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Wave climate and atmospheric forcing along the Brazilian Equatorial Margin

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Abstract

The Brazilian Equatorial Margin (BEqM) receives both remotely generated Atlantic swell and locally generated trade-wind waves, but observations across the region remain sparse. We characterise its wave climate using the WAVERYS reanalysis, evaluate significant wave height, peak period and mean direction against the Fortaleza buoy, and assess spatial consistency against the European Space Agency Sea State Climate Change Initiative (CCI) altimeter record. K-means clustering of daily fields over 1993–2022 identifies six reproducible wave patterns (WPs). Potiguar and Barreirinhas basins alternate seasonally between N–NE wave regimes, including long-period swell, during austral summer and E–SE trade-wind waves during austral winter, whereas Foz do Amazonas remains predominantly N–NE throughout the year. Atlantic-wide wave and atmospheric composites associate WP4 with a transient negative-pressure anomaly and North Atlantic extratropical cyclones, whereas WP1 coincides with positive pressure anomalies over the North Atlantic subtropical high and stronger trade winds. The composites also indicate a South Atlantic contribution to WP5, and local trade-wind forcing for WP2 and WP6. Joint significant-wave-height–peak-period distributions and wave steepness support this distinction between swell- and

wind-sea-dominated patterns. WP2 and WP6 have the longest mean consecutive-day spells (4.6 days), while WP4 is more episodic (3.2 days). Day-to-day transitions show WP3 as the most frequent intermediate state between WP4 and WP2. Because the full 1980–2022 reanalysis contains a discontinuity at the onset of altimeter assimilation, the regime analysis is restricted to 1993–2022. The classification describes wave-regime seasonality, forcing, persistence and transition structure along the BEqM.

Keywords: Brazilian Equatorial Margin, ocean waves, wave climatology, K-means clustering, wave regimes, WAVERYS

1 Introduction

The Brazilian Equatorial Margin (BEqM), extending from Rio Grande do Norte to Amapá, has become one of Brazil’s most promising and least explored frontiers for offshore oil and gas activities. The region encompasses several sedimentary basins, including Foz do Amazonas, Pará, Maranhão, Barreirinhas, Ceará and Potiguar, in which geological studies indicate active petroleum systems and substantial prospects in deep and ultra-deep waters (Almeida-Filho et al. 2005; Travassos and Freitas 2021; Praeg et al. 2022). A regional description of the sea state is therefore needed to establish the climatological setting of offshore activity along the margin.

The BEqM is a distinctive environment for waves. The Intertropical Convergence Zone migrates seasonally over the Atlantic between roughly 9°N and 2°N (Waliser and Gautier 1993; Philander et al. 1996; Schneider et al. 2014), altering the local wind forcing of the sea state through the year. Superimposed on this, the margin receives swell generated in the North Atlantic storm track, giving a wave field with two forcing mechanisms of different origin and different seasonality. The coastal zone is further modified by the discharge of the Amazon (Gibbs 1967; Callède et al. 2010), whose sediment supply sustains extensive mud banks extending up to 1500 km towards the Orinoco mouth (Anthony et al. 2010); such banks are efficient dissipators of incident

59 wave energy, and their presence separates the coastal wave climate from the offshore
60 one along much of the margin.

61 The partition of the sea state into locally generated wind sea and remotely gener-
62 ated swell is the organising framework of modern wave climatology. Swell dominates
63 the global ocean in both occurrence and energy (Semedo et al. 2011; Alves 2006),
64 and the seasonal cycle of significant wave height at any location reflects the balance
65 between local wind forcing and swell arriving from distant generation areas (Young
66 1999a; Colosi et al. 2021). Separating the two is not straightforward from integrated
67 parameters alone, and spectral partitioning remains the reference approach where
68 directional spectra are available (Portilla et al. 2009). In tropical margins facing an
69 active extratropical storm track, the same site may be swell-dominated in one season
70 and wind-sea-dominated in another.

71 For the Brazilian coast as a whole, Pianca et al. (2010) documented strong sea-
72 sonality, including alternation between N–NE waves during austral summer and E–SE
73 waves in other seasons at northern and northeastern points, with typical H_s between
74 1 and 3 m and peak periods of 6–10 s. Cotrim et al. (2022) extended this with a high-
75 resolution hindcast climatology for the entire coast, and a substantial body of work
76 has characterised the southern Brazilian shelf in detail, including its wave climate
77 variability (Cecilio and Dillenburg 2019) and its extreme events (Oliveira et al. 2019;
78 Gramscianinov et al. 2023). The equatorial margin has received far less attention. de
79 Freitas Assad et al. (2020) provided a numerical ocean climatology for the region, and
80 more recent work has begun to address its wave field: dos Reis et al. (2024) reported
81 a bimodal wave regime with a pronounced semiannual cycle over the Maranhão shelf,
82 Carvalho et al. (2025) described the offshore wave climate of the Pará-Maranhão basin,
83 and D’Anna et al. (2025) produced high-resolution wave projections for the adjacent
84 French Guiana coast. Costa et al. (2025) evaluated ERA5 and WAVEYRS specifically

85 over the margin. What remains absent is a margin-wide description that treats the
86 sea state as a set of recurrent regimes rather than as a set of time-averaged fields.

87 Classifying the atmosphere or the sea state into a small number of recurrent states
88 is the established response to that problem. The approach descends from synoptic cli-
89 matology (Harman and Winkler 1991) and from the identification of weather regimes
90 as reproducible partitions of the circulation (Michelangeli et al. 1995; Cassou et al.
91 2004), and has been transferred to wave climate in several forms: as a basis for statis-
92 tical downscaling (Camus et al. 2014), for multivariate emulation of extremes (Rueda
93 et al. 2016; Solari and Alonso 2017), and for associating extreme wave events, and the
94 coastal damage they cause, with the synoptic patterns that generate them (da Silva
95 et al. 2025; Leal et al. 2026). A regime description complements time-averaged fields
96 by showing how long recurrent sea states persist and which states tend to follow one
97 another.

98 In this study we characterise the wave climate of the BEqM and the regimes that
99 compose it, applying K-means temporal clustering to the WAVERYS reanalysis and
100 identifying the dominant wave patterns together with their persistence and transition
101 structure. We quantify the spatial and seasonal structure of significant wave height,
102 mean wave direction and peak period, evaluate the reanalysis against the Fortaleza
103 buoy, and assess its spatial consistency against the altimeter record. The result is an
104 integrated regional description of recurrent sea states and their associated atmospheric
105 forcing.

106 2 Study area

107 The study region covers the Brazilian Equatorial Margin in northern and northeastern
108 South America, approximately bounded by 60°W–30°W and 10°S–10°N (Figure 1).
109 We also use observations from the Fortaleza wave buoy (3.21°S, 38.43°W) for local
110 validation of the wave reanalyses.

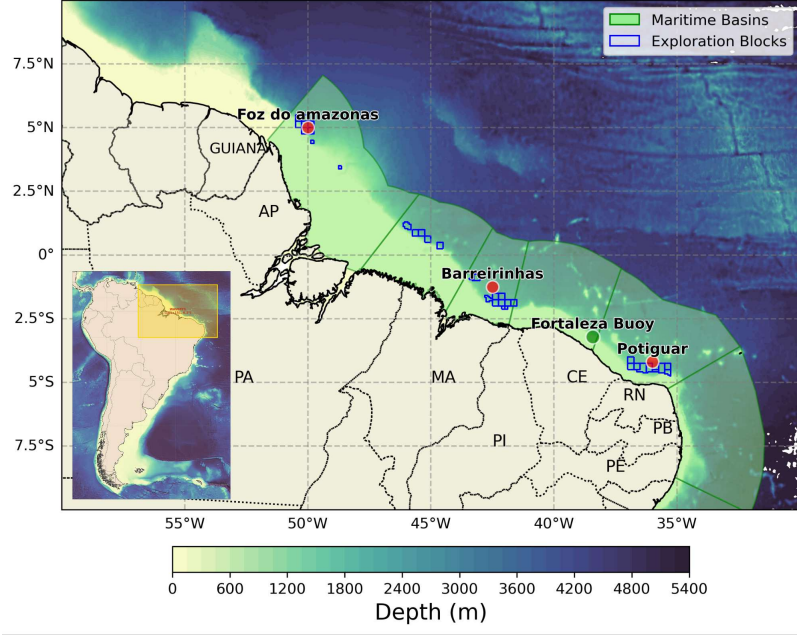


Fig. 1 Study area and its location relative to South America. Green contours indicate sedimentary basins along the BEqM. Blue squares correspond to planned oil and gas exploratory blocks. Red circles mark the three selected analysis points, associated with the Foz do Amazonas, Barreirinhas, and Potiguar basins. The green circle indicates the Fortaleza oceanographic buoy, whose data were used to validate the reanalysis products.

For point-based analyses, we selected three strategic locations associated with major sedimentary basins: (i) the Potiguar Basin (near 4.2°S, 36°W), (ii) the Barreirinhas Basin (1.25°S, 42.5°W), and (iii) the Foz do Amazonas Basin (5°N, 50°W). These points represent the eastern, central and western sectors of the margin and are located near planned exploratory blocks. Point-based analyses identify climatological similarities and contrasts among the three sectors.

117 3 Methodology

118 3.1 Datasets

119 Given the limited observational coverage in the BEqM, we rely primarily on wave
120 reanalysis products. We compare two reanalyses against available observations from
121 the Fortaleza buoy using significant wave height (H_s) and peak period (T_p), and then
122 select the most appropriate product for the climatology.

123 For local validation, we use the Fortaleza buoy from Brazil’s National Buoy Pro-
124 gram (PNBOIA; [Marinha do Brasil 2023](#); [Pereira et al. 2017](#)), shown as the green
125 marker in Figure 1. Due to the lack of observations elsewhere along the margin, val-
126 idation is limited to this single site. [Costa et al. \(2025\)](#) also compared ERA5 and
127 WAVERYYS with satellite-altimeter H_s across the BEqM (2021–2023), reporting higher
128 agreement for WAVERYYS ($r = 0.967$, RMSE = 0.121 m) than for ERA5 ($r = 0.906$,
129 RMSE = 0.210 m).

130 ERA5 is the global atmospheric and wave reanalysis produced by the European
131 Centre for Medium-Range Weather Forecasts ([Hersbach et al. 2023](#)). We use three-
132 hourly wave parameters on the distributed 0.5° grid for the buoy comparison and
133 0.25° 10-m winds and mean sea-level pressure for the atmospheric composites. Its wave
134 component is based on WAM and assimilates altimeter H_s .

135 WAVERYYS is the Copernicus Marine Service global wave reanalysis based on
136 MFWAM ([E.U. Copernicus Marine Service Information \(CMEMS\) 2023](#); [Law-Chune
137 et al. 2021](#)). It is forced by ERA5 winds, includes sea level and surface currents from
138 GLORYS12, and provides three-hourly fields on an irregular $1/5^\circ$ grid. WAVERYYS
139 assimilates altimeter H_s and, in the later record, satellite directional spectra. We use
140 H_s , T_p and mean wave direction from 1 January 1980 to 31 December 2022. The
141 observing system changes at the onset of altimeter assimilation, so 1993 is adopted as
142 the analysis boundary and the wave-regime analysis is restricted to 1993–2022; the full
143 annual series and the screening of that boundary are given in Figure S2 and Text S2.

