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1 Seasonal to interannual variability of the tide in the Amazon 2 estuary

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15

16 Abstract

17 The Amazon River exports the largest volume of fresh water to the ocean worldwide..
18 Although previous studies have revealed the spatiotemporal tidal variability of the
19 estuary, its hydrodynamics is still poorly understood. Here we evaluate the seasonal
20 and interannual variability of the tide from Óbidos (800 km upstream) to the Atlantic
21 Ocean and show how it is affected by the hydrological regime of the Amazon River. A
22 high-resolution 2D hydrodynamic model was applied in this region at the scale of the
23 whole estuary. The tide model is validated using data from 14 water level stations
24 and shows an average complex error of 16 cm in the low flow season and 23 cm in
25 the high flow season. The semi-diurnal tide is highly variable at seasonal timescales,
26 and the seasonality of the discharge affects the tidal amplitude, the geographic
27 extent of tidal influence, the tidal wave celerity, and the tidal flow reversal. Notably,
28 the tidal influence on water level remains detectable up to Óbidos during the low flow
29 season while during the high flow season it extends from the ocean to only 300 km
30 downstream of Óbidos. On the other hand, the upstream limit of the domain where
31 the tide induces a periodic flow reversal is different from the limit of tidal influence on
32 the water level. The upstream limit of this flow reversal is shifted by 170 km (from 500
33 km to 670 km downstream of Óbidos) along the year due to the seasonality of the
34 discharge. At interannual scale, anomalous hydrological discharges affect the tidal
35 amplitude by up to 30% in the central reach of the estuary. Our findings open

36 unprecedented opportunities to understand biogeochemical and geomorphological
37 processes, help navigation, and assess flooding hazards.

38

39 **Highlights**

40 Advances in modeling the impact of Amazon River variability on tidal modulation

41 Tidal amplitude and phase are well represented with a complex error of order 20 cm

42 River discharge controls tidal range, tidal celerity, and flow reversal

43 Extreme discharges induce changes of 10-25% of the tidal range in the central
44 estuary

45

46 **1. Introduction**

47 The Amazon is the largest continental freshwater supply to the world ocean,
48 with an average discharge of 200 thousand m^3/s (Callède et al., 2010). It drains a
49 watershed of more than 6 million km^2 , encompassing about one-third of South
50 America. The lower part of the watershed consists of a very long estuary extending
51 over 800 km downstream of Óbidos meeting the Atlantic Ocean (Figure 1; Kosuth et
52 al., 2009). On one hand, the tide propagates up to Óbidos due to the weak slope of
53 the riverbed. On the other hand, the consistently high discharge throughout the
54 seasonal cycle prevents salty ocean waters from entering the estuary (Geyer and
55 Kineke, 1995), unlike most estuaries. The knowledge of temporal (seasonal to inter-
56 annual) variability of tide with freshwater inflow is required to better understand the
57 sediment transport and morphodynamics of the estuary and adjacent floodplains
58 (Fricke et al., 2019; Nittrouer et al., 2021), as well as the ecology and biogeochemical
59 balance of the river and floodplains (Junk et al., 2012; Melack et al., 2021;
60 Sawakuchi et al., 2017).

61 The Amazon River flood period (high flow) occurs in May/June and the
62 drought period (low flow) in October/November (Figure 1d). This annual variation in
63 water level results in the periodic inundation of the large and shallow floodplains in
64 the upper reach of the estuary (~250 km in extent; Fricke et al., 2019). The tidal
65 influence in this reach is observed only during the low flow period and is smaller than
66 in the downstream part of the estuary (Kosuth et al., 2009). However, the adjacent
67 floodplains may exert some, yet unknown, effect on tidal variability (Fortunato and

68 Oliveira, 2005). The middle reach of the estuary (Almeirim region, Figure 1) has few
69 floodplains more connected to the river due to absence of levees (Fricke et al., 2019)
70 and a straight river channel. Downstream of this point, the river splits into two large
71 channels and ends in a deltaic network of tributaries, where the tide has the most
72 significant influence on the water level.

73 The mouths of the Amazon outflow over a broad, shallow shelf and are
74 characterized by a macrotidal regime. The tidal amplitude reaches 2 m in the
75 Amazon mouth, with values over 3 m locally on the northern side of the Amazon
76 mouth, making it one of the most energetic tidal regions of the tropical Atlantic basin
77 (Ruault et al., 2020). The large tidal amplitude at the Amazon mouths results from the
78 combination of two effects. The first one is the ideal geometry of the Amazon shelf
79 regarding the resonance of the semi-diurnal tidal waves incoming from the deep
80 ocean (Beardsley et al., 1995; Clarke and Battisti, 1981). The second is the
81 consistent presence of extended fluid mud layers deposited by the Amazon plume,
82 limiting tidal dissipation on the bottom over the shelf (Gabioux et al., 2005; Kineke et
83 al., 1996; Le Bars et al., 2010).

84 The observational study of Kosuth et al. (2009) described the characteristics of
85 the tide propagating in the Amazon estuary, based on an original set of in situ gauge
86 records collected along the various reaches in the late 1990s. They documented the
87 seasonal variability of the tidal range and the phase speed of the tidal waves,
88 showing a contrasting situation between the high and the low flow periods. During the
89 high flow season, the tidal amplitude is typically twice as weak as during the low flow
90 season, all over the central part of the Amazon estuary, some 400 km downstream of
91 Óbidos.

