characteristics, along with multiple forcings, make the hydrodynamics of the ACS scientifically interesting and complex. The ACS shelters pristine systems including estuaries, islands, beaches, bays, and the largest mangrove system worldwide (Souza-Filho et al., 2009). The ACS is also adjacent to the planned oil and gas exploration regions, where there is an ongoing legal dispute between oil companies and the Brazilian Environmental Agency (IBAMA). Furthermore, the significant ecological and socio-economic importance of this wide region (Demaster and Pope, 1996; Isaac and Ferrari, 2017; Araújo et al., 2022) requires a more comprehensive understanding about the spatio-temporal variability of the physical mechanisms driving the hydrodynamics on the shelf.

The temporal variability of the trade winds in the equatorial Atlantic modulates the subtidal hydrodynamics on the ACS (Geyer et al., 1996) and is directly related to the migration of the Intertropical Convergence Zone (ITCZ). During the austral summer, the northeast trade winds dominate, while during the austral winter, the southeast trade winds prevail. Thus, the trade winds drive fluctuations in the velocity components on time scales of days to months, and influence the spread of the Amazon plume on the shelf (Lentz, 1995a; Castro et al., 2006).

The tides play a crucial role in the sea level, currents and structure of Amazon plume variability on the ACS, presenting the dominance of the semidiurnal component M_2 and cross-shelf tidal currents speed higher than 2 m s^{-1} (Geyer et al., 1996; Ruault et al., 2020). Along the coast to AP (western) shelf (Fig. 1), M_2 has an amplitude higher than 1.5 m, and a tidal range of up to 6 m near Cabo Norte. In São Marcos Bay, on the MA (eastern) shelf, the tidal range (H) can be higher than 8 m with current speeds of up to 2.4 m s^{-1} during equinoctial spring tides (Beardsley et al., 1995; Geyer et al., 1996; González-Gorbeña et al., 2015).

The morphological and sedimentological characteristics of the ACS modulate the spatial variability of M_2 tidal energy dissipation on the middle and inner shelf (depth <20 m) (Beardsley et al., 1995; Gabioux et al., 2005). Furthermore, the interaction between the barotropic tidal currents and bottom topography near shelf break generates Internal

Tides on the ACS (Lentini et al., 2016; Tchilibou et al., 2022), which play an important role in regional fine sediment transport (Molinas et al., 2020) and can modulate the Sea Surface Temperature (SST) on the shelf (Assene et al., 2024).

River discharge along the ACS drives biogeochemical fluxes at the continent-ocean interface and modulates salinity, temperature, and currents on the shelf. The Amazon River stands out in this context due to its high discharge, which reaches a maximum of about $200,000 \text{ m}^3 \text{ s}^{-1}$ during the austral summer (Oliveira et al., 2018). It plays an important role in the dynamics of suspended sediments (Gensac et al., 2016; Yu et al., 2022), and in the formation of a plume of low-salinity water that exhibits a northwestward and/or eastward dispersion on the shelf, driven by the magnitude of the river discharge, and the intensity and direction of the trade winds (Lentz and Limeburner, 1995; Lentz, 1995b). In addition, in the eastern part of the ACS (MA shelf), typical local estuarine waters are observed up to 60 km away from the coast modulating the stratification up to mid-shelf (Cavalcanti-Lima et al., 2023).

On the continental slope adjacent to the ACS, the NBC flows northwestward, with an average velocity of 1.0 m s^{-1} , a vertical structure covering the upper 1000 m of the water column, and an average horizontal position that is partially over the outer shelf (Johns et al., 1998; Schott et al., 1998; Stramma et al., 2005). Thus, the NBC drives low-frequency fluctuations in the alongshelf velocity component on the ACS and plays an important role in the advection of mass at the shelf-ocean interface (Prestes et al., 2018; Aguiar et al., 2022; Freitas et al., 2024).

Valuable contributions to the knowledge of the physical oceanography of the ACS come from 3 major observational initiatives: “AmasSeds” (A Multidisciplinary Amazon Shelf SEDiment Study) (Geyer et al. 1991, 1996; Lentz, 1995a), “Revizee” (Assessment of the Sustainable Potential of the Living Resources of the Exclusive Economic Zone) (Silva et al., 2010), and “Amandes” (Jeandel, 2007), conducted between 1989 and 1991, 1995–2001, and 2007–2008, respectively. Despite the important scientific contributions generated by these important projects

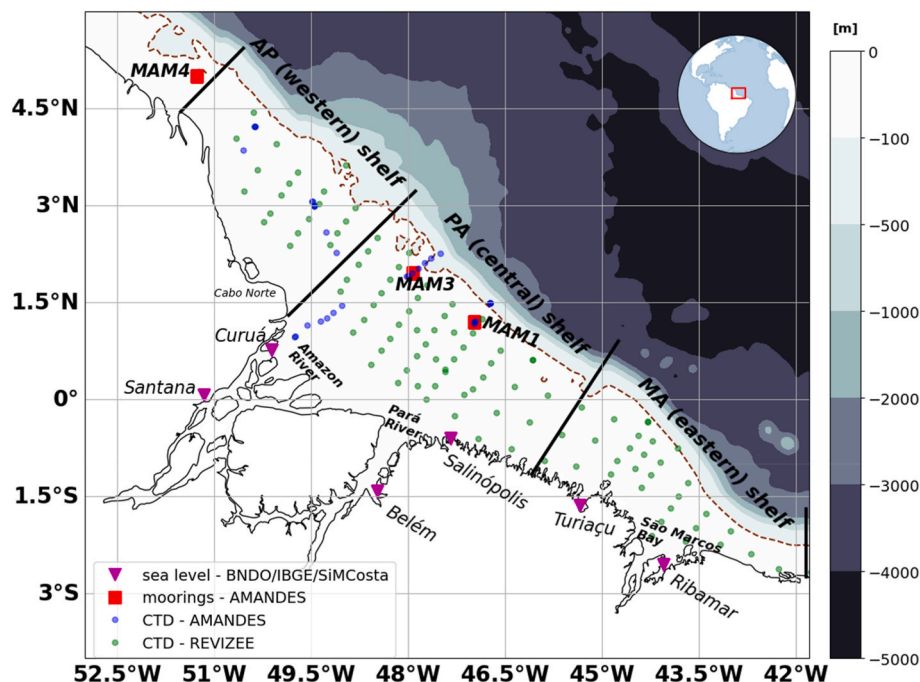


Fig. 1. Bathymetry of the Amazon Continental Shelf (ACS) (shaded), including the Maranhão shelf [MA], Pará shelf [PA] and Amapá shelf [AP]. The dotted line indicates the 100 m isobath. The black line indicates the boundaries between the ACS sectors. The magenta dot indicates the coastal stations of the IBGE/BNDO/SiMCosta sea level measurements. The red square and blue dot indicate the moorings and CTD profiles from the AMANDES project. The green dot indicates the CTD profiles from the REVIZEE project. The inset indicates the area of analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

to the characterization of the main physical forcing mechanisms in the region, gaps in observational studies concerning the spatio-temporal variability of the hydrodynamics on the ACS considering MA (eastern), PA (central) and AP (western) shelves (Fig. 1) still remains. In this context, there are gaps in knowledge in terms of: i) quantifying the percentage of time during which tidally associated sea level oscillations along the Amazon coast exhibit macro ($H \geq 4$ m), meso ($2 \text{ m} < H < 4 \text{ m}$), or micro ($H < 2 \text{ m}$) tidal range; ii) determining the percentage contribution of subtidal/tidal band to the temporal coastal sea level and velocity variability along the shelf; (iii) assessing the importance of wind for along-shelf and cross-shelf velocities; and (iv) a characterization the spatial variation of the relative importance of stratification and turbulence along the ACS.

Thus, based on sea level measurements at 6 stations along the Amazon coast, 3 current meter moorings on the outer shelf, vertical profiles of CTD, and drifters measurements of velocity along the ACS, the present study aims to characterize the spatial-temporal variability of hydrodynamics on the ACS. This includes: i) characterizing the spatio-temporal variability of tidal range on the coastal sea level; ii) quantifying the importance of tidal and subtidal bands to the coastal sea level and velocity variability on the shelf; and iii) characterizing the spatio-temporal variability of the relative importance between stratification and turbulence on the ACS.

2. Data and methods

2.1. Coastal sea level

This study used hourly time series of sea level height from 6 coastal stations along the ACS (Fig. 1 and Table 1) provided by the Geodetic Permanent Tide Gauge Network (RPMG) of the Brazilian Statistics Institute (IBGE) (<https://www.ibge.gov.br>), the Brazilian National Oceanographic Data repository (BNDO) (<https://www.marinha.mil.br/chm/bndo>), and the Brazilian Coastal Monitoring System (SiMCosta) (<https://simcosta.furg.br/home>).

2.2. Moorings

This study also used hourly time series of velocity, temperature and salinity from 3 moorings (MAM1, MAM3 and MAM4) of the AMANDES III project (Jeandel, 2008) located in the outer portion of the ACS (Fig. 1 and Table 2). The moorings were equipped with a 1200 kHz Nortek Aquadopp current profiler (upper) and an Aanderaa RCM7 current meter (lower), both equipped with temperature, and conductivity sensors in the upper (lower) water column.

Table 1
Description of coastal sea level data along the Amazon Continental shelf.

Locations	Lon/Lat	Period	Time Length (days)	Repository
Curuá [AP (western) shelf]	50.11°W 0.76°N	January 1st, 2019 to December 17th, 2019	351	BNDO
Santana [AP (western) shelf]	51.16°W 0.06°N	October 1st, 2005 to December 31st, 2021	5914	IBGE
Belém [PA (central) shelf]	48.48°W 1.43°S	November 29th, 2019 to December 31st, 2021	763	IBGE
Salinópolis [PA (central) shelf]	47.35°W 0.61°S	January 1st, 1955 to December 31st, 1955	365	BNDO
Turiacu [MA (eastern) shelf]	45.35°W 1.64°S	March 2nd, 1978 to February 28th, 1979	364	BNDO
Ribamar [MA (eastern) shelf]	44.05°W 2.56°S	February 18th, 2019 to June 16th, 2020	484	SiMCosta

Table 2

Description of the moorings MAM1, MAM3 and MAM4 along the Amazon Continental Shelf used as source for velocity, temperature and conductivity data.

Locations	Lon/Lat	Period	Length of data (days)	Measurement Depth [m]	Isobath [m]
MAM1 [PA (central) shelf]	46.97°W 1.19°N	April 12th, 2008 to July 15th, 2008	94	23 m and 37 m	54
MAM3 [PA (central) shelf]	47.93°W 1.94°N	April 13th, 2008 to July 15th, 2008	93	17 m and 38 m	54
MAM4 [AP (western) shelf]	51.27°W 5.00°N	April 17th, 2008 to July 12th, 2008	85	25 m and 51 m	68

The MAM4 mooring is located on the Guyana continental shelf very close to the AP (western) shelf (Fig. 1), which allows us to use it as a proxy for the analysis of this sector of the ACS. The mooring positions along the PA (central) and AP (western) shelves and the temporal concurrence of the measurements make these data valuable for analyzing the spatial variability of the importance of the tidal and subtidal bands for the current variability, as well as for the variability of turbulence and stratification. It is noteworthy that the data from two of these moorings (MAM3 and MAM4) are being analyzed for the first time from the perspective of spatio-temporal characterization of hydrodynamics in the ACS.

2.3. CTD profiles

We analyzed 104 CTD profiles (Seabird SBE-19) collected during the REVIZEE project campaign between March 15th, 1995 and May 13th, 1995 distributed in 24 cross-shelf transects along the ACS. Here, only measurements taken at depths equal to or less than 100 m were considered (Fig. 1), following the isobath criterion for the Amazon shelf break of Nittrouer and DeMaster (1986). In addition, we analyzed 23 CTD profiles (Seabird Electronics SBE 911) from the AMANDES project, which was conducted between April 11th and 13th, 2008 as 3 cross-shelf transects on the PA (central) shelf and along the AP (western) shelf (Fig. 1). These data were used to characterize the stratification and water masses in the different sectors of the ACS.