3.2 Validation

No in situ buoy observations are assimilated by either reanalysis. We therefore use the Fortaleza buoy for local validation and the Sea State Climate Change Initiative (CCI) altimeter observations (Dodet et al. 2020; *E.U. Copernicus Marine Service Information (CMEMS) 2024a*), the great majority of which are assimilated, only to assess spatial consistency. Table S2 lists the satellite missions assimilated by WAVERYS and the period over which each is used (*E.U. Copernicus Marine Service Information (CMEMS) 2024b*).

To quantify differences between the reanalysis products and the observations, we compute bias (BIAS), root-mean-square error (RMSE), scatter index (SI), and the Pearson correlation coefficient (r), following standard metocean validation practice (Rodgers and Nicewander 1988; Wilks, D. S. 2014). Let M_i denote model values and O_i observed values for $i = 1, \dots, n$:

$$\text{BIAS} = \frac{1}{n} \sum_{i=1}^n (M_i - O_i) \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (M_i - O_i)^2} \quad (2)$$

$$\text{SI} = \frac{1}{\bar{O}} \sqrt{\frac{1}{n} \sum_{i=1}^n [(M_i - O_i) - \text{BIAS}]^2} \quad (3)$$

$$r = \frac{\sum_{i=1}^n (M_i - \bar{M}) (O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (M_i - \bar{M})^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (4)$$

where $\bar{M}$ and $\bar{O}$ are the sample means of the model and observed series, respectively. The SI is the bias-removed root-mean-square difference normalised by the observed mean. BIAS close to zero indicates low systematic error; lower RMSE and SI indicate better agreement; and r close to 1 indicates strong temporal co-variability.

161 3.3 Clustering analysis

162 This section sets out how the daily wave field is classified and what the classification
163 is then used for. K-means assigns every day of the record to a single wave pattern, so
164 each pattern is also a set of dated occurrences, and it is on this that the rest of the
165 methodology rests. Knowing the days on which a pattern occurs allows the wave and
166 atmospheric fields of the preceding week to be composited, which is how the generating
167 system is identified, while group velocity and wave steepness test whether the implied
168 travel time and the maturity of the sea state are consistent with that origin. The
169 same daily labels are used to stratify the directional wave climate at the three analysis
170 points and to measure how long each regime persists before it changes. The section is
171 organised in that order.

172 We use K-means clustering to identify dominant wave patterns in time. K-means
173 partitions the data into K clusters by minimizing within-cluster variance; it was intro-
174 duced by [MacQueen et al. \(1967\)](#) and refined by [Hartigan and Wong \(1979\)](#). The
175 number of patterns was selected by reproducibility rather than by within-cluster com-
176 pactness, following the classifiability criterion established for atmospheric regimes by
177 [Michelangeli et al. \(1995\)](#). For each K between 4 and 8 the classification was refitted
178 with 20 random seeds and 100 calendar-year block bootstrap replicates of the study
179 period, and agreement with the canonical solution was measured by the adjusted
180 Rand index. $K = 6$ maximises every reproducibility measure considered, while $K = 7$
181 reduces the minimum separation between centroids by 13.3% and shrinks the smallest
182 regime to 6.7% of days. We retain six wave patterns and make no claim that this is
183 a global optimum of any single index; the criteria, their disagreement, and the sup-
184 porting evidence are set out in Text S1, Table S1 and Figure S1. K-means has been
185 widely applied in atmospheric and wave-climate classification studies (e.g., [Jiménez](#)
186 [et al. 2009](#); [Bettolli et al. 2010](#); [Nguyen-Le et al. 2017](#); [Nguyen-Le and Yamada 2019](#);
187 [Yi et al. 2021](#); [Neal et al. 2020](#); [Pringle et al. 2014](#); [Camus et al. 2014](#); [Rueda et al.](#)

188 2016; Solari and Alonso 2017; De Leo et al. 2020; Sondermann et al. 2023; De Souza
189 et al. 2025).

190 The procedure follows the weather-pattern classifications built for the Brazilian
191 coast by da Silva et al. (2025) and Leal et al. (2026), and departs from them in two
192 further respects. Those studies cluster atmospheric fields on days already selected as
193 extreme, using the wave record only to select them; here the wave field is itself the
194 object of the classification and every day of the record enters it. And the features are
195 standardized, which those studies found unnecessary for their pressure and wind fields.

196 Each day is described by eight features: the spatial mean and standard deviation
197 of H_s , of the two components of the wave direction, and of T_p , taken from the daily
198 mean fields over a fixed valid-ocean mask and standardised. Direction is decomposed
199 into $u = -\sin \theta$ and $v = -\cos \theta$ before averaging, so that its periodicity is preserved.
200 Because a wave field, unlike a pressure field, contains land and occasionally invalid
201 cells, the mask is held fixed for the whole record: recomputing it each day would let the
202 same feature refer to different areas and would confound a change in the sea state with
203 a change in the area averaged. No day of 1993–2022 was rejected for missing data, so
204 the classification assigns a wave pattern (WP) label to each of the 10,957 days. Text S3
205 gives the construction of the feature vector and the treatment of missing cells in full.

206 To identify the generating regions of each wave pattern, we complement the BEqM
207 clustering with Atlantic-wide wave and atmospheric diagnostics. In addition to the
208 BEqM-domain WAVERYS fields used in the clustering, we extracted daily Atlantic-
209 wide wave snapshots from WAVERYS (H_s , T_p and mean wave direction) on the same
210 80°W – 20°E , 60°S – 70°N domain used for ERA5. Both the wave and the atmospheric
211 fields are daily instantaneous snapshots at 00:00 UTC, so that a given lag corresponds
212 to the same instant in the two data sets and the interval between features identified
213 in them is exact. For each occurrence of a pattern, the wave and atmospheric fields
214 were sampled at lags $\tau \in \{-7, \dots, 0\}$ days and averaged,

$$\overline{X}_{k,\tau}(\mathbf{x}) = \frac{1}{N_k} \sum_{n=1}^{N_k} X(\mathbf{x}, t_{k,n} + \tau), \quad (5)$$

with $\tau = 0$ the day the pattern occurs over the BEqM. The fields entering the average are anomalies with respect to a smoothed day-of-year climatology, because composites of the absolute fields reproduce the season in which each pattern occurs rather than the circulation specific to it. The figures show lags of -7 , -5 , -3 , -1 and 0 days. The approach follows composite studies of remote wave forcing (e.g. [Ponce de León and Bettencourt 2021](#); [Colosi et al. 2021](#); [Cheshm Siyahi et al. 2023](#)).

To assess whether the inferred travel times are dynamically plausible, we also estimate deep-water group velocity from the pattern-mean peak period:

$$c_g = \frac{gT_p}{4\pi}, \quad (6)$$

and the associated propagation distance after an interval Δt as $D = c_g \Delta t$ ([Holthuijsen 2007](#); [Young 1999b](#)). These diagnostic calculations are used only to support the interpretation of the lag composites and are not part of the clustering itself.

To further distinguish mature remotely generated swell from locally forced wind-sea conditions, we compute wave steepness from H_s and T_p assuming deep-water dispersion ([Holthuijsen 2007](#)). The peak wavelength is given by

$$L_p = \frac{gT_p^2}{2\pi}, \quad (7)$$

and wave steepness is defined as

$$S = \frac{H_s}{L_p} = \frac{2\pi H_s}{gT_p^2}. \quad (8)$$

This metric provides a compact measure of sea-state maturity, with lower values associated with long, well-dispersed swell and higher values associated with shorter, actively forced waves ([Holthuijsen 2007](#); [Young 1999b](#)). At the three BEqM analysis

233 points, all occurrences assigned to each pattern were represented in joint H_s – T_p space
 234 and classified according to a four-category wave-maturity scheme: old swell ($S <$
 235 0.004), mature swell ($0.004 \leq S < 0.010$), young swell ($0.010 \leq S \leq 0.025$), and wind-
 236 sea ($S > 0.025$). These boundaries follow the wave-maturity classification in which
 237 progressively higher steepness values correspond to decreasing wave age, from long-
 238 traveled old swell to actively forced wind-sea (Thompson et al. 1984; Umesh et al.
 239 2017). Although the scheme was originally defined using mean wave period T_{m01} , peak
 240 period T_p (available from WAVERYS) is employed here as a proxy, consistent with its
 241 use in global wave climate studies (Semedo et al. 2011; Alves 2006).

242 To characterise the local directional wave climate associated with each wave pat-
 243 tern, the WP assignment obtained from the K-means classification was used to stratify
 244 the WAVERYS daily outputs at three coastal analysis points: Foz do Amazonas
 245 (5.0°N , 50.0°W), Barreirinhas (1.25°S , 42.5°W), and Potiguar (4.2°S , 36.0°W). For
 246 each WP–site combination, the daily records of significant wave height (H_s) and mean
 247 wave direction (VMDR, expressed as direction of origin) were extracted from the
 248 same WAVERYS dataset over 1993–2022. Directional roses were computed from these
 249 stratified subsets over 16 sectors, each panel normalised to its own WP–site subset.

250 Following Michelangeli et al. (1995) and Cassou et al. (2004), a *spell* is defined as a
 251 sequence of one or more consecutive days on which the same wave pattern is assigned;
 252 a spell terminates when the WP label changes on the following day. Spell duration
 253 therefore measures the uninterrupted persistence of a given wave regime before the
 254 system transitions to a different state, analogous to the weather-regime spell used
 255 in studies of circulation-regime recurrence and quasi-stationarity (Michelangeli et al.
 256 1995; Cassou et al. 2004). The conditional transition probability matrix $P(\text{WP}_{t+1} =$
 257 $j \mid \text{WP}_t = i)$ is estimated by counting all consecutive-day pairs $(t, t+1)$ in which both
 258 days carry a valid WP label, and normalising each row to 100%. Only pairs separated

259 by exactly one calendar day are counted, so gaps at year boundaries or unlabelled
260 days do not introduce spurious transitions.

261 4 Results

262 4.1 Validation of ERA5 and WAVERY5

263 The PNBOIA Fortaleza comparison comprises 3265 collocated records. WAVERY5
264 reproduces significant wave height with a bias of -1.4 cm, a root mean square error of
265 0.17 m and a correlation of 0.90 . Mean wave direction has a circular bias of -2.3° and
266 a circular mean absolute error of 8.2° , with 95.5% of records falling within one 22.5°
267 compass sector of the observation. Peak period is the weakest variable, but its error is
268 confined to the short-period end: the bias falls from $+2.55$ s below 6 s to -0.54 s above
269 14 s. This asymmetry is physically expected. Long-period swell is generated by large-
270 scale systems and reaches the margin after dispersion over thousands of kilometres,
271 and is well reproduced; the shorter locally forced sea depends on wind detail that a
272 global reanalysis resolves less well. The steepness-based partition between swell and
273 wind sea inherits that asymmetry: it reproduces the buoy classification on 74.6% of
274 the 3261 collocated records, and the disagreement falls almost entirely at the wind-sea
275 end.