92 The modelling of the tidal dynamics of the Amazon estuary and adjoining shelf
93 remains a challenging research topic. Whereas there exist several numerical
94 modeling studies that investigated the tidal hydrodynamics of the Amazonian shelf
95 (Durand et al., 2022; Fontes et al., 2008; Gabioux et al., 2005; Molinas et al., 2020,
96 2014; Nikiema et al., 2007; Ruault et al., 2020), the past studies dedicated to the
97 hydrodynamic modeling of the inner Amazon estuary are scarce. However, they
98 provided valuable insights on the mechanisms of tidal propagation and its interaction
99 with the Amazon discharge. The pioneering modelling study of Gallo and Vinzon
100 (2005) shed light on the non-linearity of the tidal dynamics in the lower Amazon,

101 yielding strong shallow-water tidal constituents that give rise to a marked asymmetry
102 of the semi-diurnal tide, as well as to a strong signature of the fortnightly tide.
103 Furthermore, they provided evidenced for the key role of bottom friction in generating
104 both M4 and MSf constituents all along the estuary. The gradual increase of MSf
105 fortnightly constituent combined with the gradual decay of primary semi-diurnal
106 constituents M2 and S2 from the mouths towards upstream was found to induce a
107 peculiar behavior of the Amazon spring-neap cycle. Over the central reach of the
108 estuary, low waters at spring tide were found to be sitting at levels typically 0.2 m
109 higher than the low waters at neap tide. Despite these already documented complex
110 hydrodynamic features, to date, a seamless hydrodynamic modeling framework
111 encompassing the whole Amazon estuary at high resolution and resolving the
112 seasonal to interannual timescales of variability of the tide is still lacking.

113 There have been numerous studies investigating the relationship between
114 river discharge and tidal characteristics in other large estuaries (e.g., Cai et al., 2014;
115 Elahi et al., 2020; Godin, 1999; Guo et al., 2015; Helaire et al., 2019; Jay et al., 2011;
116 Losada et al., 2017; Matte et al., 2014). To the best of our knowledge, however, the
117 present study is the first to model the hydrodynamics over the Amazon estuary with a
118 high-resolution numerical model, explicitly accounting for the seasonal-to-interannual
119 variability of the hydrological regime of the river discharge. It relies on a seamless
120 unstructured-grid numerical model extending from Óbidos down to the deep Atlantic
121 Ocean. Our objective is to document the characteristics of the tide all along the
122 Amazon estuary and across its timescales of variability from the high-low flow
123 seasonal cycle to the interannual anomalous hydrological events.

124 Section 2 presents the numerical modeling framework and the datasets we
125 use for the model validation. Section 3 is dedicated to the validation of the model. In
126 section 4, we present the seasonally-varying tidal characteristics of the Amazon
127 estuary. Section 5 investigates the case of the anomalous years, contrasting positive
128 and negative discharge extremes. A brief conclusion ends the paper (Section 6).

129

130 **2. Data and methods**

131 The study relies on a hydrodynamical modeling platform implemented over the
132 whole Amazon Estuary down to the adjoining Atlantic Ocean shelf and beyond, until
133 the Atlantic abyssal plain. For developing the model, we have used a state-of-the-art

134 bathymetric atlas of the region (Fassoni-Andrade et al., 2021). We hereafter detail
135 the salient features of the modeling tool, the bathymetric atlas, and the independent
136 datasets we used for model validation.

137 **2.1 Model**

138 The SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System)
139 model (Zhang et al., 2016) was used to simulate the tides and river flow of the
140 Amazon River along the estuary. SCHISM solves the 3D shallow-water equations
141 using finite-element and finite-volume schemes. It was designed to model barotropic
142 and baroclinic flows over a broad range of spatial scales, spanning from the deep
143 parts of the open ocean to very shallow estuaries and lagoons (e.g., Huang et al.,
144 2021; Khan, 2021; Khan et al., 2020). It comprises a wetting/drying scheme for the
145 shallow zones. The model was used in depth-averaged 2DH mode, similar to
146 previous studies of comparable tropical mega-delta regions conducted with this
147 model (e.g., Khan et al., 2020; Krien et al., 2016).

148 The model domain covers the 435 thousand km² from Óbidos to the ocean,
149 encompassing floodplains and intertidal zones. The ocean open boundary is limited
150 to tracks 024 and 215 of the Jason series satellite altimetry missions (Figure 1a).
151 Spaceborne altimetry allows to accurately estimate tidal constituents available
152 through the AVISO products (www.aviso.altimetry.fr/en/data/products/auxiliary-products/coastal-tide-xtrack.html). Aligning the model open boundaries along
153 altimetric tracks enables the imposition of the accurate tidal boundary conditions
154 observed there, following the strategy of Testut and Unnikrishnan (2016). The
155 altimetric tidal constituents along these tracks are indeed more accurate than in
156 state-of-the-art tidal atlases (Le Bars et al., 2010). Besides, a large domain extending
157 far from the Amazon mouths ensures that the shallow-water non-linear tidal
158 constituents can develop and propagate freely within the model interior domain
159 (Gallo and Vinzon, 2005). The tidal constituents considered at the boundary
160 conditions were M2, M3, M4, M6, Mf, Mm, MN4, MS4, MU2, N2, NU2, O1, P1, Q1,
161 R2, S1, S2, S4, SA, SSA, T2, Msf, K2, K1, J1, and 2N2. Inside the model domain,
162 the tidal potential of M2, S2, T2, Q1, P1, O1, NU2, N2, MU2, L2, K2, and K1
163 constituents is imposed.
164