2.4. Drifters

For the surface characterization of the currents on the ACS, this study used hourly trajectories and velocity data collected by satellite-tracked surface drifting buoys (drifters) from the NOAA Global Drifter Program (GDP) (<https://www.aoml.noaa.gov/phod/gdp>). A search for drifters was conducted in the area between 40°W and 53°W and 6°S - 6°N for the period 2001 to 2020, and a total of 201 drifters with trajectories in the ACS were selected (Figs. 2 and 3). The 100 m isobath was used as the continental shelf boundary criterion (Nittrouer and DeMaster, 1986).

2.5. Wind data

This study used hourly time series of zonal and meridional wind components from the ECMWF Reanalysis v5 (ERA5) (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>) to investigate its effect on the temporal variability of coastal residual sea level and velocity. The timing and duration of these series are consistent with those shown in Tables 1 and 2. The zonal wind component, without rotation, was used for cross-spectral analysis with residual sea level and currents.

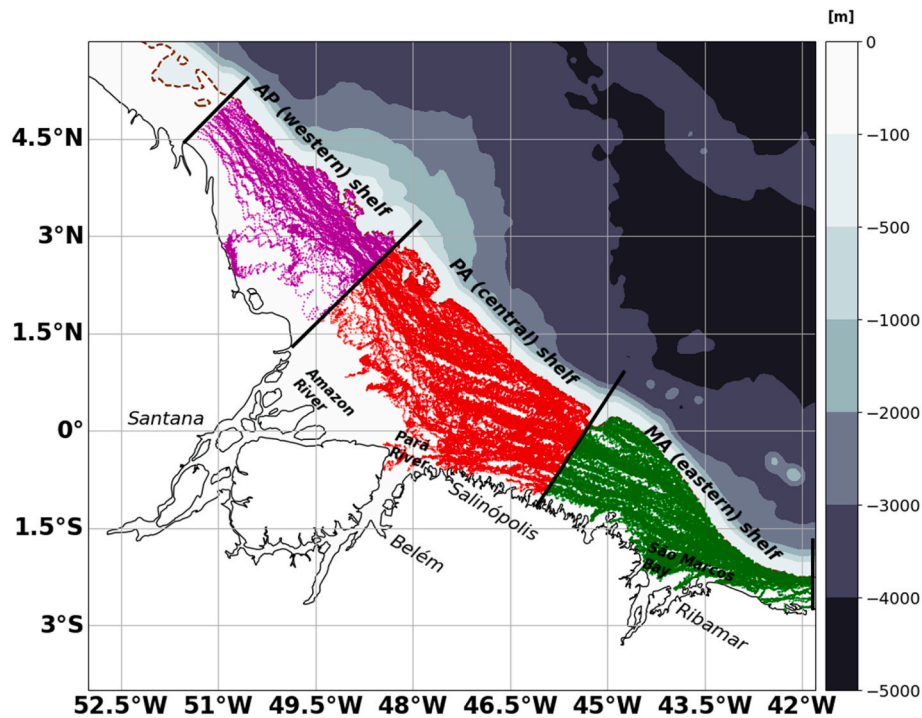


Fig. 2. Bathymetry of the Amazon Continental Shelf (ACS) (shaded), including the MA (eastern), PA (central) and AP (western) shelves. The dotted line indicates the 100 m isobath. The black line indicates the boundaries between the ACS sectors. The green, red, and magenta dots indicate the trajectory of 201 drifters on the MA (eastern), PA (central) and AP (western) shelves, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

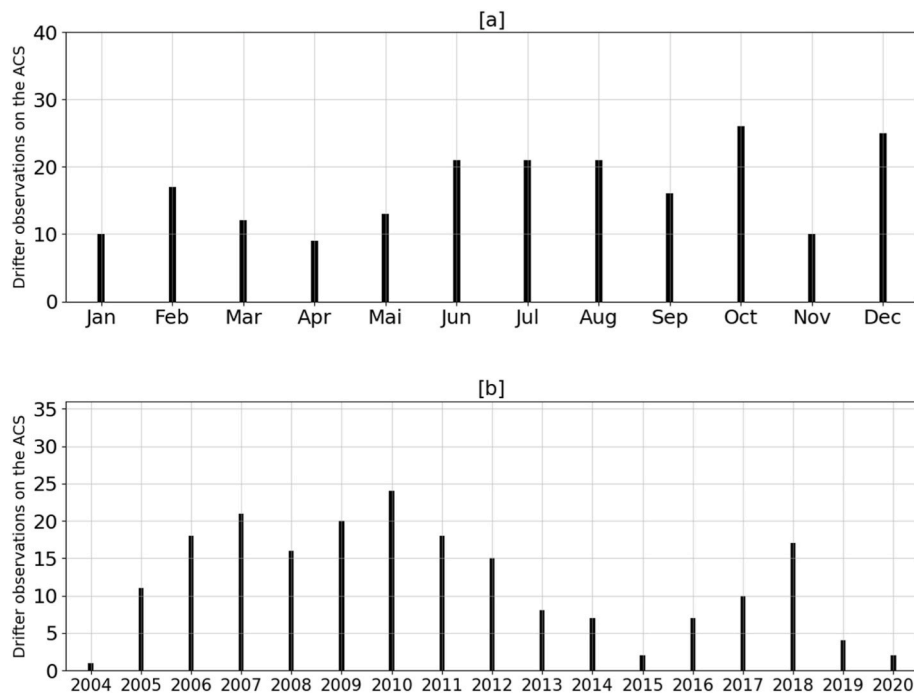


Fig. 3. Temporal occurrence of the 201 drifters analyzed on the Amazon Continental Shelf from 2001 to 2020. [a] Accumulated number of drifter observations per month during the whole period. [b] Number of drifter observations per year.

2.6. Analysis

Harmonic tidal analysis was performed on the sea level time series from the Curuá (AP (western) shelf), Santana (AP (western) shelf), Belém (PA (central) shelf), Salinópolis (PA (central) shelf), Turiaçu (MA

(eastern) shelf) and Ribamar (MA (eastern) shelf) coastal stations (Fig. 1 and Table 1) with the purpose of obtaining the sea level tidal variation. The residual sea level was estimated by subtracting the tidal signal from the raw series. A spectral analysis (FFT) of the raw and residual (without tide) sea level series was then performed to quantify the energy level in

the frequency domain associated with the tidal and residual signals. Finally, based on the tidal harmonic constituents obtained, a 20-year tidal prediction (2002–2022) was performed for the 6 coastal stations to characterize the temporal and spatial variability of the tidal range in terms of macro ($H \geq 4$ m), meso ($2 \text{ m} < H < 4$ m) and micro ($H \leq 2$ m) tidal conditions along the Amazon coast. The tidal prediction period for the 2000s was chosen to mitigate the effect of temporal heterogeneity in the analyzed dataset, as the velocity measurements from the AMANDES moorings and drifters fall within this period, while some historical sea level data date back to 1955 (e.g. Salinópolis-PA shelf).

The trajectories of the 201 drifters on the ACS (Figs. 2 and 3) were separated into the MA (eastern), PA (central), and AP (western) shelves according to their position. A rotary spectral analysis was performed on the velocity estimated by the drifters to characterize the energy in the surface currents on the ACS in the frequency domain and in terms of cyclonic and anticyclonic motion. The analysis of the drifters velocity measurements helps to reduce the uncertainties associated with the limited spatial coverage of the AMANDES mooring velocity measurements, which do not cover the MA shelf. However, since the measurement periods are mostly shorter than 15 days, the analysis allows a statistically reliable quantification of the semidiurnal tidal range.

The meridional and zonal velocity components from moorings MAM1, MAM3, and MAM4 (Fig. 1 and Table 2) were rotated relative to the orientation of the isobaths and are referred throughout the text as alongshelf and cross-shelf, respectively. Harmonic tidal analysis was performed in velocity series to obtain the tidal signal. Alongshelf and cross-shelf residual velocities were calculated by subtracting the tidal signal from the raw series and then applying a low-pass filter (butter) with a cutoff frequency of 72 h. This cutoff frequency was chosen based on the spectral gap.

Rotary spectral analysis was performed on the raw velocity series (top and bottom) to characterize the energy levels of the tidal and subtidal bands in the currents along the ACS. The spectrum was estimated using the Hanning spectral window and smoothed by running average. The temporal variability of the residual along-shelf and cross-shelf velocities were investigated based on wavelet analysis (Torrence and Compo, 1998; Liu et al., 2007) to characterize events of high energy in the frequency domain.

The relative importance of turbulence and stratification on the ACS was estimated based on the Richardson number estimated using the time series of temperature, salinity, and velocity from the moorings (Fig. 1 and Table 2).

$$Ri = \frac{-\frac{g}{\rho} \frac{\partial \rho}{\partial z}}{\left(\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right)} \quad (1)$$

where, g denotes the gravity acceleration, ρ the density, u and v the alongshelf and the cross-shelf components of the velocity, respectively and z the depth.

In addition, 127 CTD profiles from the REVIZEE and AMANDES projects were analyzed in the form of Temperature-Salinity (TS) diagrams to characterize the water masses along the MA (eastern), PA (central), and AP (western) shelves. Although the measurements were made in different years, both datasets were collected during periods of high Amazon River discharge (Fassoni-Andrade et al., 2023).

3. Results

The results are presented in three sections, which address: i) the spatio-temporal variability of the coastal sea level, ii) the spatio-temporal variability of the current and its characterization in terms of energy levels of the tidal and subtidal bands, and iii) the spatio-temporal variability of the relative importance of turbulence and stratification.

3.1. Spatio-temporal variability of coastal sea level on the ACS

Fig. 4 shows the spectral analysis of the raw and residual time series of the coastal sea level stations. The spectrum based on the raw series (blue lines) shows prominent peaks in periods of 0.5 and 1 day associated with semi-diurnal (M_2 and S_2) and diurnal tidal constituents (O_1 and K_1), respectively. Furthermore, at Curuá (AP (western) shelf), Santana (AP (western) shelf), Belém (PA (central) shelf) and Turiaçu (MA (eastern) shelf) stations (Fig. 4 [a,b,c,e]), distinct energy peaks are observed at 15 and 30 days, associated with the spring/neap and monthly tidal cycles. The spectral analysis of the residual series (red lines) shows a significant reduction of the energy level ($>10^2 \text{ m}^2 \text{ cph}^{-1}$) in periods shorter than 2 days and a smaller reduction in periods longer than 2 days. The spectrum of the raw and residual series at Salinópolis (PA (central) shelf), Turiaçu (MA (eastern) shelf) and Ribamar (MA (eastern) shelf) (Fig. 4 [d,e,f]) shows a smaller difference between the energy levels in the periods 7–30 days.

The temporal variability of the tidal range along the Amazon coast was characterized based on the 20-year tidal prediction (2002–2022), and Fig. 5 illustrates the temporal series in 2022. The stations of Turiaçu (MA (eastern) shelf) (Fig. 5 [e]) and Ribamar (MA shelf) (Fig. 5 [f]) present the highest tidal range, with maximums of 7.5 m and 6 m, respectively, while the stations of Belém (PA (central) shelf) (Fig. 5 [c]) and Santana (AP (western) shelf) (Fig. 5 [b]) show lower tidal range, with maximums of 3.8 m and 3.5 m, respectively. The small difference between the minimum and maximum tidal range at Curuá, Belém and Santana suggests a stronger effect of the bathymetry constricting margins in attenuating the tidal range (Gallo and Vinzon, 2005).

Fig. 6 shows the spatio-temporal variability of tidal range in terms of macro, meso and micro tidal conditions along the Amazon coast. The stations Ribamar (MA (eastern) shelf), Turiaçu (MA (eastern) shelf), Salinópolis (PA (central) shelf) and Curuá (AP (western) shelf) exhibit macro-meso tidal conditions, with tidal range exceeding 4 m (macro tide) 57 %, 75 %, 41 % and 16 % of the time, respectively. At Belém (PA shelf) and Santana (AP shelf) stations, meso-micro tidal conditions dominate, with meso tidal range during 75 % and 90 % of the time, respectively. The increase in tidal range at Curuá (AP (western) shelf) compared to Santana (AP shelf) and Belém (PA shelf) confirms that the inland location of these stations within the Amazon/Pará Rivers leads to an attenuation of the tidal range.