276 Spatial coverage of the domain is assessed against the ESA Sea State CCI multi-
277 mission altimeter record (Dodet et al. 2020), distributed by the Copernicus Marine
278 Service as a Level-3 along-track product (*E.U. Copernicus Marine Service Information*
279 *(CMEMS) 2024a*). Altimeter significant wave height from the great majority of these
280 missions is assimilated by both reanalyses (Section 3.1; Table S2), so close agreement
281 is expected by construction and carries no information about accuracy. What the
282 comparison can establish is whether that agreement is uniform: an assimilating model
283 may still depart from the observations where passes are sparse, near the coast, or at
284 the extremes of the sea-state distribution. The question here is therefore spatial, and

specifically whether the performance demonstrated at Fortaleza holds north of the equator, where no in situ reference exists. The same distinction applies to previous regional assessments, in which agreement with an assimilated altimeter record has been reported as independent validation.

The collocated record comprises 13.9 million 1 Hz observations from eleven satellite missions over 1993–2022, grouped into 80 464 seasonally balanced passes and matched to the nearest model grid cell and three-hourly step (Figure 2). Across the three basins and the open domain (Figure 3), WEVERYS shows a bias between +0.077 and +0.087 m, a root mean square error between 0.180 and 0.191 m, a scatter index between 0.093 and 0.105, and correlations between 0.881 and 0.954. ERA5 has larger root mean square errors (0.23–0.26 m) and lower correlation in every stratum. The spread across strata is narrow, so the agreement is uniform along the margin and does not degrade north of the equator.

That agreement is not only a consequence of the assimilation. Of the collocated observations, 8.0% come from missions the reanalysis does not ingest: Sentinel-3B over its whole record from June 2018, which the product documentation does not list, and SARAL before March 2016 (Table S2). Restricted to those 1.1 million pairs, the WEVERYS bias ranges from +0.079 to +0.087 m across the four strata, against +0.073 to +0.084 m for the full record, while the root mean square error rises from 0.18–0.19 to 0.20 m and the correlation falls by 0.01–0.03, as expected of a twelvefold smaller, single-mission sample (Table S4). The reanalysis therefore departs from observations it has never ingested by about as much as from those it has. This remains a weaker statement than independent validation, because the CCI record is inter-calibrated across missions against the assimilated Jason series, and because the model field is constrained at the same time and place by the missions that are ingested; but it shows that the spatial agreement is not an artefact of the assimilation alone.

311 The bias is sea-state dependent. In the open domain WEVERYS overestimates
312 low sea states by +0.236 m below 1 m and converges towards the observations as
313 H_s increases, reaching -0.031 m above 3 m; ERA5 spans a much wider range, from
314 +0.361 to -0.264 m. This is a weaker peak underestimation than the Fortaleza record
315 indicates locally, and altimeter retrievals carry their own uncertainty at high sea states
316 ([Dodet et al. 2020](#)).

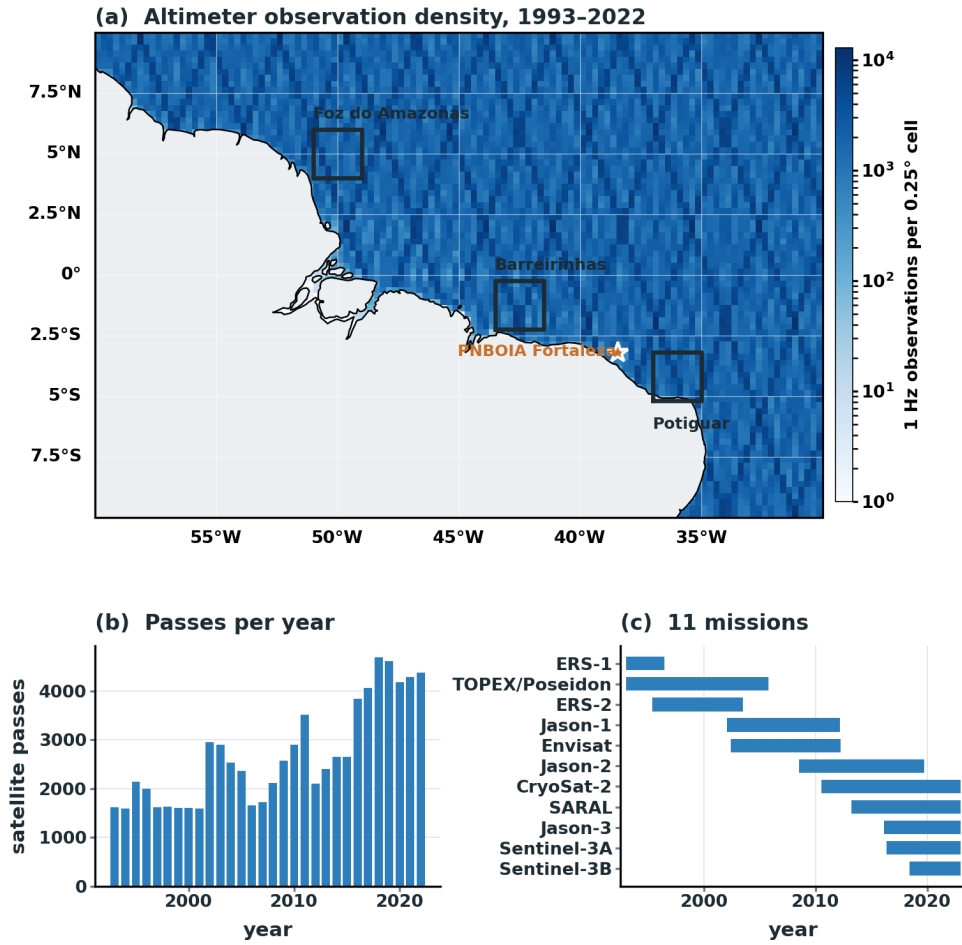


Fig. 2 Altimeter coverage of the BEqM domain, 1993–2022. (a) Density of collocated 1 Hz observations per 0.25° cell, on a logarithmic scale, with the three analysis strata outlined and the PNBOIA Fortaleza buoy marked. (b) Satellite passes per year. (c) Operating period of each of the eleven altimeter missions contributing to the record.

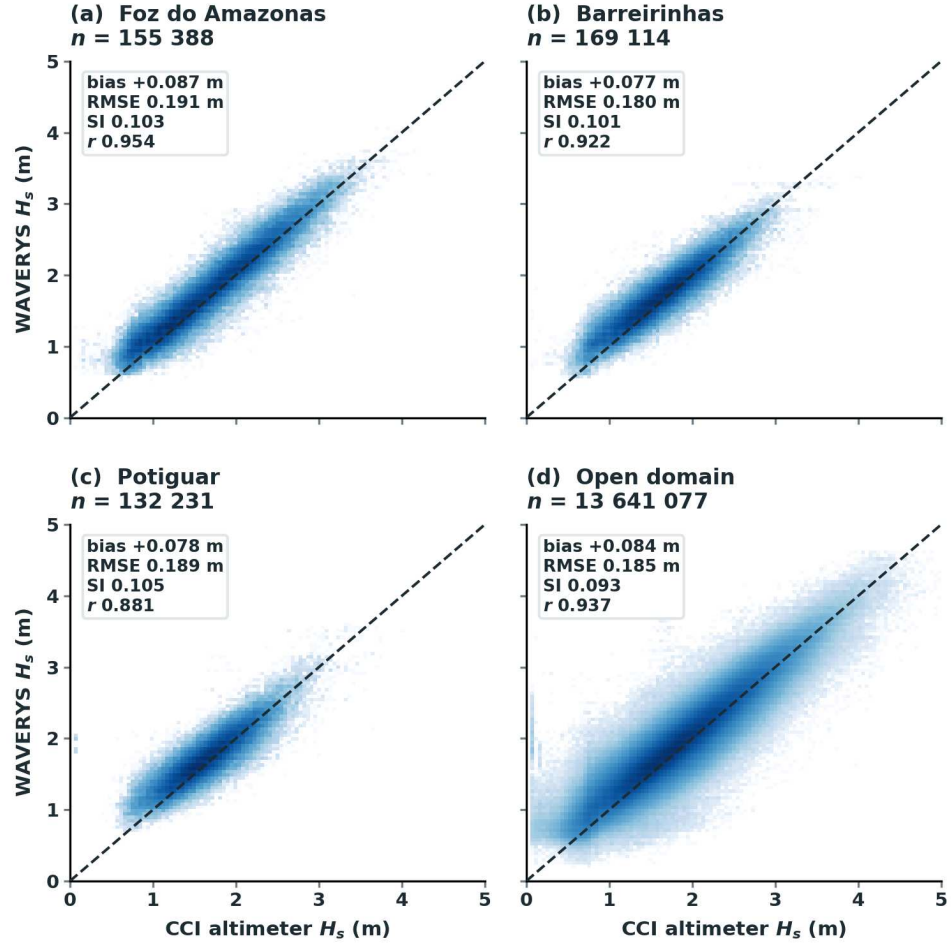


Fig. 3 Consistency of Waverys with the CCI altimeter record by stratum, 1993–2022, at a 25 km distance-to-coast threshold. Panels show the joint density of collocated significant wave height, on a logarithmic count scale, with the 1:1 line dashed, for (a) Foz do Amazonas, (b) Barreirinhas, (c) Potiguar, and (d) the open domain.

Figure 4 compares H_s and T_p from ERA5 and Waverys against the Fortaleza observations, both products interpolated to the buoy location and collocated with the same 3265 records. For H_s , ERA5 yields RMSE = 0.17 m, BIAS = -0.01 m, SI = 0.11

320 and $r = 0.89$, while WAVERYS yields $\text{RMSE} = 0.17$ m, $\text{BIAS} = -0.01$ m, $\text{SI} = 0.10$
321 and $r = 0.90$. Thus, WAVERYS shows slightly better performance for H_s at this
322 site. The regression line against the reference also lies closer to unity for WAVERYS
323 (Figures 4b,d).