165 A pre-defined flood mask limits the model domain over the continent, as
166 follows. The maximum water level was estimated following the methodology defined

167 in the study by Fassoni-Andrade et al. (2021). First, over the inner river, it was
168 estimated considering data from 2015 to 2018 at gauge stations. Then, over the
169 coastal region, it was estimated based on a proxy of the syzygy tidal amplitude
170 defined from the sum of M2 and S2 constituent amplitudes from the FES2014 tidal
171 atlas (Carrère et al., 2016). This estimated maximum water level was then increased
172 by 2 m for safety and interpolated by the nearest-neighbor method over the domain
173 of a Digital Elevation Model (DEM; described in the next section). Subsequently,
174 considering this maximum water level, the floodable/non-floodable pixels over the
175 whole DEM were identified to create a flood mask. Therefore, the model domain
176 consists of the area located up to 2 m above the maximum water level observed
177 during the 2015-2018 period (in the inner estuary) and up to 2 m above the maximal
178 tidal level (along the ocean shoreline).

179 The model was implemented on an unstructured mesh considering triangular
180 cells with a varying spatial resolution using SMS (Surface-water Modeling System)
181 software (© Aquaveo; Figure 1b). The elements' size was defined by a combination
182 of two geographic criteria, one based on the value of the local bathymetry and
183 another based on the strength of the bathymetry gradient, in a fashion similar to
184 Krien et al. (2016). This meshing strategy ensures a faithful representation of the
185 propagation of gravity waves both in shallow waters and in regions with higher
186 bottom slope. The minimum mesh elements size reaches 250 m, all along the bed of
187 the estuary. It amounts to about 400 m in the upstream floodplain region (Area 1 in
188 Figure 1a) and gradually increases offshore of the estuary mouths, up to 5000 m in
189 the deeper parts of the ocean (Area 2 in Figure 1a). In addition, the orientation of the
190 mesh cell faces on the riverbanks was imposed along the levees to better represent
191 the flow exchange between the river and the adjacent floodplains. Altogether, this
192 unstructured meshing strategy allows to represent the inundation satisfactorily in the
193 shallow areas of the upper floodplains (depth ~1m in low flow period) and also allows
194 to avoid unnecessary, costly mesh cells in the deep ocean. The mesh has 688'636
195 nodes and 1'362'336 elements in total.

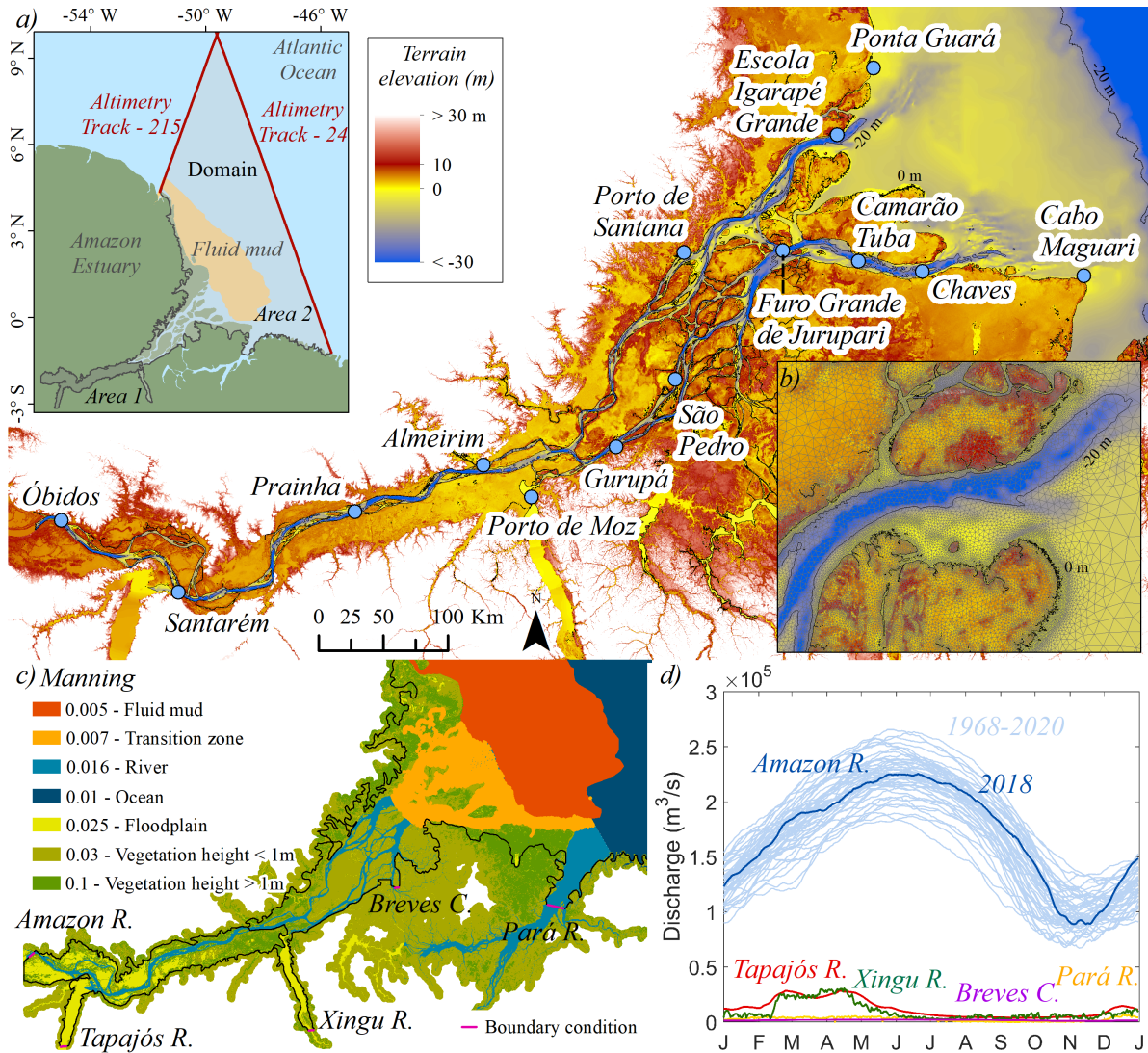
196 Friction was represented by a Manning's roughness coefficient based on the
197 classification of Bunya et al. (2010), according to the classes displayed on the map in
198 Figure 1c. Vegetation was classified according to height (greater and less than 1 m)
199 according to Global Forest Canopy Height (GED1, Potapov et al., 2021), which