The residual sea level (without tides) shows statistically similar range average values along the Amazon coast (0.1 m) (Table 03). However, residual level can cause significant variations of up to 1.0, as observed in Belém, Salinópolis and Turiaçu. It is important to note that the absolute values of the residual sea level range, especially those of the maximum events, are sensitive to the precision of the instruments and should be analyzed with caution, as in the case of the Salinópolis station, which has historical data from 1955. The relative importance of the residual water level for sea level variability along the Amazon coast and its relationship with the wind are discussed in Section 4.

3.2. Spatio-temporal variability of the currents on the ACS

The characteristics of the currents along the ACS was studied using measurements of velocity from drifters and moorings (Figs. 1 and 2). Fig. 7 displays the spatially averaged rotary spectrum of velocities measured by 201 drifters on the AP (western), PA (central), and MA (eastern) shelves. Across all sectors of the ACS, a prominent energy peak is observed at periods of 0.5 days, with similar energy levels of both cyclonic and anticyclonic motion components. The confidence level (shading) of the total spectrums suggests no significant difference in energy levels within the semidiurnal tidal band along the ACS.

The time series of alongshelf and cross-shelf velocities from moorings MAM1, MAM3, and MAM4 on the PA (central) and AP (western) shelves are shown in Figs. 8–10, respectively. The total (raw) alongshelf currents observed at all moorings (Fig. 8[a], 9[a], and 10[a]) show a strong

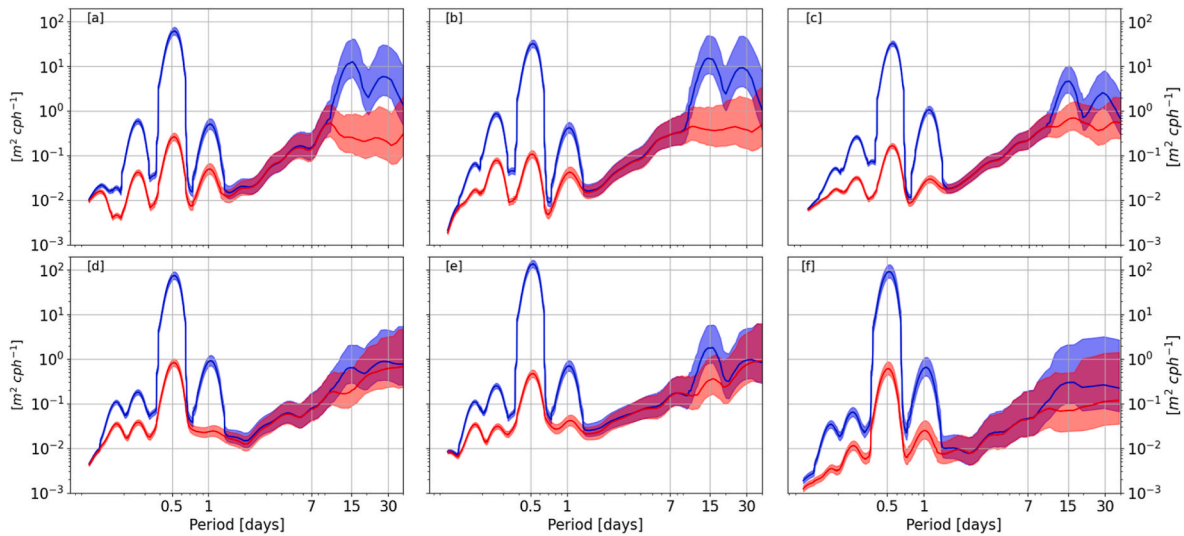


Fig. 4. Spectrum of raw (blue line) and residual (red line) coastal sea levels at Curuá (AP (western) shelf) [a], Santana (AP (central) shelf) [b], Belém (PA (central) shelf) [c], Salinópolis (PA (central) shelf) [d], Turiacu (MA (eastern) shelf) [e] and Ribamar (MA (eastern) shelf) [f]. The shading represents the 99 % confidence interval. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 1, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

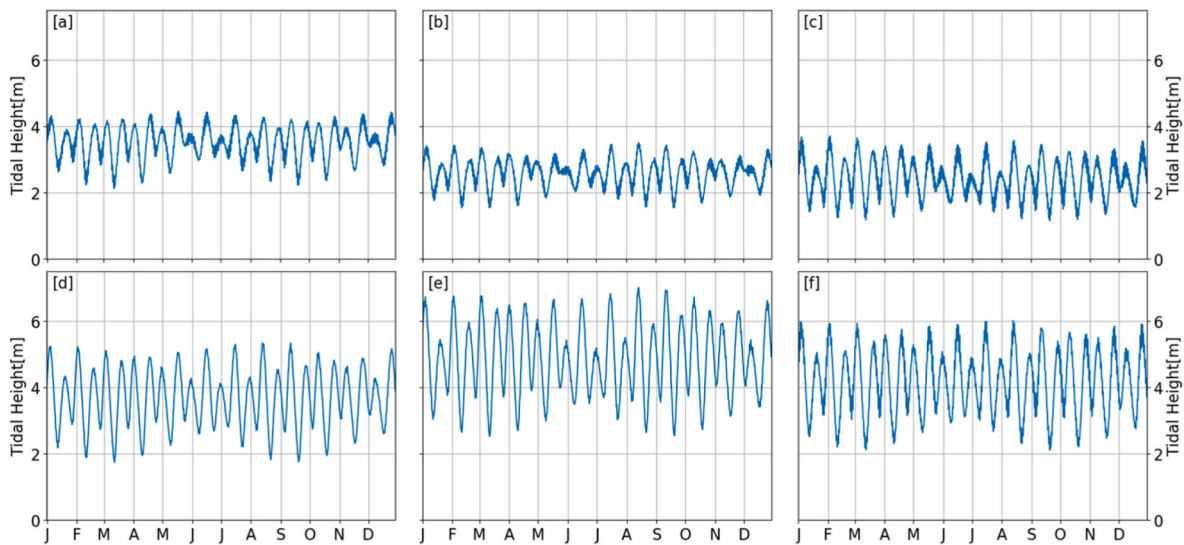


Fig. 5. The temporal variation of the tidal range based on the tidal prediction for the year 2022 at Curuá (AP (western) shelf) [a], Santana (AP (central) shelf) [b], Belém (PA (central) shelf) [c], Salinópolis (PA (central) shelf) [d], Turiacu (MA (eastern) shelf) [e] and Ribamar (MA (eastern) shelf) [f]. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 1, respectively.

northwestward flow most of the time, while the raw cross-shelf component (Fig. 8[b], Fig. 9[b], and Fig. 10[b]) shows tidally modulated currents.

The tidal alongshelf currents (Fig. 8[c], Fig. 9[c], and Fig. 10[c]) present maximum magnitudes during spring tides in the upper (lower) water column (see Table 2) of 65 cm/s (45 cm/s), 24 cm/s (40 cm/s), and 47 cm/s (−17 cm/s) at MAM1 (PA (central) shelf), MAM3 (PA (central) shelf), and MAM4 (AP (western) shelf), respectively. The tidal cross-shelf currents (Fig. 8[d], Fig. 9[d], and Fig. 10[d]) exhibit the highest velocity amplitudes, with values in the upper (lower) water column of 155 cm/s (120 cm/s), 120 cm/s (97 cm/s), and 52 cm/s (28 cm/s) at MAM1 (PA (central) shelf), MAM3 (PA (central) shelf), and MAM4 (AP (western) shelf), respectively. The amplitude of the tidal currents decreases northwestward in both components.

The residual (without tides and filtered) alongshelf currents are stronger than the cross-shelf currents and present in the upper (lower)

water column maximum values of 92 cm/s (55 cm/s) (Fig. 8[e]), 91 cm/s (55 cm/s) (Fig. 9[e]), and 128 cm/s (47 cm/s) (Fig. 10[e]) at MAM1 (PA (central) shelf), MAM3 (PA (central) shelf), and MAM4 (AP (western) shelf), respectively.

Fig. 11 shows a rotary spectrum analysis based on the raw alongshelf and cross-shelf velocities in the upper (lower) water column from moorings MAM1, MAM3 and MAM4, respectively (see Table 2). The spectrums display a prominent energy peak at 0.5-day periods for all moorings and at both the upper and lower parts of the water column, associated with semi-diurnal tides. The spectrums at MAM1 (Fig. 11[a, b]) and MAM3 (Fig. 11[c, d]) exhibit energy peaks at a 1-day period, linked to the diurnal tides, which is less pronounced at MAM4 (Fig. 11[e, f]). The energy level within the semi-diurnal and diurnal tidal frequency bands decreases by an order of magnitude from MAM1 ($10^5 \text{ cm}^2 \text{ s}^{-2} \text{ cph}^{-1}$) to MAM4 ($10^4 \text{ cm}^2 \text{ s}^{-2} \text{ cph}^{-1}$). The cyclonic (blue line) and anticyclonic (red line) motions present similar importance in the semi-diurnal and

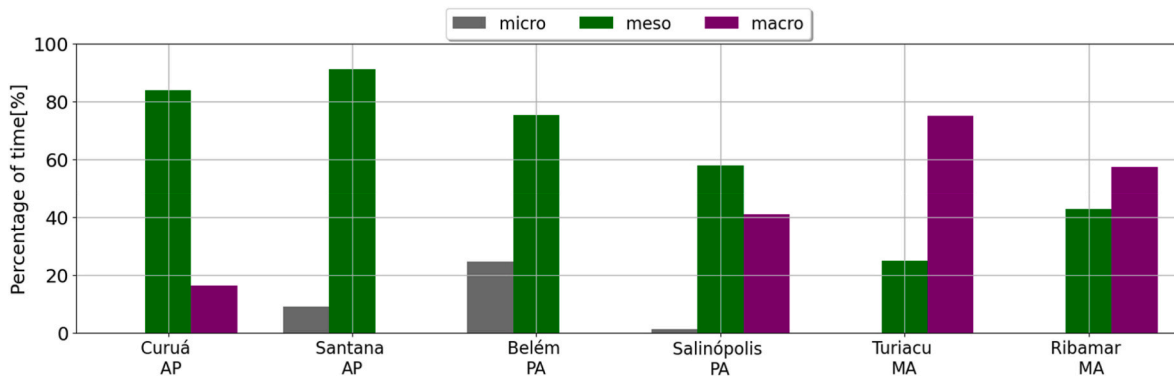


Fig. 6. Percentage of time where tidal range (H) exhibits macro ($H \geq 4$ m), meso ($2\text{m} < H < 4$ m), and micro ($H \leq 2$ m) tidal conditions at Curuá (AP (western) shelf), Santana (AP (western) shelf), Belém (PA (central) shelf), Salinópolis (PA (central) shelf), Turiaçu (MA (eastern) shelf) and Ribamar (MA (eastern) shelf). The geographical locations of the stations and their periods are shown in Fig. 1 and Table 1, respectively.

Table 03

Characterization of the residual coastal sea level.

Locations	Residual Sea Level Range (average)	Residual Sea Level Range (Deviation)	Residual Sea Level Range (max)
Curuá [AP (western shelf)]	0.16 m	± 0.12 m	0.8 m
Santana [AP (western shelf)]	0.16 m	± 0.12 m	0.9 m
Belém [PA (central) Shelf]	0.14 m	± 0.12 m	1.0 m
Salinópolis [PA (central) Shelf]	0.23 m	± 0.23 m	2.0 m
Turiaçu [MA (eastern) shelf]	0.19 m	± 0.17 m	1.8 m
Ribamar [MA (eastern) shelf]	0.22 m	± 0.20 m	0.8 m

diurnal tidal frequency bands across all moorings. In the subtidal band (>1 day), anticyclonic motions exhibit energy peaks at 4-day periods at MAM1 (Fig. 11[a, b]) and MAM3 (Fig. 11[d]), probably associated with the local wind. The confidence limits (shading) of the bottom velocity spectrum at MAM4 (Fig. 11[e,f]) within the subtidal band (>1 day period) are wider compared to the other moorings, indicating greater temporal variability of the currents.