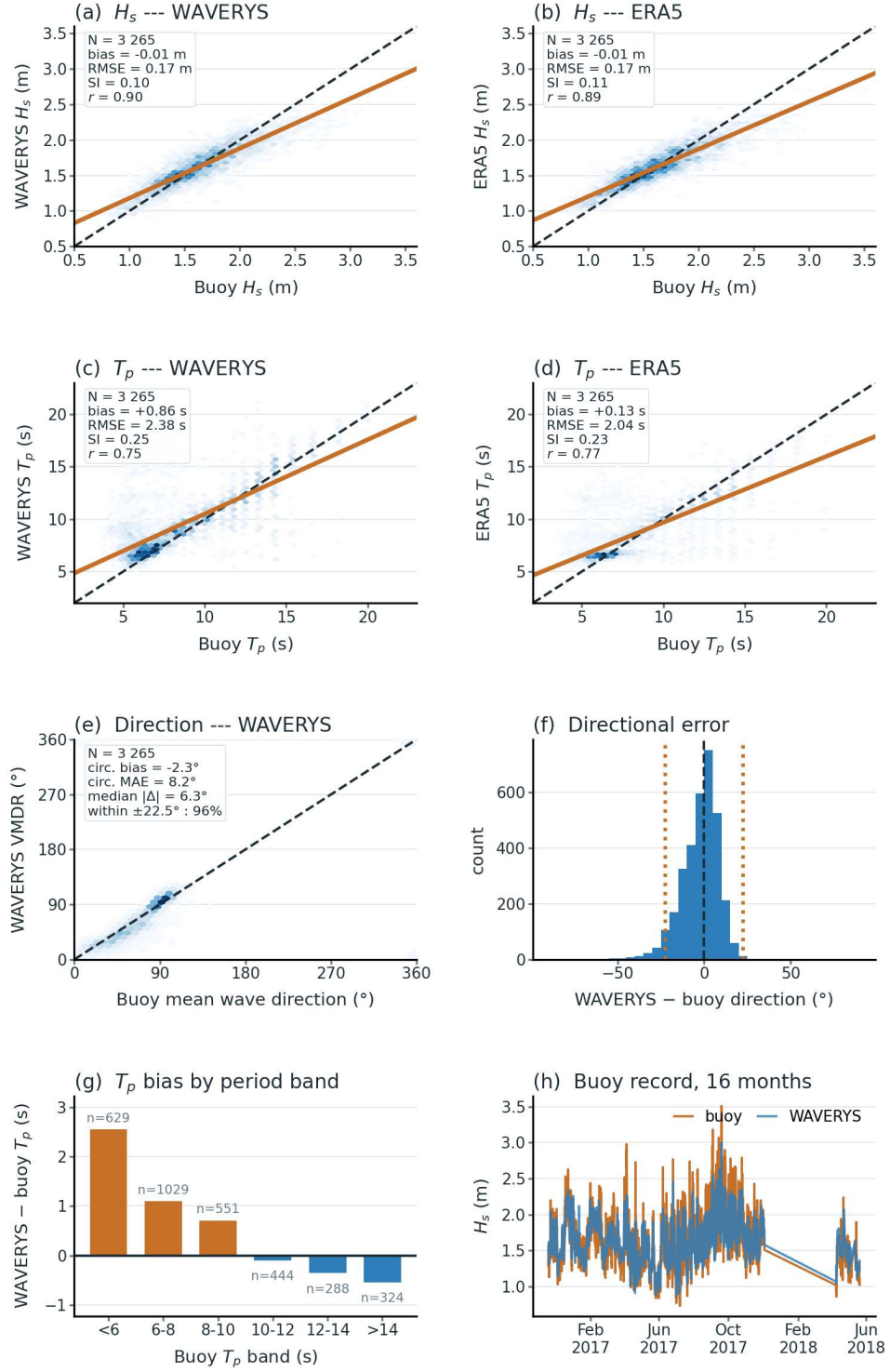


Fig. 4 Validation of Waverys and ERA5 against the PNBOIA Fortaleza buoy over November 2016 to May 2018. (a–d) Joint density of collocated significant wave height and peak period for each product, with the 1:1 line dashed and the least-squares fit solid; the scatter index follows Eq. (3). (e) Joint density of collocated mean wave direction for Waverys. (f) Distribution of directional error, with dotted lines at one 22.5° compass sector. (g) Peak-period bias by observed period band, with the number of collocated records above each bar. (h) The complete buoy record, comprising sixteen months of observations within the eighteen-month interval.

324 For T_p , ERA5 yields RMSE = 2.04 s, BIAS = 0.13 s, SI = 0.23 and $r = 0.77$, while
325 WEVERYS yields RMSE = 2.38 s, BIAS = 0.86 s, SI = 0.25 and $r = 0.75$. In this
326 case, ERA5 performs slightly better than WEVERYS.

327 Given the comparable overall skill and the higher spatial resolution ($1/5^\circ$ against
328 0.5°) and assimilation capabilities of WEVERYS (including altimeter H_s and SAR
329 directional spectra), we adopt WEVERYS as the primary data set for the BEqM
330 wave climatology. Additional observational data across the margin would allow a more
331 robust intercomparison in the future.

332 4.2 Temporal wave patterns (K-means clustering)

333 We used K-means to identify the dominant wave patterns in the WEVERYS record
334 over 1993–2022, with six patterns retained on the reproducibility criterion described
335 in Section 3.3. Figure 5 shows the centroid wave fields for each pattern, and Figure 6
336 presents their monthly distribution.

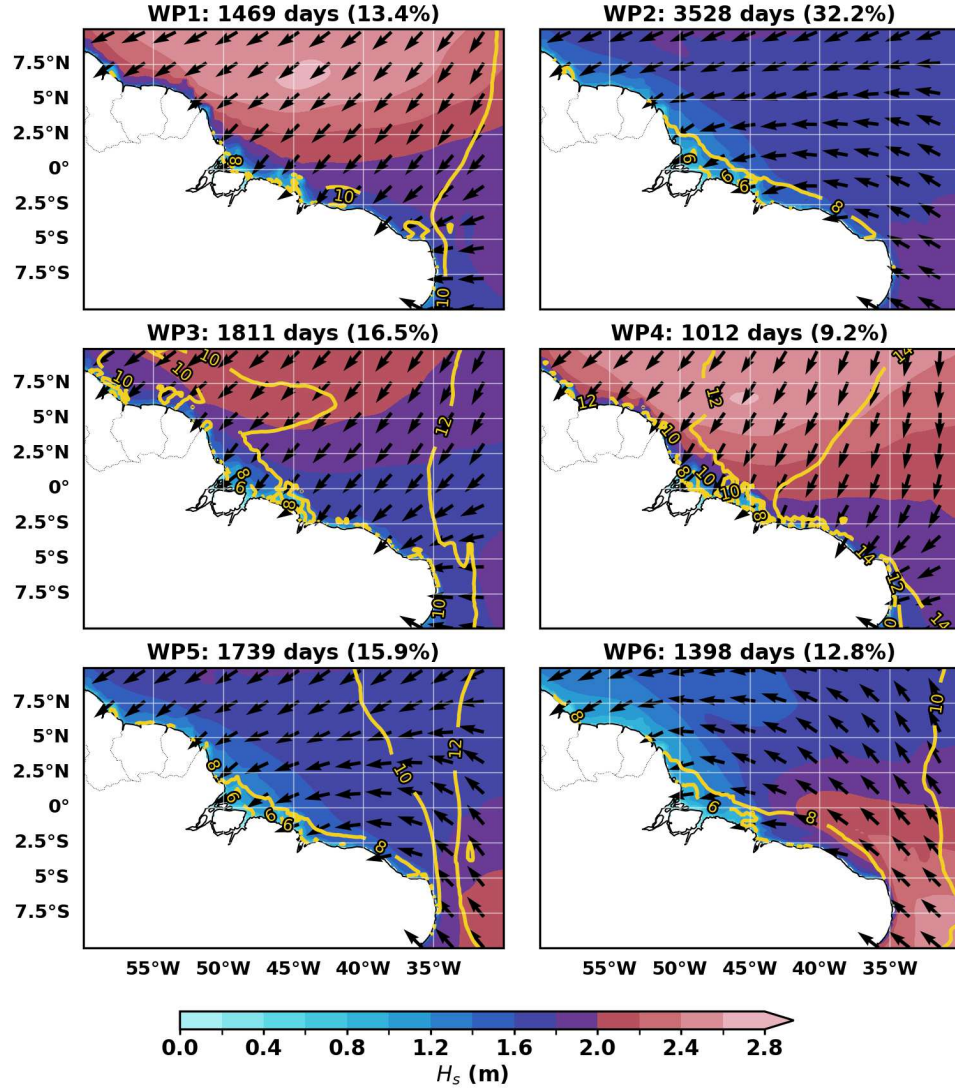


Fig. 5 Centroid wave fields for the six dominant wave patterns (WP1–WP6) identified by K-means clustering of the daily mean WAVERYS fields over 1993–2022. Shading indicates H_s (m) and vectors indicate mean wave propagation direction. The percentage in each panel denotes the relative frequency of occurrence.

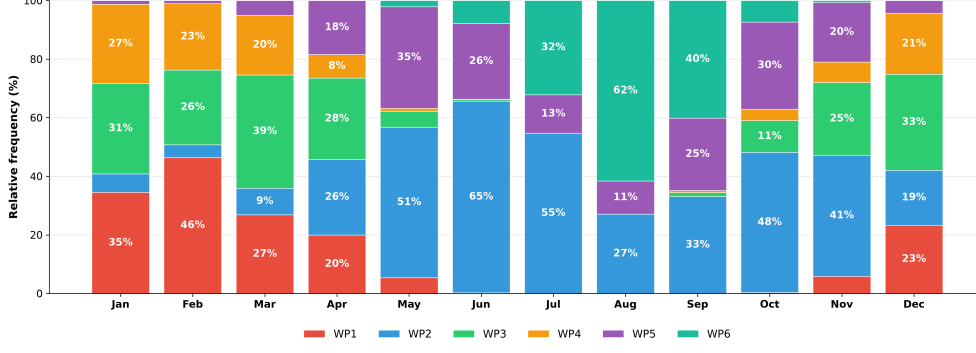


Fig. 6 Monthly relative frequency distribution of the six WAVERYS-derived wave patterns (WP1–WP6) over 1993–2022. Percentages are labelled for segments occupying at least 8% of the month. WP1 and WP4 (N–NE wave patterns) dominate during austral summer, while WP2 and WP6 (trade-wind patterns) prevail during austral winter.

WP1 (13.4% of days) represents energetic waves arriving from N–NE, with elevated H_s across the domain ($\bar{H}_s \approx 2.1$ m) and propagation vectors pointing broadly south-westward to southward. It occurs predominantly from December to March (Figure 6), peaking in February. WP4 (9.2%) is the longest-period pattern of all six ($T_p \approx 13$ s), with H_s comparable to WP1 at the BEqM ($\bar{H}_s \approx 2.43$ m at Foz do Amazonas; 1.94 m at Barreirinhas; 1.83 m at Potiguar) and the same N–NE direction of origin. It is the less frequent of the two, concentrated in December–March and associated with energetic long-period North Atlantic swell conditions. WP3 (16.5%) also comprises waves arriving from N–NE, with intermediate H_s values ($\bar{H}_s \approx 1.8$ m), occurring primarily from November to March, and represents a weaker manifestation of the swell regime. WP2 (32.2%) is the most frequent pattern, characterised by moderate waves arriving from E–SE with $H_s \sim 1.5$ – 1.7 m and broadly westward propagation. It dominates from May through July, peaking in June (65%) and July (55%), while WP6 becomes dominant in August (62%) and September (40%). WP2 becomes the leading pattern again in October and November. WP5 (15.9%) presents a similar

352 easterly direction of origin but with a slight northward component and comparable
 353 H_s ($\bar{H}_s \approx 1.7$ m), occurring predominantly during the transition months of April–
 354 May and October–November. WP6 (12.8%) is a trade-wind pattern characterised by
 355 a strong east-to-west H_s gradient: lowest wave energy near the Amazon mouth ($\bar{H}_s \approx$
 356 1.21 m at Foz do Amazonas) and the highest values at the eastern margin ($\bar{H}_s \approx$
 357 1.97 m at Potiguar). Across the year the six patterns therefore alternate between two
 358 regimes, with the N–NE patterns dominant from December through March and the
 359 easterly trade-wind patterns from June through September, and with April–May and
 360 October–November as transitions in which WP5 and WP2 coexist with the retreating
 361 or returning N–NE patterns. The atmospheric forcing systems associated with each
 362 pattern are examined in the following sections.