200 represents the height of vegetation globally at 30 m resolution (Landsat; available at
201 www.glad.umd.edu/dataset/gedi). The water class on this map was classified into
202 river, floodplain, and ocean. The fluid mud extent off the mouths was considered
203 according to Gabioux et al. (2005). The Amazon River exports a large amount of
204 sediments to the ocean (1.1×10^9 tons per year; Armijos et al., 2020), and fluid mud
205 gets deposited in the shallow region situated in the vicinity of the mouths. It
206 contributes to reduced energy dissipation of the tide. Gabioux et al. (2005) showed
207 that not representing the mud in a hydrodynamic model of the region can drastically
208 underestimate the amplitude of M2 tide. By conducting a set of sensitivity
209 experiments of our model with or without this region of low friction (red area in Figure
210 1c), as well as with or without the transition zone upstream of it (orange area in
211 Figure 1c), we could confirm that the realism of the modeled tide improves
212 significantly when both these features are present in our modeling setup (not shown).

213 Discharges of the Amazon, Tapajós, Xingu, and Pará rivers were used as
214 boundary conditions in the model considering the year 2018 (Figure 1d). That year
215 can be considered as a roughly normal year in terms of runoff for the Amazon, which
216 is by far the main contributor to the freshwater delivered to the Atlantic Ocean. The
217 Amazon River discharge at Óbidos varies from $100'700 \text{ m}^3 \cdot \text{s}^{-1}$ to $225'210 \text{ m}^3 \cdot \text{s}^{-1}$
218 between November and May, with average annual values of $168'480 \text{ m}^3 \cdot \text{s}^{-1}$
219 (climatology between 1968 and 2020). Based on sparse in situ observations, it was
220 reported that about 1% of the Amazon River discharge flows through the Breves
221 Channel into the Pará River estuary (Callède et al., 2010). Therefore, the value of 1%
222 of the Amazon runoff imposed in our model was considered an outflowing boundary
223 condition through the Breves Channel (see location in Figure 1c). The discharges of
224 the Tapajós (Itaituba Station), Xingu (Belo Monte Station) and Pará (Tucuruí Station)
225 rivers were obtained by the Operador Nacional do Sistema Elétrico Nacional
226 ([www.ons.org.br/Paginas/resultados-da-operacao/historico-da-](http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/dados_hidrologicos_vazoes.aspx)
227 [operacao/dados_hidrologicos_vazoes.aspx](http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/dados_hidrologicos_vazoes.aspx)), and the Amazon River discharge from
228 Agência Nacional de Águas (ANA; Óbidos Station;
229 www.snirh.gov.br/hidroweb/serieshistoricas).

230 Thanks to its semi-implicit time-stepping combined with an Eulerian-
231 Lagrangian method to treat the momentum advection, the model allows for using
232 large time steps corresponding to CFL conditions well above unity, despite the

233 relatively high spatial resolution of the mesh (Zhang et al., 2016). We used in this
 234 study a 10 min timestep. We integrated the model from November 2013 to January
 235 2019, starting from rest. We discarded the first 3 months to allow for the initial spinup.
 236



237
 238 Figure 1. Bathymetry and topography of the study area and in situ stations with (a)
 239 the location of the model domain (black outline + altimetry tracks); (b) inset of the
 240 model mesh at the mouth of the Amazon; (c) Manning coefficient map; (d) Rivers
 241 discharges considered in the boundary conditions.