Fig. 12 shows the percentage contribution of tidal and residual (and

filtered) currents to the temporal variability of both alongshelf and cross-shelf currents on the PA (central) and AP (western) shelves. Tidal currents dominate the cross-shelf velocity component on the PA (central) shelf and decrease in importance on the AP (western) shelf, accounting for 80 % and 90 %, 71 % and 86 %, and 46 % and 54 % of the variability of currents in the upper and lower water column at MAM1 (PA (central) shelf), MAM3 (PA (central) shelf), and MAM4 (AP (western) shelf), respectively. On the other hand, the residual currents are more important for the alongshelf component, accounting for 68 % and 61 %, 95 % and 73 %, and 77 % and 90 % of the variability of the currents at the upper and lower of the water column at MAM1 (PA (central) shelf), MAM3 (PA (central) shelf), and MAM4 (AP (western) shelf), respectively.

Wavelet analysis was performed on the residual alongshelf (Fig. 13) and cross-shelf (Fig. 14) currents at MAM1, MAM3, and MAM4 to characterize high-energy events with statistical confidence in the frequency domain on the PA (central) and AP (western) shelves. The power spectrum (Morlet) show that the highest energy levels occur in the upper water column, and indicate high energy events within the period band between 4 and 64 days across all moorings and in both velocity components (Figs. 13 and 14 [a,c,e,g,i,k]).

The global spectrum of the residual alongshelf currents (Fig. 13 [b,d,f,h,j,l]) and cross-shelf currents (Fig. 14 [b,d,f,h,j,l]) shows that the highest energy levels with statistical significance occur within two distinct period bands: between 8 and 16 days and between 20 and 40

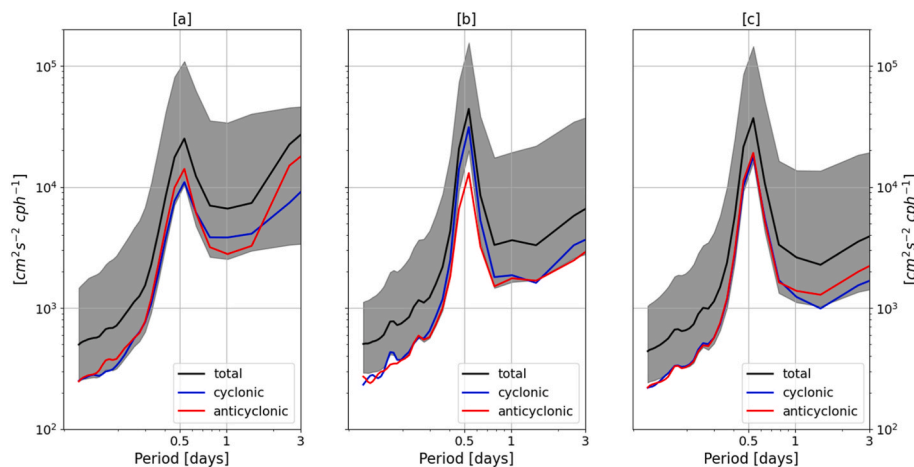


Fig. 7. Spatial average rotary spectrum analysis of the zonal and meridional velocity components measured by the drifters on the AP (western) [a], PA (central) [b], and MA (eastern) [c] shelves (see Fig. 2). The black, blue and red lines represent the total, cyclonic and anticyclonic spectrum, respectively. The shading represents the 99 % confidence interval. The trajectories of the drifters are shown in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

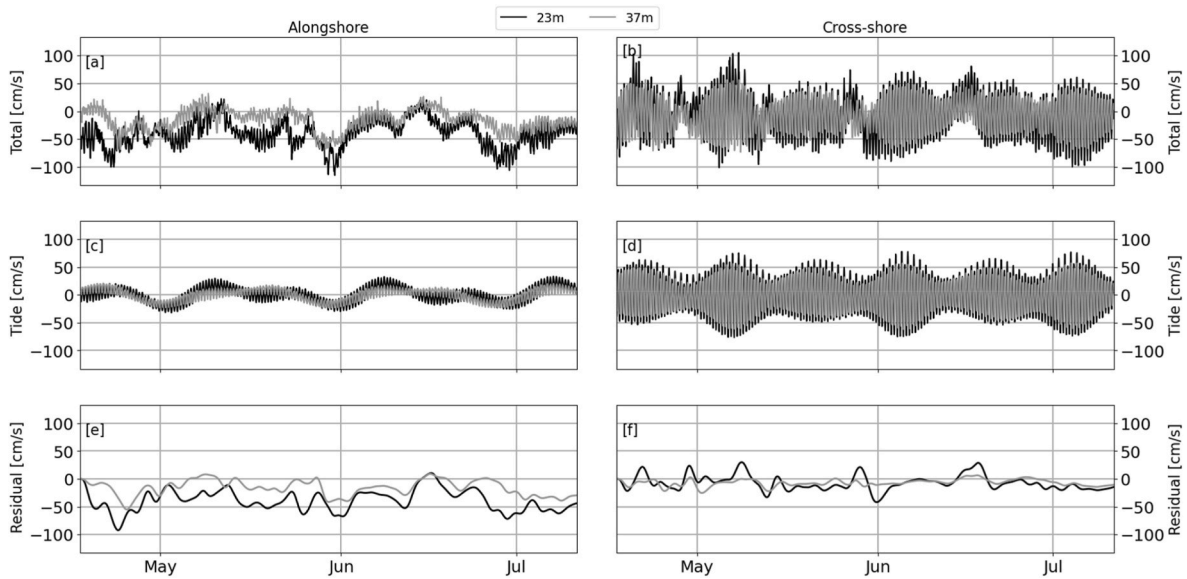


Fig. 8. Alongshelf and cross-shelf velocities: total (raw) [a,b], tidal [c,d], and residual [e,f] from mooring MAM1 (see Fig. 1 and Table 2) during April 17th, 2008 to July 12th, 2008. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively.

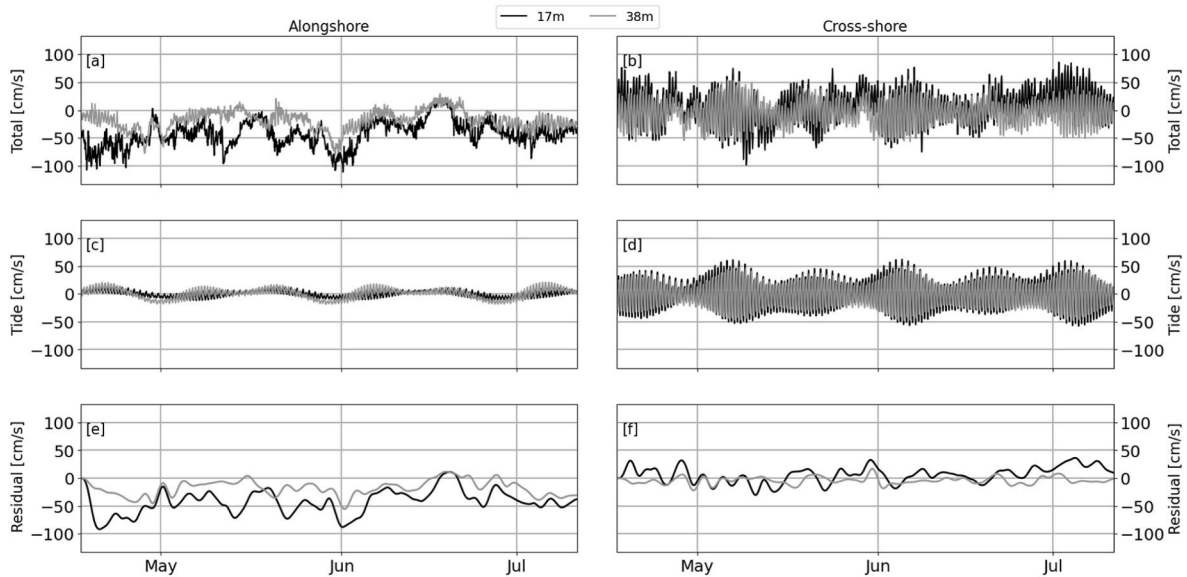


Fig. 9. Alongshelf and cross-shelf velocities: total (raw) [a,b], tidal [c,d], and residual [e,f] from mooring MAM3 (see Fig. 1 and Table 2) during April 17th, 2008 to July 12th, 2008. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively.

days at MAM1 and MAM3, both on the PA (central) shelf. At MAM4 (AP (western) shelf), however, only the 40 days period band is observed. Residual alongshelf currents have twice the energy compared to residual cross-shelf currents. Towards the AP (western) shelf (MAM4 mooring), the alongshelf currents exhibit a decrease in energy levels in the first period band (8–16 days), while the second band (20–40 days) intensifies and reaches a maximum value of 222 [cm/s]^2 (Fig. 13 [j]). The cross-shelf currents show energy levels within the 20–40 day band statistically similar at MAM4 (AP (western) shelf) compared to that observed at MAM1 (PA (central) shelf) and MAM3 (PA (central) shelf).

Considering that the residual alongshelf current at the surface has more energy (Fig. 13 [a,b,e,f,i,j]), a cross-wavelet transform analysis (Torrence and Compo, 1998; Grinsted et al., 2004) was performed between the residual alongshelf velocity at the upper of the water column from the moorings and the local filtered (low-pass filter with a cutoff frequency of 72 h) zonal wind velocity from the closest ERA 5 model grid

point (Fig. 15). The zonal component of the wind was selected for analysis due to its higher variance.

Fig. 15 illustrates the coherence coefficient from the cross-wavelet analysis between the residual alongshelf current and the local filtered zonal wind on the PA (central) and AP (western) shelves. The black arrows pointing upward (downward) indicate in-phase (anti-phase) signals. Arrows pointing to the left indicate that the wind is leading the current. The panels (Fig. 15 [a,b,c]) demonstrate high coherence values (>0.8) with statistical significance within the period bands ranging from 4 to 20 days, and from 32 to 64 days at MAM1 (Fig. 15 [a]) and MAM3 (Fig. 15 [b]). At MAM4 (Fig. 15 [c]), the period band of coherence with statistical confidence occurs between 4 and 32 days, and is less frequent over time compared to MAM1 and MAM3.

The zonal wind leads the residual alongshelf currents during periods of high common energy with statistical confidence and coherence across all the moorings. It is possible to highlight events within a period

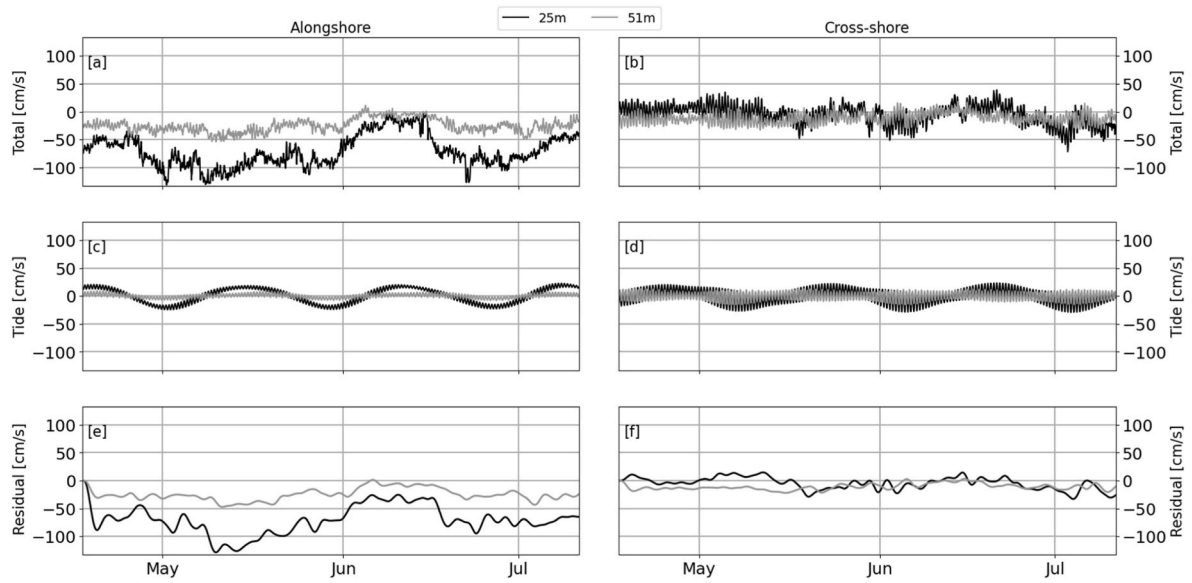


Fig. 10. Alongshelf and cross-shelf velocities: raw [a,b], tidal [c,d], and residual [e,f] from mooring MAM4 (see Fig. 1 and Table 2) during April 17th, 2008 to July 12th, 2008. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively.