363 **4.3 Atmospheric forcing and wave generation**

364 To examine the large-scale conditions associated with each wave pattern, we com-
 365 posited Atlantic-wide WAVERYS wave fields (H_s and direction; Figure 7) and ERA5
 366 fields of mean sea-level pressure (MSLP) and 10-m wind (Figure 8) at lags of -7 , -5 ,
 367 -3 , -1 and 0 days from its occurrence at the BEqM, as anomalies with respect to the
 368 day-of-year climatology (Section 3.3). The extratropical minimum of each hemisphere
 369 is marked in Figure 8 where it exceeds 1.2 hPa in magnitude.

370 WP4 (long-period N–NE swell) carries the clearest remote signature of the six
 371 and is associated with a transient negative-pressure precursor. A negative pressure
 372 anomaly in the North Atlantic, already -6.6 hPa at lag -7 , deepens to -8.9 hPa at
 373 lag -5 , centred near 45°N , 33°W and accompanied by a closed cyclonic circulation in
 374 the 10-m wind anomaly. It then fills, to -4.8 hPa at lag -1 and -3.7 hPa on the day
 375 the pattern is observed. The wave field follows it: in the same region the H_s anomaly
 376 grows from $+0.53$ m at lag -7 to a maximum of $+1.38$ m at lag -3 , two days after
 377 the pressure minimum, and extends south-westward towards the margin by day 0

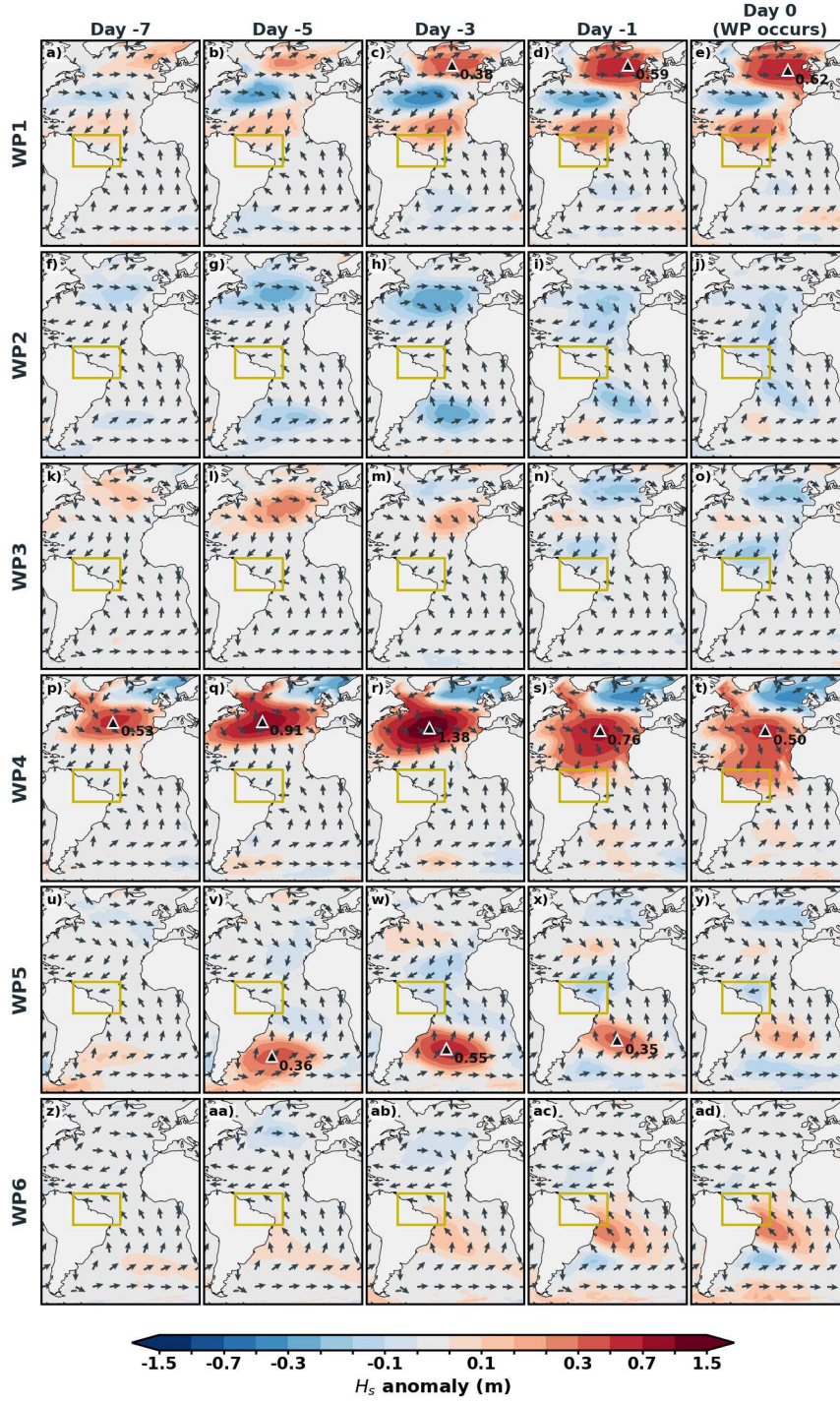


Fig. 7 Composite anomalies of Waverys significant wave height (shading) by wave pattern and lag, expressed as departures from a smoothed day-of-year climatology over 1993–2022. Vectors show propagation direction derived from the absolute mean wave direction.

(Figure 7). The interval between the two is what deep-water propagation predicts. The great-circle distance from the pressure centre to the BEqM is approximately 4750 km, and the group velocity for the pattern peak period ($T_p = 13.2$ s) is 890 km day^{-1} , giving a travel time of 5.3 days, so swell leaving the cyclone at its deepest arrives at the margin on the day the pattern is identified, as expected of North Atlantic extratropical cyclones (e.g. Ponce de León and Bettencourt 2021; Cheshm Siyahi et al. 2023).

WP1 (energetic N–NE waves) has a distinct atmospheric signature, associated primarily with a positive MSLP anomaly over the North Atlantic subtropical anticyclone (Davis et al. 1997), whose southern flank drives the trade winds that reach the tropical Atlantic. The anomaly reaches +4.5 hPa at lag -3 and is accompanied by stronger trade-wind flow over the tropical North Atlantic and the BEqM. A negative anomaly over the far North Atlantic is also present, but it deepens monotonically towards day 0, from -1.9 hPa at lag -7 to -5.9 hPa near 61°N , 27°W on the day itself. Because it strengthens with the pattern instead of preceding it, it is not identified as a generating cyclone. The H_s anomaly likewise grows steadily towards the day of occurrence, from $+0.18$ m at lag -7 to $+0.62$ m at day 0, whereas the WP4 anomaly peaks at lag -3 and is already decaying when the pattern is observed. At the WP1 peak period ($T_p = 9.5$ s), propagation from 61°N would require approximately ten days, beyond the seven-day window. These fields characterise WP1 as a strengthened subtropical-high and trade-wind circulation state associated with less-dispersed, recently generated N–NE waves, distinct from the transient negative-pressure precursor and long-period swell associated with WP4.

WP3 (attenuated N–NE swell) is associated with a North Atlantic minimum that is both shallower than the WP4 one and behaves differently. Its centre migrates: it lies at 50°N , 19°W at lag -7 and reaches 33°N , 40°W by day 0, covering 3350 km in seven days, or 479 km day^{-1} , equatorward and westward. The WP4 minimum is quasi-stationary by comparison, moving 1265 km over the same interval while deepening and

405 filling in place, and it is four to six times deeper: -1.1 to -1.5 hPa for WP3 against
406 -3.7 to -8.9 hPa for WP4.

407 The same travel-time test does not close for WP3. At its peak period ($T_p = 10.9$ s,
408 $c_g = 735$ km day $^{-1}$), swell generated at the deepest point of the track, lag -5 , would
409 reach Foz do Amazonas 1.9 days after the pattern is identified, and even the earliest
410 position sampled, at lag -7 , arrives 0.9 days late. The H_s anomaly in the region is cor-
411 respondingly weak, peaking at $+0.25$ m at lag -5 and not reaching the margin within
412 the window. The composite therefore resolves a coherent but shallow and migrating
413 cyclone whose own swell arrives too late to be the one observed: the waves present
414 on the day of the pattern were generated before the seven-day window opens. This
415 is consistent with WP3 as an older, attenuated expression of the same N-NE regime
416 rather than the signature of a single generating event.

417 For WP5, the anomaly composite shows a negative pressure anomaly in the South
418 Atlantic reaching -2.8 hPa at lag -5 , centred near 38°S , 20°W , with a closed cyclonic
419 wind anomaly. Its centre shifts equatorward as the lag approaches zero. At lag -5 ,
420 the mean source-region peak period is 11.2 s, corresponding to an estimated deep-
421 water travel time of 5.4 days over the approximately 4100 km to the margin. The
422 wave composite shows a South Atlantic H_s anomaly that peaks at lag -3 and extends
423 north-westward by day 0. At the margin the signature is in the period rather than in
424 the height. Over the eastern half of the domain WP5 arrives from 102° , essentially the
425 same direction as the trade-wind pattern WP2 at 100° , and with a comparable H_s
426 (1.75 against 1.73 m), but with a peak period of 11.1 s against 9.0 s. Its domain-mean
427 H_s anomaly is in fact slightly negative at every lag, between -0.01 and -0.05 m. WP5
428 is therefore not a pattern of enhanced wave energy but one of longer waves entering
429 from the east into a weak trade-wind sea, which is what a remote swell contribution
430 superimposed on local forcing produces.

WP2 and WP6 are both trade-wind patterns, but they are not the same kind of state. WP6 has the strongest positive pressure anomaly of the six, reaching +2.7 hPa at lag -1 as its maximum shifts north-eastward across the South Atlantic, a structure consistent with a migratory post-frontal anticyclone and enhanced SE-to-E trade winds over the equatorial South Atlantic. It coincides with the strongest east-to-west H_s gradient of any pattern, from approximately 1.21 m at Foz do Amazonas to 1.97 m at Potiguar.

WP2 is the opposite: the most frequent pattern of the six (32.2% of days) and the one with the weakest composite. Over the whole Atlantic domain its mean sea-level pressure anomaly averages 0.18 hPa and nowhere exceeds 0.82 hPa at day 0, below the 1.2 hPa threshold used to mark extrema in Figure 8, which is why no centre is marked in its row. Because the classification is fitted to every day of the record rather than to selected extremes, one pattern is expected to absorb the ordinary background state in which no organised system acts on the margin, and WP2 is that pattern: frequent, persistent (mean spell 4.6 days) and atmospherically featureless.