242
 243 **2.2 Data and processing**

244 We implemented the model on the bathymetric atlas of the region, described
 245 in Fassoni-Andrade et al. (2021; available in
 246 <https://data.mendeley.com/datasets/3g6b5ynrdb/2>), that represents the topography

247 of river, floodplain, riverbanks, and ocean at 30 m resolution with accuracy of 7.2 m
248 (riverbed) and 1.2 m (non-vegetated intertidal floodplains). The information is derived
249 from a synthesis of global databases such as MERIT DEM ([http://hydro.iis.u-](http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_DEM/)
250 [tokyo.ac.jp/~yamada/MERIT_DEM/](http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_DEM/); Yamazaki et al., 2017), GEBCO
251 (<https://www.gebco.net/>) and local estimates of the river and floodplains depth.

252 Fassoni-Andrade et al. (2021) reported a bias of the elevation in seasonally-
253 flooded areas of the bathymetric atlas (e.g., floodplains and river banks), which
254 magnitude increases with decreasing flood frequency, i.e., higher areas have a larger
255 error. To simply correct this bias, a linear fit between the bias and the flood frequency
256 (*FF*) was considered in the areas with flood frequency between 0 and 78.85%
257 following the equation:

$$258 \quad \textit{bias} = -0.03769 * FF + 2.972 \quad (1)$$

259 The biases observed along 6 in situ cross-sections of the Amazon River, with
260 values ranging from 0.58 m to 11.68 m (Fassoni-Andrade et al., 2021), were also
261 accounted for to correct the river bathymetry, which was achieved through linear
262 interpolation of the observed biases between each pair of cross-sections. The
263 resulting bathymetry and topography are shown in Figure 1.

264 In such a geographical context, where complex geometry implies strong
265 spatial variability of the tides, special care must be devoted to validating the modeled
266 tide. This validation was based on a set of in situ water level records of several
267 stations that we could access along the estuary course. The gauge records originate
268 from Agência Nacional das Águas of Brazil, from the Brazilian Navy, from the
269 brazilian Instituto Brasileiro de Geografia e Estatística (IBGE) and from the french
270 Institut de Recherche pour le Développement (IRD; Alain Laraque, personal
271 communication). The water level records were vertically referenced to EGM08 geoid
272 height, based on the leveling procedure explained in Fassoni-Andrade et al. (2021).
273 Additionally, we collected a tidal record from the São Pedro station in a field
274 campaign. In total, 14 gauging stations could be considered. Table 1 shows the
275 characteristics of these water level records used in validation (locations are displayed
276 in Figure 1), the list of the main tidal constituents considered in the harmonic analysis,
277 and the period we could analyze, contrasting low and high flow seasons. The
278 harmonic analysis was performed using the COMODO-toolbox (Allain, 2016), equally

279 for the modeled and observed water level records considering a 32-day window,
 280 which allows analyzing the constituents M2, S2, M4, Mm, and MSf, known as the
 281 dominant ones over our area (Gallo and Vinzon, 2005). For some stations, however,
 282 the observational record was shorter, which did not allow to analyze MSf, nor to
 283 document the low vs high flow seasons (these stations are mostly located in the
 284 downstream-most region of the estuary, see Table 1).

285 The error of the model tide was computed as the modulus of the complex
 286 difference for the constituents M2, S2, Mm, and M4 for each station, following the
 287 method used in Krien et al. (2016):

288

$$|\Delta z| = |A_m e^{i\theta_m} - A_o e^{i\theta_o}|$$

289

290 where A and θ are the amplitude and phase, respectively, of the tidal harmonic for
 291 the model (m) and the observation (o). Following Andersen et al. (1995), the total
 292 complex error at a given station is:

$$\sigma = \sqrt{\frac{1}{2} \sum_{M2, S2, M4, Mm} |\Delta z|^2}$$

293

294 Table 1. List of tide gauge records available. The relative distance is expressed in km
 295 downstream from Óbidos (for the stations located along the main course of the
 296 Amazon and the northern channel of the delta) or from Porto-de-Moz (for the stations
 297 located along the southern channel of the delta).

Station	Position	Data source	Relative distance (km)	Location	Constituents	Period analyzed	
						Low flow	High flow
Óbidos	55.51816°W 1.91866°S	ANA	0.00	Amazon R.	M2, S2, M4, Mm, Msf	Oct 2018	May 2018
Santarém	54.725°W 2.41667°S	ANA	115.83	Amazon R.	M2, S2, M4, Mm, Msf	Oct 2018	May 2018
Praíha	50.48055°W 1.80917°S	IRD	284.91	Amazon R.	M2, S2, M4, Mm, Msf	Sep 2000	May 2000
Almeirim	52.5769°W	ANA	397.08	Amazon R.	M2, S2, M4,	Oct	Junho