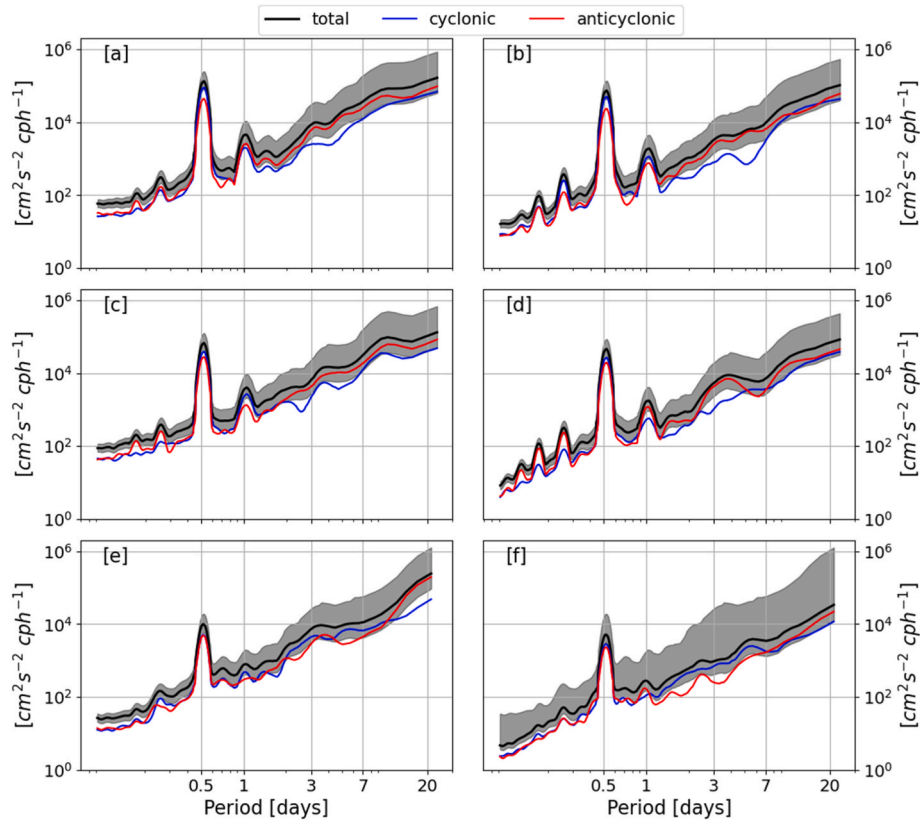


Fig. 11. Rotary spectrum of the raw alongshelf and cross-shelf velocity at the top [a,c,e] and bottom [b,d,f] at MAM1 [a,b], MAM3 [c,d] and MAM4 [e,f] (see Fig. 1 and Table 2). The black, blue and red lines represent the total, cyclonic and anticyclonic spectrum, respectively. The shading represents the 99 % confidence interval. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

between 4 and 20 days in early May (Fig. 15 [a,b,c]) and June (Fig. 15 [a]), and within a period between 32 and 64 days in June and July (Fig. 15 [a,b]). The forcing mechanism between the residual currents and the local zonal wind is discussed in Section 4 based on the energy levels of the wind over time and in the frequency domain.

3.3. Turbulence and stratification on the ACS

Based on the raw time series of salinity, temperature, and velocity in the upper and lower water column at the MAM1 (PA shelf), MAM3 (PA shelf), and MAM4 (AP shelf) moorings (Fig. 1 and Table 2), the Richardson number was calculated to quantify the relative importance

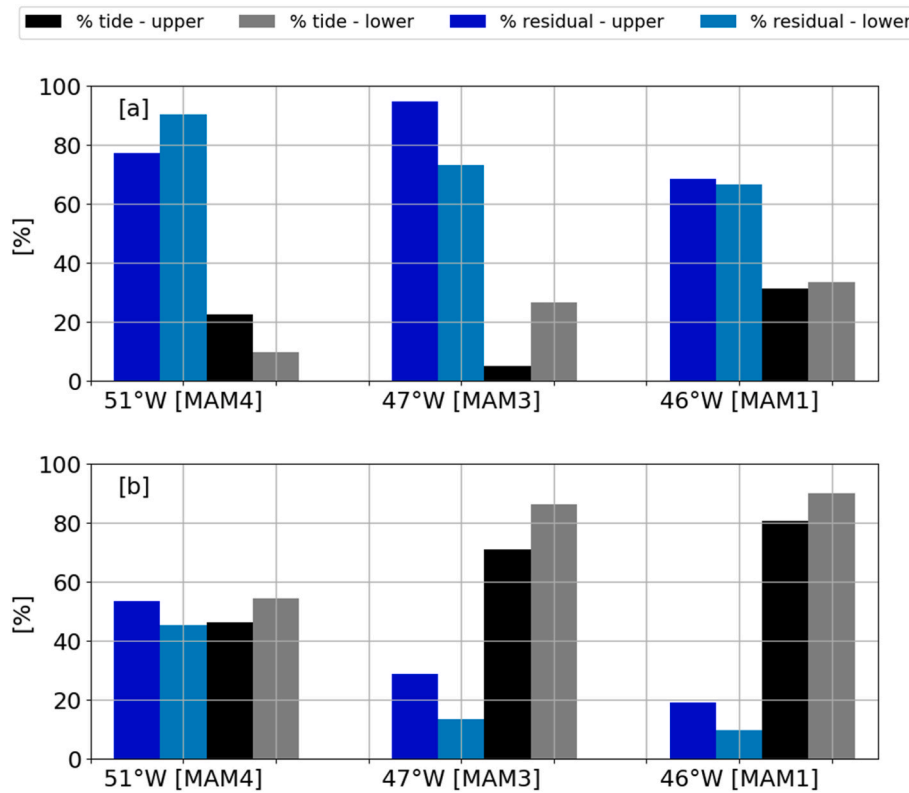


Fig. 12. Percentage contribution of tidal (black and gray) and residual (blue and light blue) currents to the temporal variability of the alongshelf [a] and cross-shelf components [b] of the velocity at moorings MAM1, MAM3 and MAM4 at the top and bottom of the water column. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of stratification and turbulence on the PA (central) and AP (western) shelves (Fig. 16). The panels of Fig. 16 [a, d, g] show the time series of the Richardson number on a logarithmic scale (continuous line) and the critical value (dotted line) of $Ri = 0.25$ (-1.38 in logarithmic scale), and reveal that stratification dominates during most time across all moorings. The vertical shear of the horizontal velocity (turbulence) only overcomes stratification (stability) during 25 %, 12 %, and 30 % of the time at MAM1, MAM3, and MAM4, respectively.

The panels of Fig. 16 [b, e, h] show the scatter of the time series of stratification (N^2) and vertical shear of the horizontal velocity (S^2) parameters, with a black dotted line indicating when $\log(N^2) = \log(S^2)$. There is a significant increase in N^2 and S^2 values below -10 between the MAM1 (PA (central) shelf) and MAM4 (AP (western) shelf) moorings. This increase in stratification and turbulence causes the scatter to shift to the left and downward, as shown in Fig. 16[h]. The spectrum of the temporal series of the Richardson number show peaks of energy in the tidal period band (0.25, 0.5 and 1 days) at MAM1 (Fig. 16 [c]) and MAM3 (Fig. 16 [f]), and an increase of energy level in periods higher than 3 days at MAM4 (Fig. 16 [i]).

Fig. 17 shows TS diagrams based on CTD profiles of the AMANDES [a,b] and REVIZEE projects [c,d,e]. Based on data from AMANDES, the maximum temperatures range from 28.3°C on the PA (central) shelf to 29.4°C on the AP (western) shelf at depths shallower than 10 m (Fig. 17 [a,b]). In contrast, minimum temperatures show greater variability across the ACS, ranging from 20°C to 24°C on the PA (central) and AP (western) shelves, respectively, at depths greater than 80 m (outer shelf). The maximum values of salinity on the AP (western) and PA (central) shelves range from 37.6 to 18.9, respectively. Freshwater (salinity 0) occurs on the PA (central) shelf at depths less than 20 m (near the Amazon river mouth).

Based on the CTD profiles performed by the REVIZEE project (Fig. 17 [c,d,e]), the AP (western) shelf (Fig. 17 [c]) and the PA (central) shelf

(Fig. 17 [d]) show larger temperature variations, ranging from 22.6°C to 28.7°C and from 24.8°C to 28.3°C , respectively. The MA (eastern) shelf (Fig. 17 [e]) presents warmer waters and less variation, ranging from 27.8°C to 29.8°C . The maximum and minimum temperatures occur at depths of less than 10 m and greater than 60 m, respectively.

The AP (western) and PA (central) shelves (Fig. 17 [c,d]) show analogous variations in salinity values, ranging from 9 to 36, while the MA (eastern) shelf (Fig. 17[e]) shows a range from 16 to 35. The maximum and minimum salinity is similar to that observed for temperature, with low salinity near the coast (at depths shallower than 10 m) and high salinity on the outer shelf (depths greater than 60 m). The σ_θ isopycnals (black dotted line) in Fig. 17 indicate the presence of coastal water influenced by the discharge (0–22), a mixing water (22–24) and the oceanic water (>24) on the ACS (Prestes et al., 2018, Silva et al., 2010).

4. Discussion

Contributions have been made in describing the amplitude and phase of the semi-diurnal tide in the sea level on the ACS (Beardsley et al., 1995; Geyer et al., 1996; Gabioux et al., 2005). In this study, we present an analysis of 6 coastal sea level time series along the Amazon coast covering the MA (eastern), PA (central), and AP (western) shelves (section 3.1). The importance of the tides for the variability of the Amazon coastal sea level reaches at least 95 % at all stations, while the residual sea level explains 2 %, 5 %, 2 %, 2 %, 1 % and 1 % at Curuá (AP (western) shelf), Santana (AP (western) shelf), Belém (PA (central) shelf), Salinópolis (PA (central) shelf), Turiaçu (MA (eastern) shelf) and Ribamar (MA (eastern) shelf), respectively. The energy level in the semi-diurnal tidal frequency (Fig. 4) presents a similar energy level to the low-frequency band and reinforces the importance of tides for coastal sea level variability at all stations.