A South Atlantic origin for the WP6 waves, generated by a distant cyclone and steered towards the margin by the following anticyclone, is not supported by the period. A negative pressure anomaly is indeed present in the far South Atlantic in the WP6 composite, reaching -2.3 hPa at lag -3 , but it sits near 60°S and more than 6800 km from Potiguar; swell from there would arrive several days after the pattern, and after that distance it would arrive dispersed and long. WP6 instead has the shortest peak period of the six (8.8 s domain mean, against 13.2 s for WP4) and arrives from 134° , tracing back to the subtropical rather than the polar South Atlantic. The waves are therefore raised within the strengthened trade flow itself, under and ahead of the migrating anticyclone, rather than radiated from a remote storm.

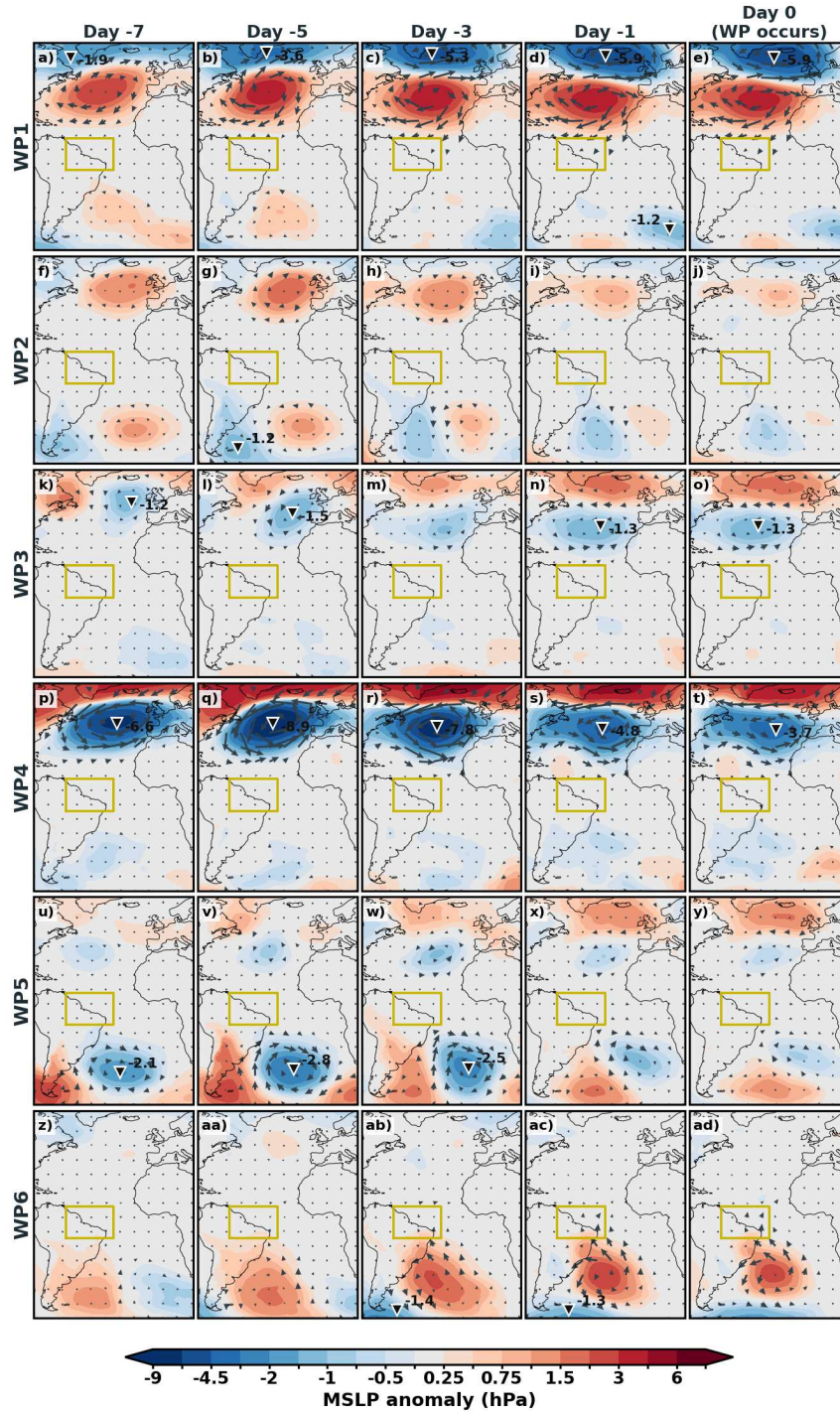


Fig. 8 Composite anomalies of ERA5 mean sea-level pressure (shading) and 10-m wind (vectors) by wave pattern and lag, expressed as departures from a smoothed day-of-year climatology over 1993–2022. Rows are the six wave patterns; columns are lags of -7, -5, -3, -1 and 0 days relative to occurrence of the pattern at the BEqM.

456 Taken together, the anomaly composites distinguish several forcing signatures.
 457 WP4 has the clearest transient negative-pressure and North Atlantic extratropical
 458 precursor, while WP1 is associated with positive MSLP anomalies over the North
 459 Atlantic subtropical high and stronger trade winds. WP5 is consistent with a South
 460 Atlantic contribution, with a lag sequence that agrees with the travel time estimated
 461 from peak period. WP6 is associated with a migratory post-frontal anticyclone over
 462 the South Atlantic and the trade flow it strengthens, and WP2 with the background
 463 trade-wind state, the most frequent and the least organised of the six. WP3 shows a
 464 weaker North Atlantic association that cannot be linked to a specific generating event
 465 within the seven-day window.

466 4.4 Swell versus wind-sea classification

467 To further characterise the wave generation regime associated with each WP, we con-
 468 structed joint H_s - T_p scatter diagrams (Figure 9) by pooling all daily WAVERYS
 469 outputs at the three analysis points (Foz do Amazonas, Barreirinhas, and Potiguar)
 470 that occurred on days assigned to each cluster. Each observation was then classified
 471 into one of the four wave-maturity categories defined in Section 3.3.

472 WP4 exhibits the highest median T_p of all patterns (14.0 s) and the largest com-
 473 bined old-swell and mature-swell fraction, consistent with long-period, well-dispersed
 474 remotely generated swell. WP1 has a median T_p of 9.6 s and a median H_s of 1.90 m,
 475 but only 17.0% of its occurrences fall in the old and mature classes against 82.1% in
 476 young swell. Its distribution is therefore more consistent with moderately energetic,
 477 recently generated swell than with long-travelled, well-dispersed wave energy.

478 WP3 occupies an intermediate position, with 56.4% of its occurrences in the old
 479 and mature classes and a median T_p of 10.8 s: more dispersed than WP1, less so
 480 than WP4. WP2 and WP6, in contrast, are dominated by shorter-period conditions

481 ($T_p \sim 8\text{--}9$ s) with large wind-sea and young-swell fractions, consistent with local SE
 482 trade-wind generation.

483 WP5 shows intermediate T_p values with a broad distribution spanning all four cat-
 484 egories, consistent with a mixed regime of trade-wind waves and a South Atlantic swell
 485 contribution. Together with the lag composites, the steepness distributions support a
 486 stronger remote-swell signature for WP4 and WP3, a weaker one for WP1, dominant
 487 local trade-wind forcing for WP2 and WP6, and mixed conditions for WP5.

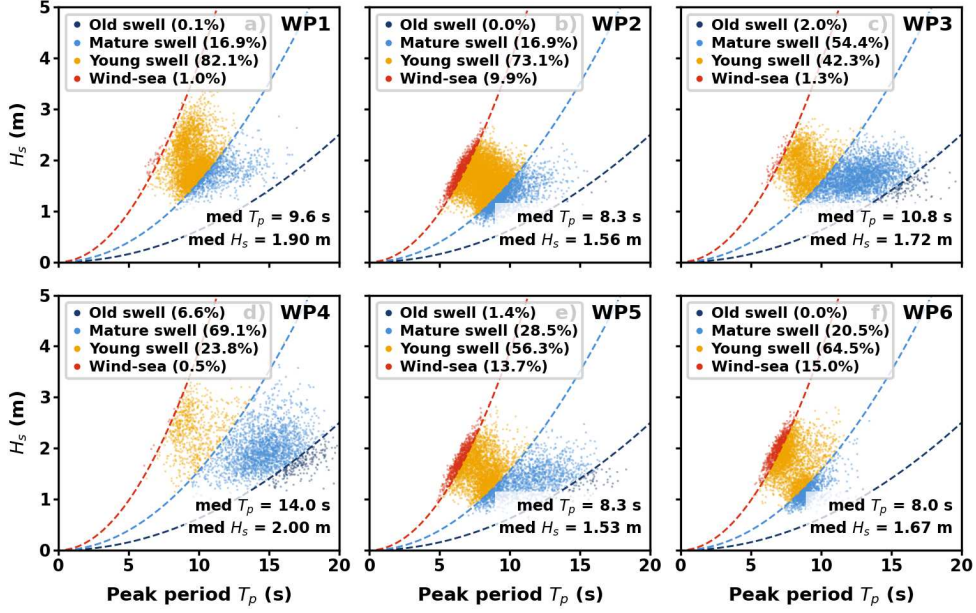


Fig. 9 Joint H_s – T_p scatter diagrams at the three analysis points (Foz do Amazonas, Barreirinhas and Potiguar), one point per daily observation at one site on a day assigned to the pattern. Colours give the four wave-maturity classes defined in Section 3.3, from old swell in dark blue to wind-sea in red, and the dashed lines mark the three steepness boundaries between them. Median H_s and T_p are given in the lower-right corner of each panel.

488 4.5 Directional distributions at the analysis points

489 The WP-stratified wave roses (Fig. 10) provide the pointwise directional signature
 490 of each WP at three contrasting sites along the BEqM, translating the large-scale

491 clustering into localised wave exposure conditions. Because the E sector straddles the
492 90° boundary between the two quadrants, a pattern may have E as its dominant sector
493 while most of its days still fall in the N–NE quadrant, and both statistics are reported
494 where that occurs.

495 At Foz do Amazonas, all six WPs are dominated by waves arriving from the N–NE
496 quadrant, which accounts for 80.4–100% of days depending on the pattern. WP1 and
497 WP4 have the highest mean H_s (2.38 and 2.43 m) and the largest proportions of days
498 above 2 m (88.6% and 85.1%), consistent with the long-period swell character of WP4
499 and the energetic, less-dispersed N–NE waves of WP1. WP1 is strongly concentrated
500 in the NE sector (87%; circular dispersion 6.4°), whereas WP4 is more northerly
501 and more dispersed (mean direction 31.8° ; dispersion 11.9°). WP3 is intermediate in
502 direction and energy. WP2 and WP5 both have mean H_s near 1.5 m and substantial
503 ENE components. WP6 has the largest easterly contribution (ENE 41%, E 39%) but
504 the lowest mean H_s (1.21 m), so its directional shift is not accompanied by high wave
505 energy at this site.