	1.53317°S				Mm, Msf	2018	2018
Porto de Santana	51.16774°W 0.06135°S	IBGE	672.34	North C.	M2, S2, M4, Mm, Msf	Oct 2017	May 2017
Escola Igarapé Grande	50.11536°W 0.761667°N	Brazilian Navy	827.11	North C.	M2, S2, M4, Mm, Msf	Oct 2018	May 2018
Ponta Guar	49.883333° W 1.216667°N	Brazilian Navy	892.11	Coast	M2, S2, M4, Mm	April 1970	
Porto de Moz	51.241175° W 1.753283°S	IRD	0.00	South C.	M2, S2, M4, Mm, Msf	Nov 2000	May 2000
Gurup	51.65090°W 1.40794°S	IRD	73.56	South C.	M2, S2, M4, Mm, Msf	Sep 2000	May 2000
So Pedro	0°56'24"S, 51°14'57"W	This study	157.63	South C.	M2, S2, M4, Mm	May 2020	
Furo Grande de Jurupari	50.58500°W 0.02666°S	Brazilian Navy	291.90	South C.	M2, S2, M4, Mm	April 2008	
Camaro Tuba	49.51987°W 0.23006°S	Brazilian Navy	355.14	South C.	M2, S2, M4, Mm	April 2008	
Chaves	49.98383°W 0.16640°S	Brazilian Navy	405.06	South C.	M2, S2, M4, Mm	July 1966	
Cabo Maguari	48.41662°W, 0.25298°S	Brazilian Navy	535.06	Coast	M2, S2, M4, Mm	April 2008	

298

299 **3. Model validation and limitations**

300 Over such a long and flat estuary (< 1.5 cm/km; Birkett et al., 2002) the tidal
301 propagation results from a delicate balance between various factors, in particular the
302 geometry of the river bed, its elevation profile with respect to the geoid, the spatial
303 structure of the bottom roughness, and the intensity of the residual river flow (eg.,
304 Gabioux et al., 2005; Gallo and Vinzon, 2005; Le Bars et al., 2010). To make sure
305 that we do not have prominent error compensations among these various factors in
306 the modeled tide, we present the following two-steps validation strategy: we first
307 validate the tidal amplitudes and phases along the estuary, then we validate the
308 mean (in a sense: tide-free) water slope. For the observations, the mean water level
309 is referenced to the EGM08 geoid model (Fassoni-Andrade et al., 2021). The model-
310 data tidal comparison is made separately during the low flow and the high flow

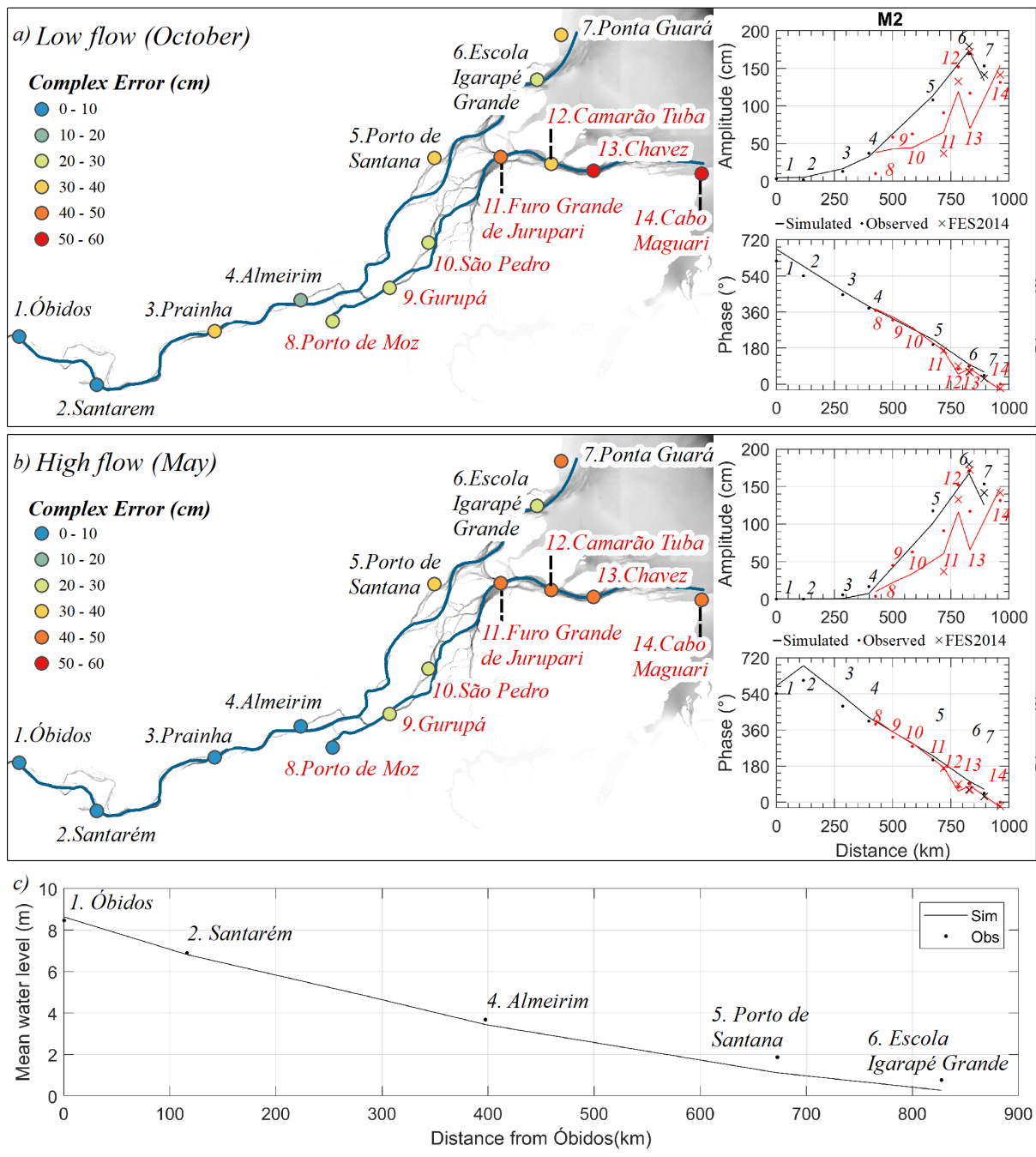
311 seasons, as the tidal dynamics of the estuary are known to be markedly different in
312 these two seasons (Gallo and Vinzon, 2005; Kosuth et al., 2009).