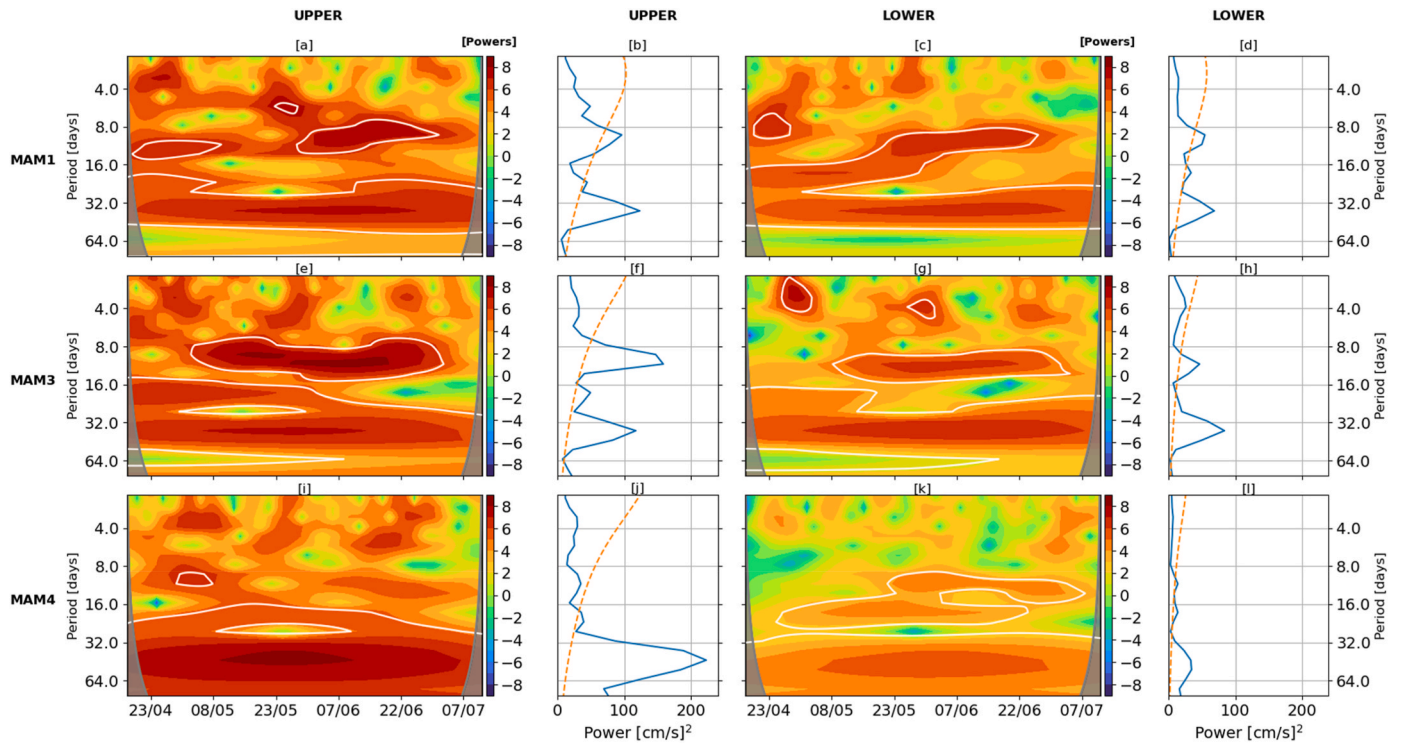


Fig. 13. Wavelet analysis of the residual alongshelf component of the velocity in the upper [a,b,e,f,i,j] and lower [c,d,g,h,k,l] water column at MAM1 [a-d], MAM3 [e-h] and MAM4 [i-l] (see Fig. 1 and Table 2). The [a,c,e,g,i,k] panels indicate the power spectrum (Morlet), where the colorbar represents the normalized variance and the white contour indicates the 95 % confidence level. The hatched area represents the cone of influence. The [b,d,f,h,j,l] panels indicate the global wavelet spectrum $[\text{cm/s}]^2$ (blue line) and the 95 % confidence level (dashed line). The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

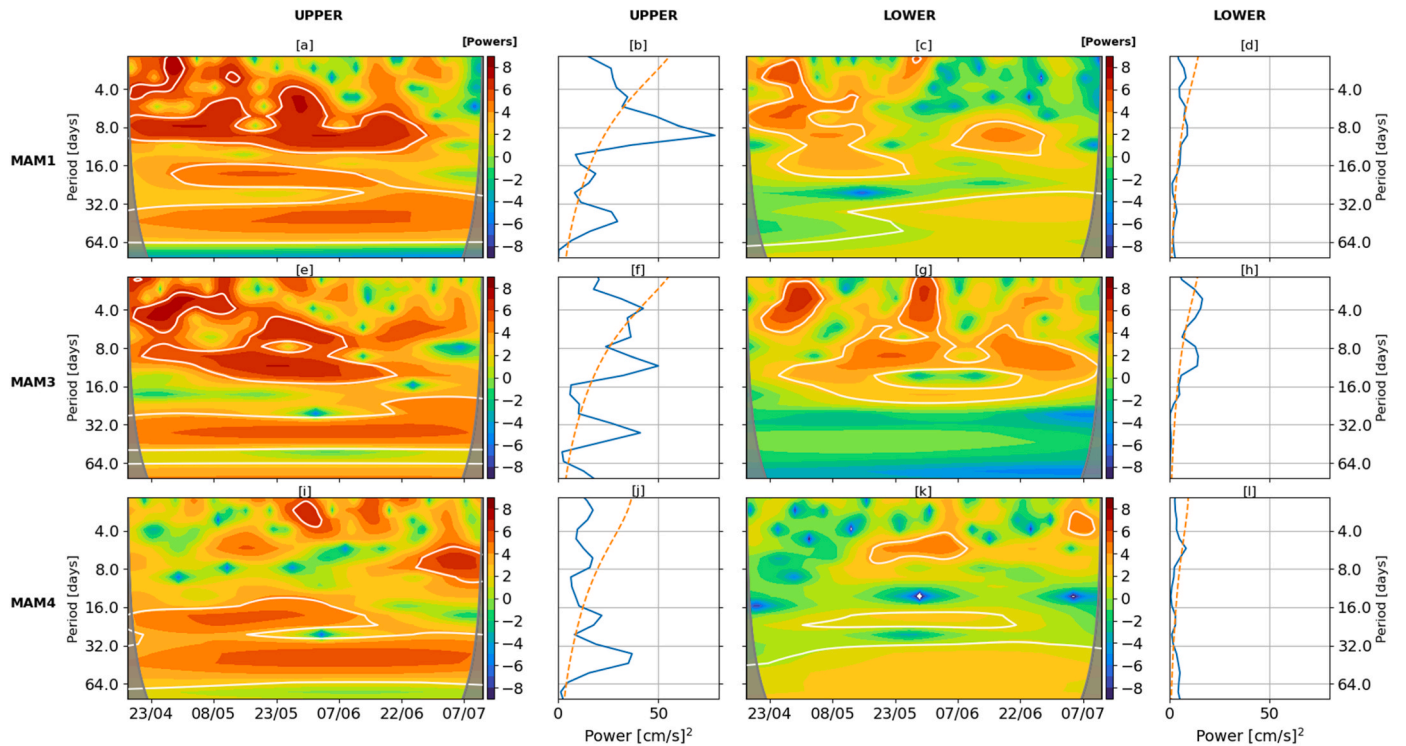


Fig. 14. Wavelet analysis of the residual cross-shelf velocity in the upper [a,b,e,f,i,j] and lower [c,d,g,h,k,l] water column at MAM1 [a-d], MAM3 [e-h] and MAM4 [i-l] (see Fig. 1 and Table 2). The [a,c,e,g,i,k] panels indicate the power spectrum (Morlet), where the colorbar represents the normalized variance and the white contour indicates the 95 % confidence level. The hatched area represents the cone of influence. The [b,d,f,h,j,l] panels indicate the global wavelet spectrum $[\text{cm/s}]^2$ (blue line) and the 95 % confidence level (dashed line). The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

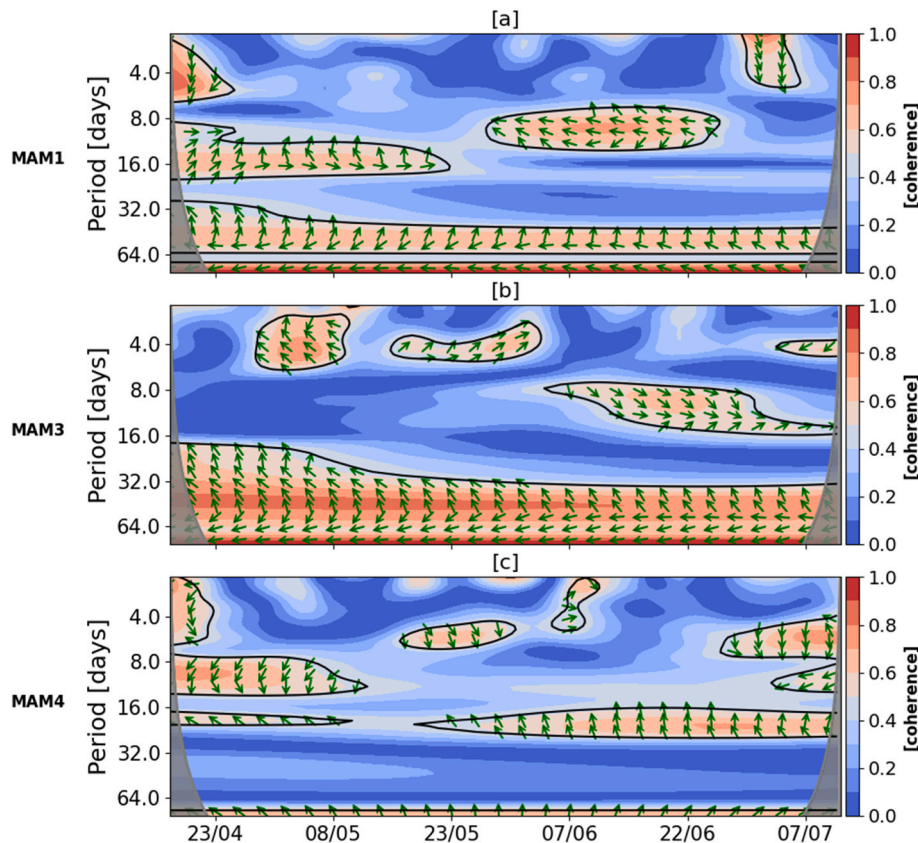


Fig. 15. Cross-Wavelet analysis between the surface alongshelf residual component of the velocity from moorings MAM1 [a], MAM3 [b] and MAM4 [c], and the local alongshelf component of the local wind from ERA5 Reanalysis during April 17th, 2008 to July 12th, 2008. The hatched area represents the cone of influence. The black contour indicates the 95 % confidence level. The green arrows indicate the phase signals. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The spatial variation of tidal range conditions shows a pattern along the Amazon coast, with meso and macro tidal conditions prevailing westward and eastward, respectively. It is important to emphasize that the location of Belém and Santana stations in the Pará and Amazon rivers, respectively, implies a reduction of the tidal range due to friction, morphology and sedimentological characteristics of the seabed (Gallo and Vinzon, 2005; Gabioux et al., 2005).

The residual sea level spectrum shows the highest energy level at all stations for periods longer than 2 days (Fig. 4). However, residual energy peaks are observed at periods of 0.5 and 1 day, with energy levels 2 orders of magnitude lower than in the raw spectrum but comparable to the rest of the spectrum in terms of energy level. A cross-spectral analysis was performed between residual coastal sea level (Table 1) and local zonal wind (component with the highest variance) from the ERA5 reanalysis (section 2.5) to determine the coherence coefficient in the frequency domain (Fig. 18) along the amazon coast. The spectra show isolated peaks of coherence with statistical significance at 3, 5, and 10 day periods at all stations. These results suggest that a small fraction of the residual coastal sea level temporal variability is due to local wind. With the exception of the Salinópolis station, isolated peaks of 1-day coherence are observed at all stations, probably related to diurnal breezes. Other factors, such as local (small rivers) and regional (Amazon River) freshwater discharge (Durand et al., 2022), may also contribute to the temporal variability of the residual level, especially at lower frequencies.

The location of sea level measurements in complex coastal regions, such as bays, estuaries, and coastal inlets (Fig. 1), combined with the ERA5 spatial resolution of approximately 28 km (0.25°), imposes limitations on the accuracy of cross-analysis. The spatial resolution of ERA5 may not be sufficient to accurately capture wind variability at local

scales, likely leading to a reduction in the correlation coefficient across the entire frequency domain associated with residual coastal sea level dynamics. In this context, it is possible to suggest that the correlation between residual sea level and local wind may be stronger and extend over longer periods.

The velocity time series from all moorings (Figs. 8–10) show a northwestward flow along the ACS most of the time and a pronounced tidal modulation in the cross-shelf component. Rotary spectral analysis of velocity data from drifters and moorings (Figs. 7 and 11) reveals that tides have a significant importance in the temporal variability of surface currents along the ACS. The rotary spectrum of the residual velocity at the moorings reveals lower energy levels for cyclonic and anticyclonic motions at periods of 0.5 and 1 day (Supplementary Material), indicating that semi-diurnal tidal currents exhibit both motions. In addition, for periods longer than 2 days, the energy level of the residual velocity is similar to the raw series, indicating a broad subtidal band modulated by non-tidal forces.