506 At Barreirinhas, the N–NE wave patterns remain predominantly in that direction-
507 of-origin quadrant (WP1 100%, WP3 99.8%, WP4 95.6%), with WP4 showing the
508 most northerly mean direction (20.6°). WP2 and WP5 shift towards the easterly
509 sectors, although most days remain below the 90° quadrant boundary. WP6 differs
510 more clearly: E accounts for 86% of days, the E–SE quadrant for 79.3%, and the mean
511 direction is 93.1° , with a mean H_s of 1.74 m.

512 At Potiguar the separation between swell and trade-wind patterns is strongest. The
513 trade-wind patterns are dominated by waves arriving from the E-to-ESE sectors (E–
514 SE quadrant: WP2 74.3%, WP5 68.3%, WP6 99.4%), while the N–NE wave patterns
515 retain that direction-of-origin quadrant (WP1 94.1%, WP3 94.8%, WP4 90.6%) but
516 with markedly broader spread than at Foz do Amazonas. WP6 is the most distinctive
517 pattern at this site: ESE accounts for 75% of days and SE for a further 23%, placing

518 99.4% of days in the E–SE quadrant at a mean direction of 118.8°; it is simultaneously
 519 the most concentrated pattern here (dispersion 7.8°) and the most energetic (mean H_s
 520 1.97 m, 45.4% of days above 2 m). That combination – high, tightly directional and
 521 short-period waves from E–SE – is what a strengthened trade flow produces locally,
 522 and is the opposite of what arrives after long-distance propagation, which broadens
 523 the period and lengthens it. WP2 is clearly distinguished from it: its dominant sector
 524 is ESE (52%) followed by E (33%), with a lower mean H_s (1.66 m) and a disper-
 525 sion of 17.9°, consistent with the interpretation of WP2 and WP6 as moderate and
 526 intensified trade-wind regimes. Among the N–NE wave patterns, WP1 and WP3 are
 527 broadly distributed across NE, ENE and NNE, with no sector exceeding 34%, while
 528 WP4 remains the most northerly (NNE 38%, N 22%) and has the largest directional
 529 dispersion of any pattern at any site (25.6°).

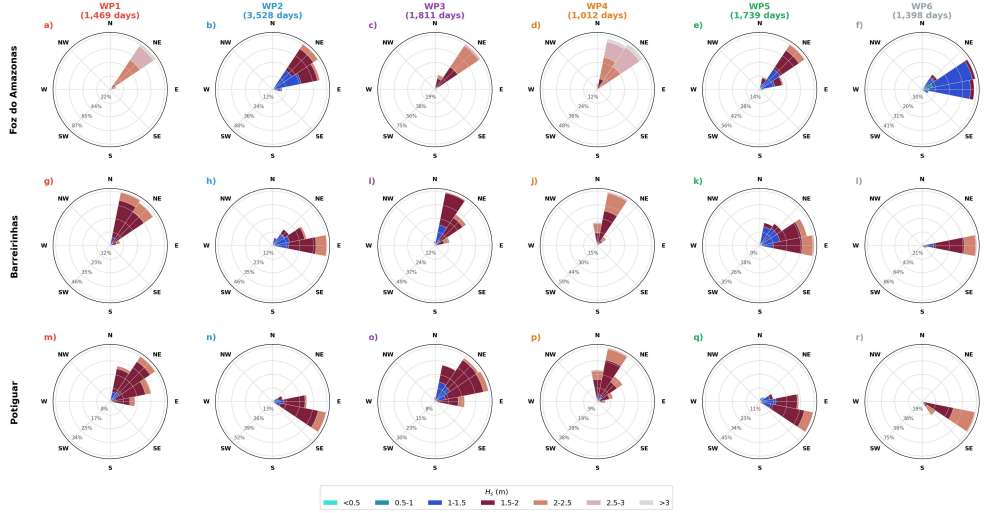


Fig. 10 Waverys wave directional roses stratified by wave pattern (WP1–WP6, columns) at the three BEqM analysis points over 1993–2022: (a–f) Foz do Amazonas, (g–l) Barreirinhas, and (m–r) Potiguar. Sectors indicate wave direction of origin and are centred on the cardinal points.

530 The three sites together document a systematic along-margin gradient, but the
 531 gradient acts on different properties in the two regime families. For the trade-wind

patterns the mean direction rotates clockwise monotonically eastward, from 58.5° to 71.4° to 98.8° for WP2, from 49.6° to 64.5° to 95.2° for WP5, and from 75.1° to 93.1° to 118.8° for WP6. Their directional dispersion contracts along the same path, WP6 narrowing from 17.1° at Foz do Amazonas to 7.8° at Potiguar. The swell patterns behave differently: their mean direction is not monotonic along the margin, reaching its most northerly value at Barreirinhas and returning eastward at Potiguar (WP1: 49.3° , 36.9° , 52.9° ; WP4: 31.8° , 20.6° , 31.3°). What does increase monotonically for the swell patterns is directional dispersion, which roughly quadruples from Foz do Amazonas to Potiguar (WP1: 6.4° , 12.8° , 23.0° ; WP3: 10.0° , 16.9° , 23.5°). These results describe an eastward rotation and narrowing of the trade-wind patterns and an increase in directional dispersion for the swell patterns, without attributing those spatial changes to a single mechanism. The mean H_s of WP6 increases from 1.21 m at Foz do Amazonas to 1.97 m at Potiguar, a 63% difference over approximately 15° of longitude. The full directional statistics are given in Table S3 of the Supplementary Information.

4.6 Wave pattern persistence and regime transitions

To characterise the temporal coherence of each wave regime, we quantified spell duration statistics and day-to-day transition probabilities from the 10,957-day WP label series over 1993–2022 (Section 3.1). Following Michelangeli et al. (1995) and Cassou et al. (2004), a *spell* is defined as a sequence of one or more consecutive days on which the same wave pattern is assigned; a spell terminates when the WP label changes on the following day. The transition probability matrix $P(\text{WP}_{t+1} = j \mid \text{WP}_t = i)$ is estimated by counting all consecutive-day pairs $(t, t+1)$ in which both days carry a valid label, and normalising each row to 100%.

Spell duration distributions are shown in Figure 11. The trade-wind patterns have the longest and nearly identical mean spells: WP6 averages 4.60 days (median 3 days,

558 maximum 33 consecutive days) and WP2 averages 4.57 days (median 3 days, maximum
 559 34 days). Among the N-NE wave patterns, WP1 is the most persistent (mean 4.3 days,
 560 maximum 27 days), while WP4 has a mean spell of 3.2 days. WP3 and WP5 have the
 561 shortest mean spells (2.8 and 2.9 days, respectively; medians of 2 days), consistent
 562 with their occurrence between the dominant N-NE and trade-wind regimes. Overall,
 563 72.7% of consecutive-day pairs retain the same pattern.

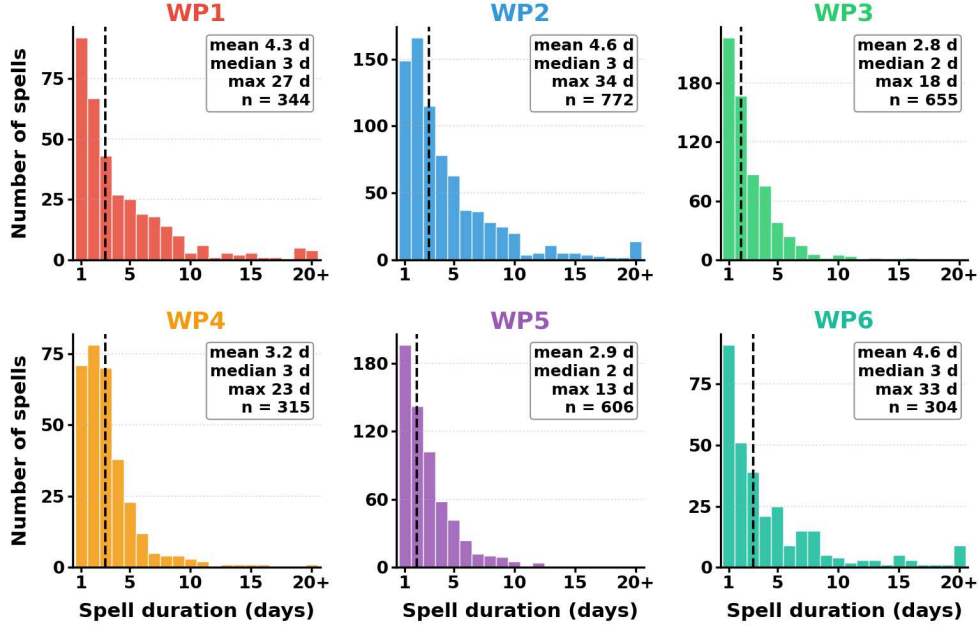


Fig. 11 Spell duration statistics for the six BEqM wave patterns, derived from the WAVERYS classification over 1993–2022. Bars show mean spell duration (days) with one standard deviation; numbers above each bar indicate the maximum observed spell duration. Values are computed from the 10,957-day WP label series.

Figure 12 presents the conditional transition probability matrix $P(j | i)$, estimated from all consecutive-day pairs in the 1993–2022 record. The diagonal dominates: self-transition probabilities are 78.3% for WP6, 78.1% for WP2, 76.6% for WP1, 68.9% for WP4, 65.2% for WP5 and 63.8% for WP3.

The off-diagonal probabilities describe the most common changes between patterns. WP4 changes most frequently to WP3 (23.0%), and no WP4→WP2 transition is observed; WP3 subsequently changes to WP2 with 10.2% probability. Along this sequence, median peak period decreases from 14.0 s to 10.8 s to 8.3 s and the combined old- and mature-swell fraction from 75.7% to 56.4% to 16.9% (Figure 9). Within the trade-wind patterns, WP6→WP2 occurs with 15.7% probability, compared with 5.7% for WP2→WP6. Direct changes between WP1 and WP2 are uncommon (5.9% for WP1→WP2 and 2.4% for WP2→WP1). These probabilities describe the observed temporal organisation of the classified regimes; they are not a forecast model.