313 In line with the previous studies (e.g., Durand et al., 2022; Gallo and Vinzon,
314 2005; Ruault et al., 2020), we observed that M2 is the dominant tidal constituent at
315 the mouths of the Amazon. Figure 2 shows the complex error of the modeled tide
316 (considering M2, S2, M4, and Mm) at the stations for the low flow period (October)
317 and high flow period (May) as well as the observed and simulated M2 amplitude and
318 phase in these two periods. In addition, for the stations located downstream of
319 750km from Óbidos (stations 6, 7, 11, 12, 13, 14), the FES2014 atlas (Carrère et al.,
320 2016) is also presented (as these stations lie within FES2014 domain). Amplitudes
321 and phases of the remaining dominant constituents (S2, M4, MSf, and Mm) can be
322 seen in Table A.1 and Table A.2 (Appendix), as well as the values of the
323 corresponding complex error Table A.3 (Appendix).

324 Overall, the model represents the amplitude and phase of the main tidal
325 constituents well, with an average complex error of 16 cm in low flow and 23 cm in
326 high flow period. The complex error is lower for most stations in the high flow period
327 (May), when the Amazon River discharge is higher than in the low flow period
328 (October), especially at the Prainha station. Note that the observational record at this
329 station was of September 2000 (Table 1) when the Amazon River discharge was
330 higher than in October 2018 (period of the model simulation). The model's realism
331 appears roughly comparable with that of the global FES2014 atlas, both for
332 amplitude and phase of M2, over the downstream-most part of the estuary (Figure 2).

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Figure 2. The total complex error along the path of the rivers for the 14 stations is shown on the map with associated color scale. On the right panel M2 amplitude and phase observed and simulated during a) low flow season (October) and b) high flow season (May). Black lines and black symbols represent the reach between Óbidos and Escola Igarapé Grande (through the Northern Channel downstream of Almeirim); red lines and red symbols represent the reach between Porto de Moz and Cabo Maguari, through the Southern Channel. The solid lines represent the model, the dots represent the observed values, and the crosses represent the FES2014 tidal atlas (which covers only the delta's downstream-most part). c) Mean annual water

345 level relative to geoid along the river, for the model (solid) and the observations (dots;
346 referenced to EGM08 geoid model).

347 The tidal amplitude for the M2 constituent at the mouth is 2 m. Due to the
348 weak slope of the terrain all along the estuary, during the low-flow period, the tide
349 propagates over 800 km upstream, up to Óbidos (and even slightly beyond in our
350 model), with typical observed tidal amplitudes of M2 amounting to about 3 cm there.
351 Overall, the phase of M2 along the estuary spans practically two cycles so that the
352 tide takes a bit less than one day to reach Óbidos. In other words, at any given time,
353 the Amazon estuary holds two successive semi-diurnal tidal waves, from its mouth to
354 Óbidos (note that the y-axis for the phase of M2 on Figure 2 goes up to 720°).

355 The M2 amplitude in the Northern Channel (black lines and dots in Figure 2)
356 appears better represented than in the Southern Channel (red lines and dots in
357 Figure 2), where larger underestimations are seen. Consistently with what was
358 known from past observational records, the observed M2 amplitude gets divided by a
359 factor of two after traveling around 500-600 km within the estuary in the low flow
360 season; during the high flow season, it gets a similar attenuation after traveling
361 around 350-400 km. Locally, we observe biases in M2 amplitude that can get as
362 strong as 50 cm at some of the coastal gauging stations where the records are
363 ancient (typically 50 years old or so; see, for instance, Chaves and Ponta Guara
364 records) and, as such, could have been affected by long-term changes of the tidal
365 characteristics resulting from morphological changes over the intervening period.
366 However, for the present study focused on the inner Amazon estuary, the bias in the
367 modeled M2 amplitude at the entrance of the estuarine system in Porto de Santana
368 is relatively weaker (17 cm or 17% in high flow season, 7 cm or 6% in low flow
369 season). Further upstream, the error in M2 amplitude further decays, along with the
370 decay of the tidal amplitude itself, in both seasons.