At all moorings, tides and residual currents play a crucial role in the temporal variability of the cross-shelf and alongshelf components of the velocity, respectively (Fig. 12). The percentual importance of tidal currents to ACS hydrodynamics increases towards MAM1 (PA (central) shelf) in both components (alongshelf and cross-shelf), consistent with the characterization of the spatio-temporal variability of tidal range at coastal sea level, which shows PA (central) and MA (eastern) shelves with greater tidal amplitude (Fig. 6). In addition, these results corroborate with the study realized by Assene et al. (2024), which identifies the shelf break adjacent to MAM1 (Fig. 1) as a region of stronger baroclinic energy dissipation associated with internal tides. The residual currents become more important in both components (alongshelf and cross-shelf) at MAM3 (PA (central) shelf) and MAM4 (AP (western) shelf), and these

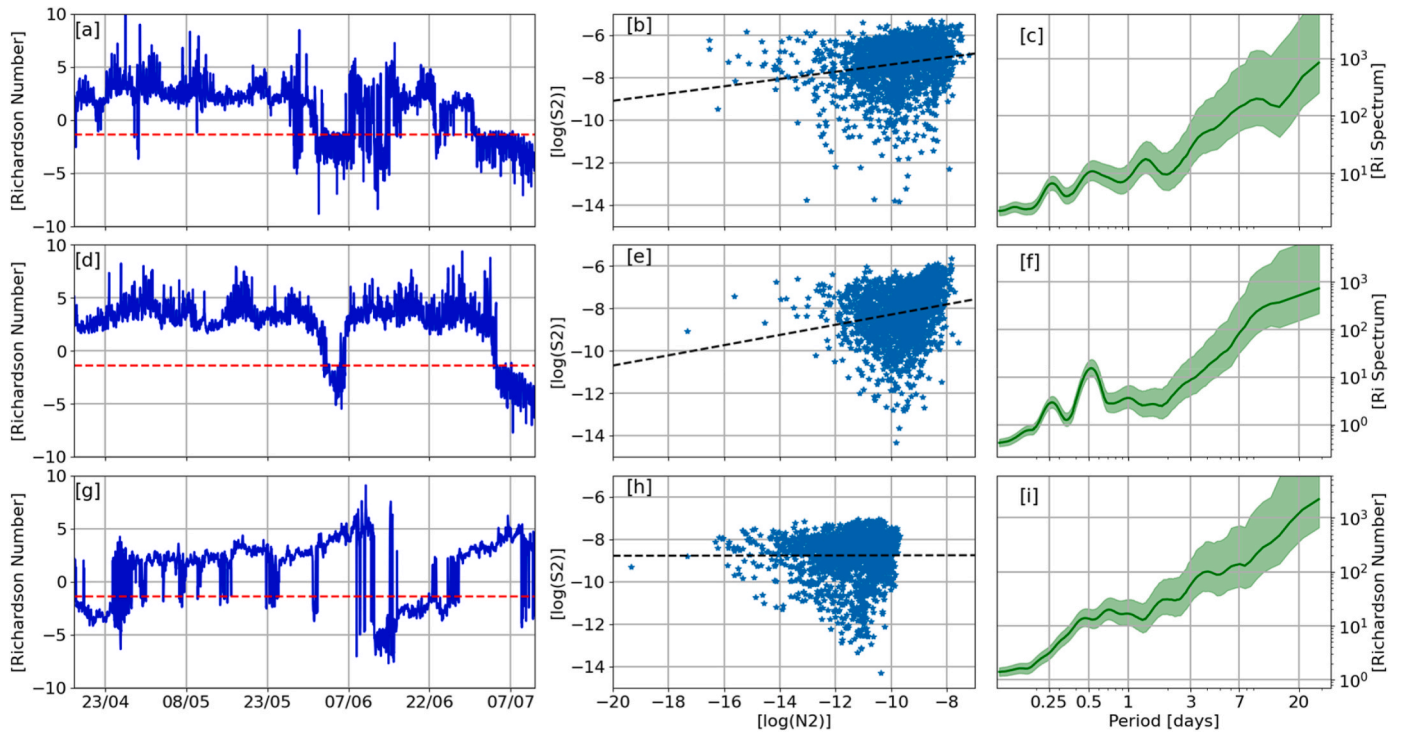


Fig. 16. Comparison between stratification and turbulence at MAM1 [a-c], MAM3 [d-f], and MAM4 [g-i] based on the Richardson Number. Panels [a, d, g] display the temporal series of the Richardson number the dotted red line indicates $Ri = 0.25$ in logarithmic scale (-1.38). Panels [b, e, h] present the scatter of stratification and turbulence parameters. The dotted black line indicates $\log(N^2) = \log(S^2)$. Panels [c, f, i] show the spectrum of the temporal series of the Richardson number. The green shading represents the 99 % confidence interval. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 2, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

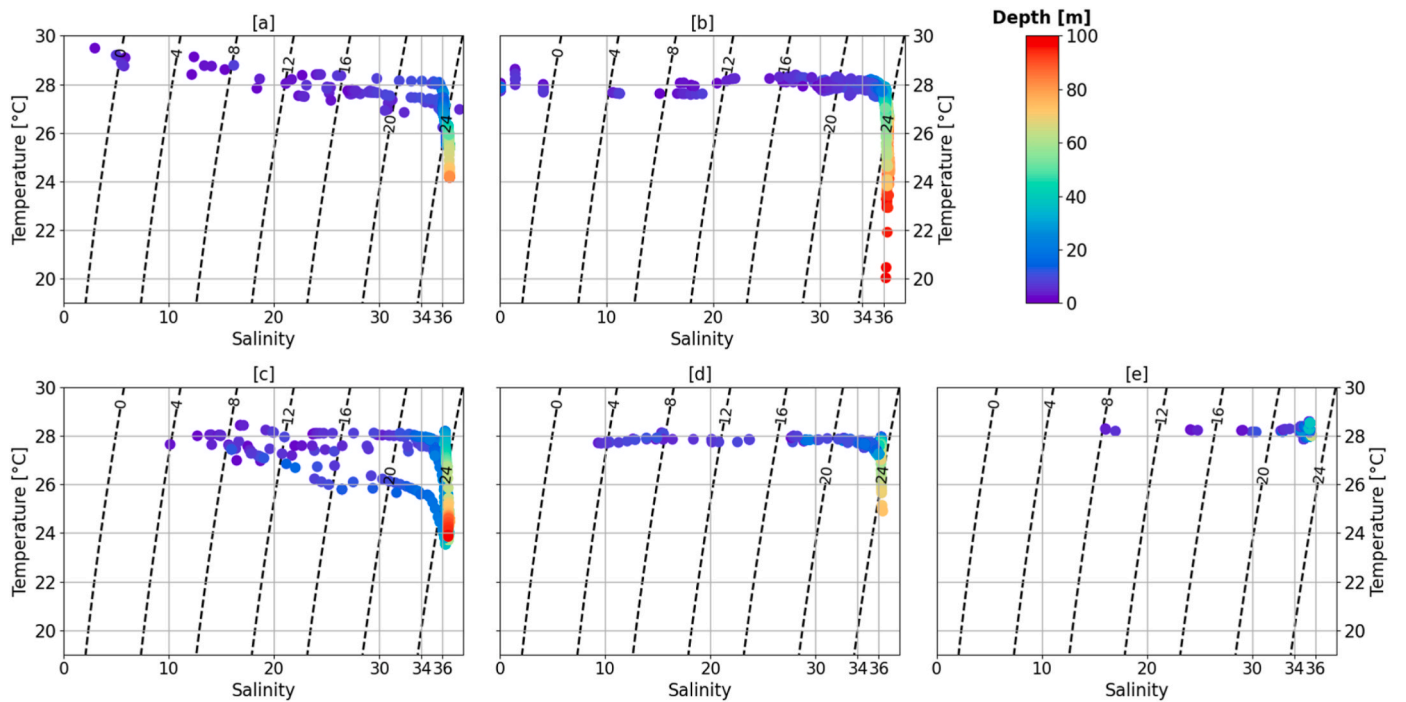


Fig. 17. Temperature-salinity (TS) diagrams based on 23 CTD profiles collected by the AMANDES project between April 11 and 13, 2008 [a,b], and 104 CTD profiles conducted by the REVIZEE project campaign between March 15th, 1995 and May 13th, 1995 [c,d,e]. Panels [a, b] represent profiles collected on the AP (western) and PA (central) shelves, while panels [c,d,e] represent profiles collected on the AP (western), PA (central) and MA (eastern) shelves, respectively. The black dotted line indicates the σ_θ isopycnals. The geographical locations of the stations and their periods are shown in Fig. 1, Table 2 and section 2.3.

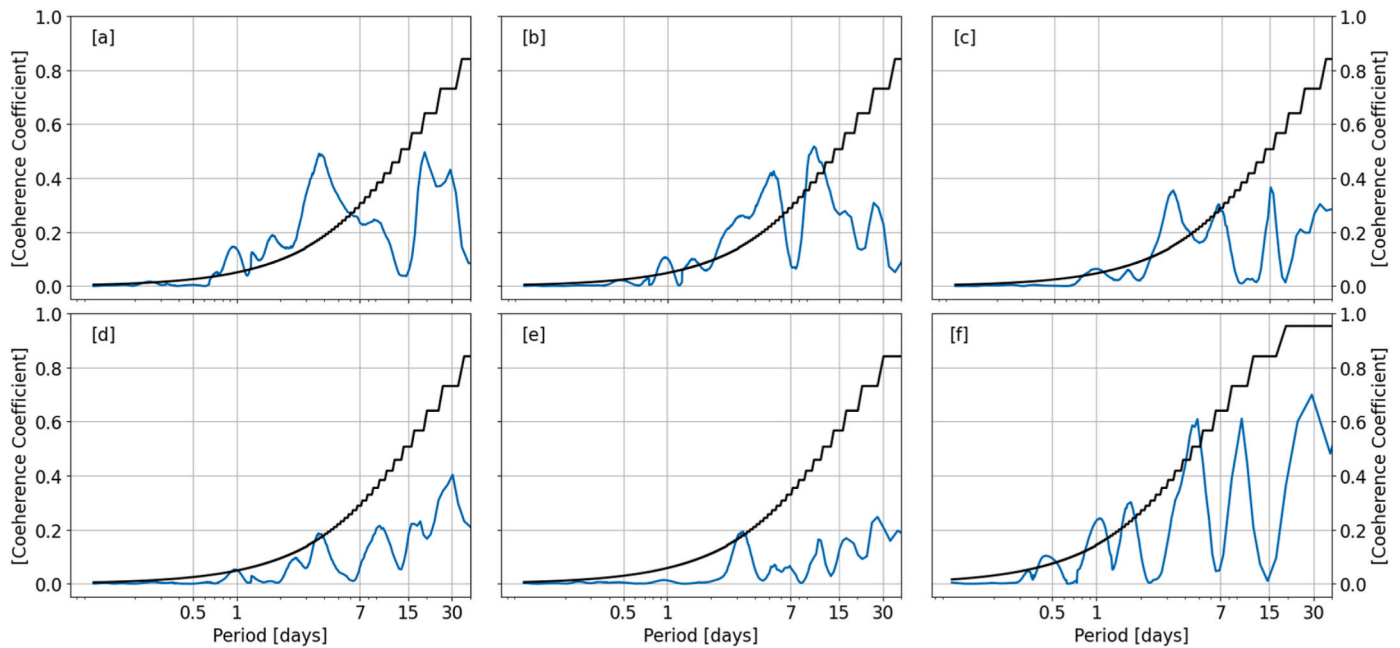


Fig. 18. Cross-spectrum between the residual coastal sea-level records at Curuá (AP (western) shelf), Santana (AP (western) shelf), Belém (PA (central) shelf), Salinópolis (PA (central) shelf), Turiaçu (MA (eastern) shelf) and Ribamar (MA (eastern) shelf) and the zonal component of local wind velocity (component with the highest variance) from ERA5 reanalysis for the same period. The black line represents the 99 % confidence interval. The geographical locations of the stations and their periods are shown in Fig. 1 and Table 1, respectively.

results can be related to the modulation of the NBC mesoscale activity in the velocity field on the outer shelf.

The global spectrum from the wavelet analysis of the residual alongshelf velocity (Fig. 13) shows an increase in energy levels towards the MAM4 mooring (AP (western) shelf) for periods longer than 20 days. These results can be explained by a combined influence of the narrowing of the ACS and the proximity of the mooring location to the shelf break, which may enhance the impact of the mean flow and mesoscale activity

of the NBC on the along-shelf currents over the outer shelf (Johns et al., 2003). The periods of high-energy events at MAM4 are consistent with the typical periods associated with mesoscale activity of the NBC (Geyer et al., 1996). These results are also consistent with the study by Aguiar et al. (2022), who used process-oriented numerical modeling identified, beginning in May, the NBC has a shallower velocity core (~ 20 m) and part of the current flows over the outer shelf at 5°N due to the narrowing of the continental shelf.