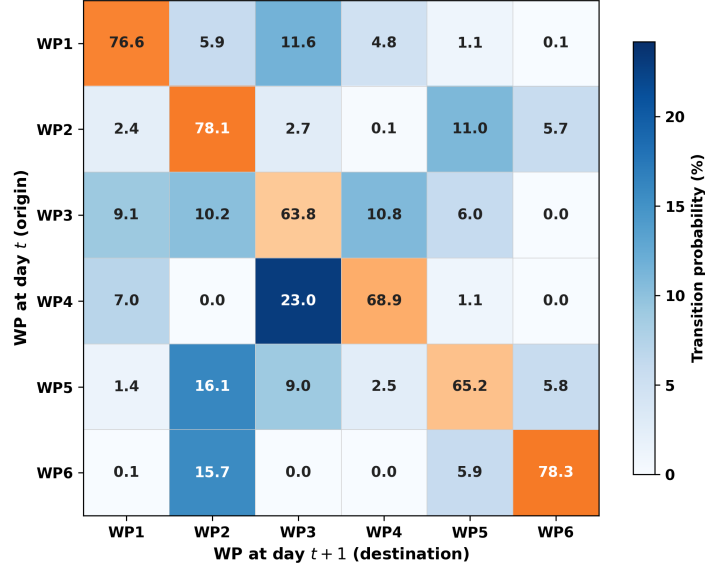


Fig. 12 Day-to-day conditional transition probability matrix $P(WP_{t+1} = j \mid WP_t = i)$ for the six BEqM wave patterns, derived from the WEVERYS classification over 1993–2022. Values are expressed as percentages. Diagonal cells (warm shading) indicate same-pattern persistence; off-diagonal cells (cool shading) indicate observed inter-pattern transitions. White cells indicate transitions not observed in this record.

5 Discussion

The seasonal wave climatology derived here broadly agrees with results reported by dos Reis et al. (2024) for the same region based on ERA5. The seasonally alternating swell/trade-wind regime identified for the Maranhão shelf is consistent with what we observe at both Barreirinhas and Potiguar; however, this bimodal character does not extend to Foz do Amazonas, which maintains a predominantly unimodal NE regime throughout the year. Carvalho et al. (2025) also documented a bimodal directional structure in the Pará-Maranhão sector, consistent with our NNE–ENE wave patterns (WP1, WP4), among which the long-period swell signature is clearest in WP4, and the ENE–ESE wind-sea patterns (WP2, WP6).

587 The six temporal wave patterns refine this seasonal description. WP1 and WP4
 588 (22.6% of all days) represent contrasting expressions of the N–NE wave regime concen-
 589 trated in December–March: WP1 contains less-dispersed, recently generated waves,
 590 whereas WP4 contains long-period swell. WP2 and WP6 (45.0%) describe the SE
 591 trade-wind regime prevalent from May to September. WP3 is the second most frequent
 592 pattern (16.5%) and is intermediate in peak period and directional concentration; it
 593 is also the most frequent intermediate state between WP4 and WP2. WP5 (15.9%)
 594 combines weaker trade-wind forcing with a possible South Atlantic swell contribution
 595 and occurs mainly during seasonal transitions. The ERA5 composites reveal differ-
 596 ent atmospheric signatures within the N–NE wave regime: WP1 coincides primarily
 597 with positive MSLP anomalies over the North Atlantic subtropical high and stronger
 598 trade-wind flow, whereas WP4 is linked to a transient negative MSLP anomaly and an
 599 extratropical-cyclone precursor. WP2 and WP6 coincide with stronger South Atlantic
 600 subtropical-high and trade-wind conditions. These associations provide a physical
 601 interpretation of the patterns without constituting attribution to individual generating
 602 events.

603 The lag composites (Figures 7 and 8) support these interpretations of wave origin.
 604 For WP4, the North Atlantic pressure minimum at lag -5 and the subsequent wave-
 605 energy maximum at lag -3 form a sequence consistent with the deep-water group
 606 velocity estimated from its peak period. For WP2 and WP6, the absence of a coher-
 607 ent remote precursor is consistent with predominantly local generation by persistent
 608 SE trade winds. The joint H_s – T_p distributions (Figure 9) provide complementary evi-
 609 dence: WP4 has the largest combined old- and mature-swell fraction, whereas WP2
 610 and WP6 are dominated by shorter-period young-swell and wind-sea conditions.

611 The dual-source structure of the BEqM wave climate is consistent with the global
 612 swell climatology of [Alves \(2006\)](#), who identified the Extra-Tropical North Atlantic
 613 (ETNA) zone as generating approximately 277 extratropical storms per year. That

614 study showed that ETNA winter swells propagate equatorward through the South
 615 Atlantic, reaching the northeast coast of Brazil, while tropical disturbances within
 616 the tropical North Atlantic zone (TNAO) generate swell primarily during the boreal
 617 summer that propagates into the Gulf of Mexico and high-latitude North Atlantic.
 618 [Prestes et al. \(2025\)](#), in a reanalysis-based study of Atlantic wave variability, reported
 619 a mean peak period of 10.3 s and a mean significant wave height of 1.77 m for the
 620 Tropical Atlantic sector, consistent with the swell-dominated environment documented
 621 here. The possible modulation of the BEqM regimes by large-scale climate indices
 622 remains a hypothesis for future work rather than an attribution attempted in the
 623 present study.

624 Read through the forcing rather than through the labels, the transition matrix
 625 (Figure 12) has a structure that the sequence of patterns alone does not reveal. The
 626 six states separate into two families that scarcely communicate. The North Atlantic
 627 family comprises the transient cyclone (WP4), its attenuated older expression (WP3)
 628 and the subtropical-high state (WP1). It exchanges internally and almost never passes
 629 directly to a trade-wind state: WP4 is followed by WP2 on no day of the record, and
 630 by WP6 on none either. The South Atlantic and trade family (WP2, WP5, WP6) is
 631 closed in the same way, with WP6 followed by WP3 or WP4 on no day. The only
 632 regular crossing between the two runs through WP3, which reaches WP2 with 10.2%
 633 probability; WP3 is thus not merely an intermediate pattern in the sense of period
 634 and directional spread, but the state through which the margin actually leaves the
 635 North Atlantic regime.

636 Within each family the transient decays towards its own background more readily
 637 than the background organises into the transient. The cyclone state is followed by
 638 the attenuated one with 23.0% probability while the reverse occurs with 10.8%; the
 639 post-frontal anticyclone state is followed by the background trade state with 15.7%
 640 against 5.7% for the reverse. Both asymmetries have the sign expected if these are

excursions imposed by passing systems on a background that is otherwise persistent, which is consistent with WP2 being at once the most frequent state and the one with the weakest composite. The same reading explains why the subtropical-high state is not an intermediary: WP1 is followed by WP2 with only 5.9% probability, because a strengthened subtropical high and a slack background trade flow are not adjacent circulation states.

Differences among wave products, and subsequent changes in the assimilated observing system within the analysis period, remain limitations for temporal interpretation (Caires et al. 2004; Sharmar et al. 2021).

Independent validation is limited to the Fortaleza buoy, since no in situ observations are assimilated by either reanalysis (*E.U. Copernicus Marine Service Information (CMEMS) 2024b*). The CCI altimeter comparison extends the spatial assessment across the margin. The missions that supply the great majority of these observations are assimilated by WAVERYS, so the comparison as a whole measures consistency rather than independent skill; the 8% of observations that are not ingested give the same bias, which narrows but does not remove that limitation, for the reasons given in Section 4.1. Direction and period cannot be validated independently across the domain because the available spaceborne spectral observations are also assimilated (Law-Chune et al. 2021). These constraints limit the analysis to a climatological interpretation of the recurrent wave regimes.

6 Conclusions

We characterised the wave climate of the Brazilian Equatorial Margin from the WAVERYS reanalysis over 1993–2022 and classified its daily fields into six reproducible wave patterns, the number of regimes being selected by the reproducibility of the partition

rather than by within-cluster compactness. The margin is governed by the superposition of remotely generated Atlantic swell and locally generated trade-wind waves, and the classification separates the two more sharply than a seasonal description does.

Grouped by the circulation that produces them rather than by label, the six states form two families. Three belong to the North Atlantic and prevail from December to March: a transient extratropical cyclone delivering the longest-period swell, its older and attenuated expression, and a strengthened subtropical high whose waves are energetic but recently generated. Three belong to the South Atlantic and the trades: a migrating post-frontal anticyclone that tightens the south-easterly flow, a mixed state in which a South Atlantic swell contribution enters beneath a weak trade sea, and the background state, at once the most frequent of the six and the one with the weakest atmospheric composite. The two trade-wind patterns account for 45.0% of days and prevail from May to September; the attenuated swell pattern is the second most frequent overall (16.5%). Joint H_s-T_p distributions and wave steepness separate the same groups independently of the composites.

The seasonal alternation is not uniform along the margin, and this is the result of most practical use. Potiguar and Barreirinhas swing between a N-NE swell regime in austral summer and an E-SE trade-wind regime in austral winter. Foz do Amazonas does not: it remains predominantly N-NE throughout the year, with its wave energy concentrated in austral summer and autumn. A single seasonal description of the BEqM would misrepresent one end of it or the other.

The regimes are organised in time as well. The trade-wind states are the most persistent, with mean spells of 4.6 days against 3.2 days for the transient cyclone state, and each family relaxes towards its own background more readily than the background organises into a transient. The two families exchange almost exclusively through the attenuated swell pattern, which is therefore the state through which the margin leaves the North Atlantic regime rather than merely an intermediate one.

692 Within the observational constraints of a region with one buoy and an assimilated
693 altimeter record, the classification describes where, when and under which circulation
694 each sea state occurs along a margin now under offshore development.

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912 Statements and Declarations

913 Author contributions

914 **Matheus Bonjour Laviola da Silva:** conceptualization, investigation, methodol-
915 ogy, formal analysis, software, visualization, data curation, writing — original draft,
916 writing — review and editing. **Danilo Couto de Souza:** investigation, methodol-
917 ogy, formal analysis, data curation, writing — review and editing. **Fernando Tulio**
918 **Camilo Barreto:** validation, investigation, supervision, writing — review and edit-
919 ing. **Leonardo Carvalho de Jesus:** investigation, writing — review and editing.
920 **Amauri Costa Bevilacqua:** investigation, writing — review and editing. **Marcia**
921 **Carolina de Oliveira Costa:** investigation, writing — review and editing. **Victor**
922 **Azevedo Godoi:** validation, supervision, investigation, writing — review and editing.
923 **Carlos Leandro da Silva Junior:** resources, supervision, project administration,
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934 **Data availability**

935 The WAVERYS wave reanalysis data are available from the Coper-
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937 GLOBAL_MULTIYEAR_WAV_001.032). ERA5 reanalysis data are available from
938 the Climate Data Store (<https://cds.climate.copernicus.eu>). The ESA Sea State
939 CCI multi-mission altimeter record is available from the Copernicus Marine
940 Service (product identifier: WAVE_GLO_PHY_SWH_L3_MY_014_005; dataset
941 `cci_obs-wave_glo_phy-swh_my_l3_PT1S-i`; <https://doi.org/10.48670/moi-00176>).
942 Fortaleza buoy data are available from the PNBOIA program (<https://www.marinha.mil.br/chm/dados-do-goos-brasil/pnboia>). Analysis scripts and
943 workflows are available from the corresponding author upon reasonable request.

945 **Competing interests**

946 Matheus Bonjour Laviola da Silva, Fernando Tulio Camilo Barreto, Leonardo Car-
947 valho de Jesus, Amauri Costa Bevilacqua, Marcia Carolina de Oliveira Costa, Victor
948 Azevedo Godoi and Carlos Leandro da Silva Junior are employed by OceanPact.
949 Danilo Couto de Souza is affiliated with the University of São Paulo and with IRB,
950 and declares no competing interests.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialLavioladaSilva2026.pdf](#)