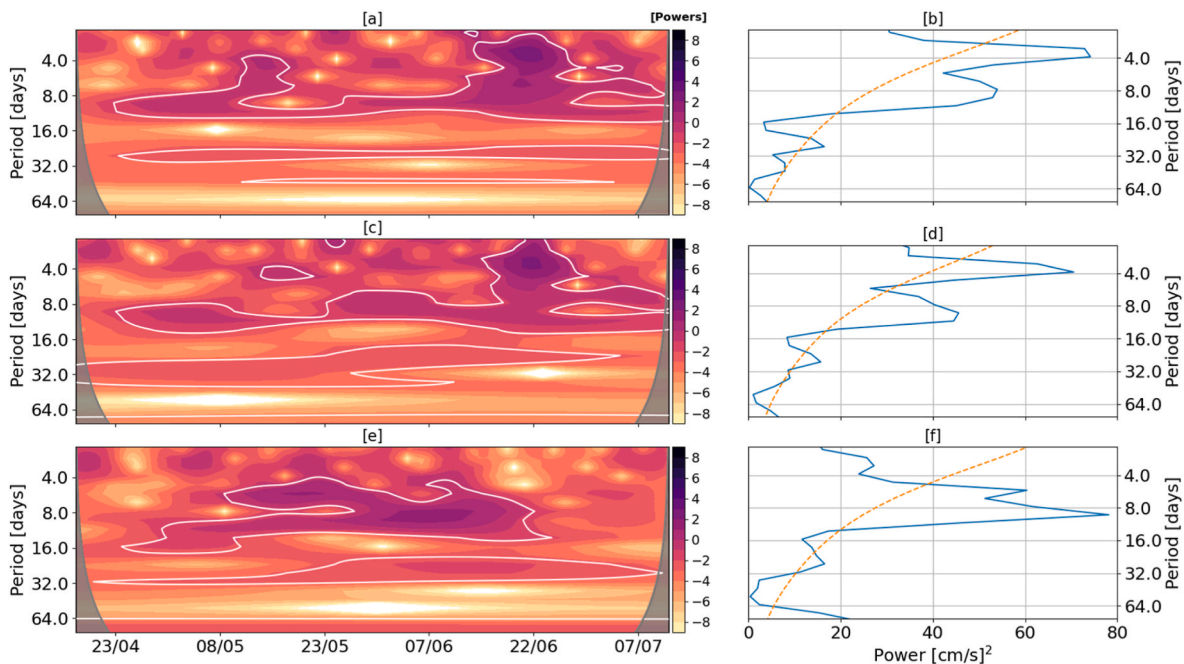


Fig. 19. Wavelet analysis of the local zonal wind at MAM1 [a,b], MAM3 [c,d] and MAM4 [e,f]. The [a,c,e] panels indicate the power spectrum (Morlet), where the colorbar represents the normalized variance and the white contour indicates the 95 % confidence level. The hatched area represents the cone of influence. The [b,d,f] panels indicate the global wavelet spectrum [cm/s^2] (blue line) and the 95 % confidence level (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The energy level in the global spectrum of the residual cross-shelf component of the velocity (Fig. 14) is significantly lower than of alongshelf component at all moorings, and the highest energy level occurs at the surface of the MAM1 mooring (PA (central) shelf) in the period bands from 8 to 16 days and longer than 20 days. These two period bands at the surface suggest modulations associated with the wind, the river discharge, and the NBC fluctuations (Nittrouer and DeMaster, 1986).

It is important to note that the mooring measurements have a temporal coverage of about three months (Table 2), which limits the analysis of low-frequency current variability in the frequency domain. However, the simultaneous measurements in different sectors of the ACS, combined with the wavelet analysis, provide concise information on the spatial and temporal variability with statistical confidence for high energy events in the 4–30 day frequency range.

Wavelet analysis was performed on the local zonal wind from ERA5 closest to the moorings positions (Fig. 19) to quantify the energy level in the frequency domain and to verify the physical relation with the coherence of the cross-wavelet analysis (Fig. 15). The power spectrums (Morlet) (Fig. 19 [a,c,e]) and the corresponding global spectrums (Fig. 19 [b,d,f]) show that the local wind has the highest energy levels with statistical significance in periods between 3 and 16 days. These results confirm that the coherence and phase between the residual along-shelf currents and the local zonal winds (Fig. 15) within the period bands ranging from 4 to 20 days with a lag of less than one day are indicative of a wind-driven circulation. Thus, due to the absence of high energy levels with statistical confidence in the global spectrum of local wind, it can be inferred that the high-energy events with periods longer than 30 days in power spectrums (Morlet) of the residual currents at MAM1, MAM3 and MAM4 (Figs. 13 and 14) can be interpreted as modulations of the NBC mesoscale activity (Bueno et al., 2022).

The analysis of the temporal series of the Richardson number at MAM1, MAM3 and MAM4 moorings (Fig. 16 [a,d,g]) reveal that PA (central) and AP (western) shelves are most part of the time (>70 %) stable. Considering that measurements were performed during the period (Table 2) of the highest Amazon River discharge, these results show the importance of the fluvial discharge in modulating the hydrodynamics of the ACS. The increase in the stratification (N^2) and vertical shear of the horizontal velocity (S^2) parameters toward MAM4 (Fig. 16 [b,e,h]) can be explained by the combined influence of the northward spreading Amazon plume driving by winds (Lentz, 1995b) and the

modulations in the velocity field associated with the NBC flow, respectively. The influence of the tides to temporal variability of the Richardson number is more prominent at MAM1 and MAM3 (PA shelf) (Fig. 16 [c,f,i]) with peaks at 0.5 days, that corroborate with the analysis of the percentage importance of tidal currents to ACS hydrodynamics (Fig. 12).

The TS diagrams, based on CTD profiles from the AMANDES and Revizee (Fig. 17) projects, illustrate the occurrence of coastal water influenced by the discharge on the inner shelf (depths shallower than 10 m), mixing water on the middle shelf (depths between 10 and 60 m), and oceanic water near the shelf-break (depths greater than 60 m). The CTD transect conducted as palinkin parkrt of the AMANDES project on the PA (central) shelf, spanning from the mouth of the Amazon River to the shelf-break (Fig. 20), illustrates the occurrence of a relatively cold water (20°C – 24°C) with a σ_θ density higher than 24 kg/m^3 on the outer shelf (depths between 60 and 80 m), with typical characteristics of oceanic water. These results are corroborated by the study carried out by Silva et al. (2010), which identified the intrusion of SACW on the ACS associated with temporal variability of the intensity of the NBC.

5. Conclusions

This study characterizes the spatio-temporal variability of hydrodynamics in the ACS based on the analysis of coastal sea level measurements, velocity data obtained from satellite-tracked drifters and moorings from AMANDES (April 2008) cruise, and CTD profiles from AMANDES and REVIZEE (1995) cruises collected across all sectors of the shelf. The results of the coastal sea level show that tides account for 95 % (Santana, AP shelf) to 99 % (Turiagu and Ribamar, MA shelf) of the sea level variability. On the coast of the MA (eastern) and PA (central) shelves, the tidal range corresponds to a macrotidal regime for up to 75 % and 41 % of the time, respectively. A small fraction of the temporal variability of the residual sea level along the Amazon coast is modulated by local winds, suggesting the influence of other factors such as fresh-water discharge on the inner shelf.

The semidiurnal tides play a crucial role in the temporal variability of the currents along the ACS, with a greater importance near the bottom and in the cross-shelf component of the velocity. The importance of tides in the temporal variability of the cross-shelf velocity component reaches a maximum of 90 % at the MAM1 mooring (PA shelf), probably related to the dissipation of internal tidal energy at the adjacent shelf break. The

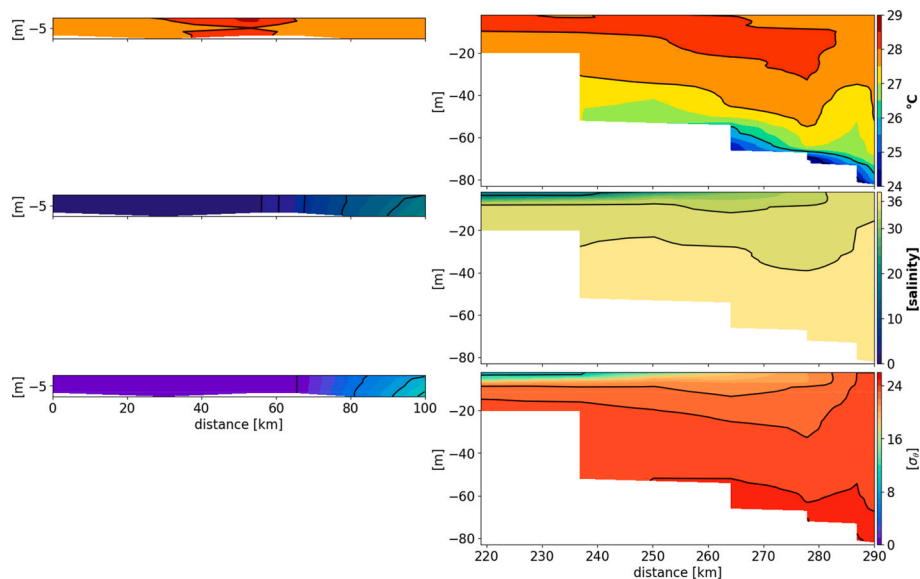


Fig. 20. Temperature (top panel), salinity (middle panels) and density (σ_θ) transect from the AMANDES project, conducted between April 11 and 13, 2008, from the mouth of the Amazon River to the continental shelf break of the PA shelf. The geographical locations of the CTD profiles are shown in Fig. 1.

residual currents (without tides) are more pronounced in the alongshelf component and show a greater importance for the temporal variability of the velocity on the outer shelf near bottom at MAM3 (PA (central) shelf) and MAM4 (AP (western) shelf), attributed to the influence of the NBC mesoscale activity. Wavelet analysis of the residual alongshelf and cross-shelf components of the velocity reveals two distinct period bands between 4 and 20 days and longer than 20 days at all moorings. The first period band is associated with wind modulations, while the second band indicates an influence of NBC fluctuations.

The time series of the Richardson number at moorings (MAM1, MAM3 and MAM4) during the period of the highest Amazon River discharge in 2008 show that the PA (central) and AP (western) shelves are stable for most of the time (>70 %). The stratification (N^2) and vertical shear of the horizontal velocity (S^2) parameters increase toward MAM4 (AP shelf) associated with the spreading of the Amazon River plume and the greater influence of the NBC on the currents of the outer shelf. Based on the TS diagram derived from data collected during the AMANDES and Revizee projects, three distinct water masses were identified on the ACS: i) a coastal water influenced by river discharge, ii) a mixed water, and iii) an oceanic water. The CTD cross-section obtained from the AMANDES project illustrates the presence of oceanic water in the outer portion of the PA (central) shelf, between depths of 60–80 m. These results indicate that a fraction of the hydrodynamic variability on the ACS is modulated by physical processes in the adjacent oceanic region.

Finally, the results of this study provide valuable insights for ongoing research on sedimentological and biogeochemical processes along the Amazon coast. Quantifying the relative importance of tidal and residual components in sea level and current variability is relevant for understanding coastal processes involving sediment transport, as well as for modulating the dispersion of biological material and/or contaminants. The temporal variability of the competition between stratification and turbulence, quantified by the Richardson number, can indicate fluctuations in the vertical profile of nutrient and gas (O_2 and CO_2) concentrations throughout the water column, potentially affecting primary production and nitrogen fixation cycles.

CRediT authorship contribution statement

Pedro Paulo de Freitas: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mauro Cirano:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Carlos Eduardo Peres Teixeira:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Sávio Jeliel Roque Melres:** Visualization, Validation, Methodology, Investigation, Formal analysis. **Antony Kadu Carvalho dos Santos de Sousa:** Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Vando José Costa Gomes:** Writing – review & editing, Validation, Methodology, Investigation. **Camilo Andrés Guerrero-Martin:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Ariane Koch-Larrouy:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.csr.2025.105491>.

Data availability

Data will be made available on request.

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