371 The phase of the M2 wave also appears satisfactorily represented by the
372 model. Both the observations and the model feature a roughly linear phase increase
373 from the mouth towards upstream, indicating a roughly constant phase speed of the
374 tidal wave in the propagation course. However, the modeled phase of M2 appears a
375 bit overestimated by the model, i.e., the phase speed of the tide is slightly too slow
376 along the river. At Porto de Santana, the error is 22° in the high flow period (45
377 minutes) and 28° in the low flow period (57 minutes). At Óbidos, the delay is 40°

378 (1h20min) and 45° (1h30min) during the high and low flow seasons, respectively. For
379 reference, Gallo and Vinzon (2005) also found low errors of the M2 amplitude (even
380 lower than ours, typically of 5-10 cm), but no information was provided about the tidal
381 phase nor its error. On the other hand, Le Bars et al. (2010) found phase errors
382 ranging from 60° (about 2 h) to 150° (about 5 h) in the downstream and central parts
383 of the estuary.

384 The simulated and observed mean water level profiles along the river
385 computed throughout 2018 are presented in Figure 2c. In Óbidos, the mean water
386 level amounts to slightly more than 8 m above the geoid. The observed mean water
387 level shows a slope of about 1 cm/km, slightly decreasing downstream, which is
388 satisfactorily captured by the model. The typical model error amounts to 15 cm from
389 Óbidos to Almeirim, and 50 cm at the mouth of the northern channel (Escola do
390 Igarapé Grande – station 6), where the mean water level gets close to geoid height.
391 We observe the most substantial bias of the model mean water level in Porto de
392 Santana (station 5), where it amounts to 75 cm.

393 There are several limitations in our modeling framework. First, we remind that
394 our model is two-dimensional. This implies that the parameterization of the bottom
395 friction in regions of extremely fine sediments such as the fluid mud layers reported in
396 the near-shore ocean off the mouths of the terminal delta may be better represented
397 in a three-dimensional modeling framework representing the dynamics of fine
398 sediments (Molinas et al., 2020). Although unprecedented at the scale of this mega-
399 estuary, the horizontal resolution of our model mesh may also benefit from further
400 refinement, particularly in the very shallow seasonally-flooded floodplains located on
401 both sides, along the main course of the estuary. Obviously, although the greatest
402 care was devoted to the assembly of our bathymetric atlas, it is also subject to biases,
403 in this highly dynamic and coarsely monitored sedimentary environment (Fassoni-
404 Andrade et al., 2021). Finally, the accuracy and consistency of the rivers discharge
405 estimates available for our model upstream boundary conditions are also subject to
406 debate.

407 This said, thanks to a novel comprehensive bathymetry-topography dataset,
408 and to an unstructured-grid high-resolution modeling system, we obtained an overall
409 acceptable simulation of the mean water line as well as of the tide across the
410 Amazon estuary. The typical error of our modeling appears in line with the

411 performances obtained in other poorly-observed, tropical mega-deltas, where the
412 issue of poorly known bathymetry is common (see, e.g., Elahi et al., 2020; Eslami et
413 al., 2019; Khan et al., 2020). The level of consistency achieved by our model with
414 regards to the in situ records allows us to investigate confidently the temporal
415 variability of the tidal characteristics all along the course of the estuary, over a broad
416 range of temporal scales from seasonal to interannual.

417

418 **4. Seasonal variability of the tide along the Amazon estuary**

419 As we saw in the introduction, the historical observations revealed a prominent
420 modulation of the tidal range along the Amazon estuary, along the course of the high-
421 low flow annual cycle (Kosuth et al., 2009). Essentially, a tidal wave propagating
422 inside an estuary can be seen as a damped shallow-water gravity wave traveling
423 through a counter-current. In the Amazon estuary, just like in most high-discharge
424 estuaries, two key parameters vary jointly during the annual cycle that are bound to
425 condition the characteristics of the propagation of a tidal wave: the mean water level
426 and the residual flow velocity. During the high flow season, the water level is higher
427 and the flow velocity is larger than during the low flow season (Callède et al., 1996).
428 Through the shoaling effect, a higher water level will favor a lower tidal amplitude so
429 as to ensure wave energy flux conservation. Conversely, a higher water level will
430 induce a reduced bottom friction, which in turn decreases tidal dissipation. In the
431 particular case of an estuary bordered by vast floodplains such as the Amazon, a
432 higher water level is also prone to induce prominent flooding of extended intertidal
433 flats, which can act as a sink of tidal wave energy through bottom friction. As for the
434 river flow velocity, the theory predicts that it increases the damping of the incoming
435 tidal waves through frictional effects at the bottom, with a magnitude of the damping
436 force scaling roughly linearly with the magnitude of the residual river flow velocity
437 (e.g., Godin, 1999). These various processes altogether contribute to shape up the
438 seasonal modulation of the tide in the Amazon. Several studies have been based on
439 idealized and/or analytical models developed to infer the sensitivity of tidal
440 characteristics to estuarine hydrodynamical conditions (e.g., Du et al., 2018; Talke
441 and Jay, 2020, and the numerous references therein). However, it is challenging to
442 infer what will be the resulting impact of the seasonally-varying hydraulic regime on
443 the tide for an estuary with such a complex geometry as the Amazon. Indeed, the

444 idealized models typically assume regular cross-section geometry (Du et al., 2018)
445 and/or linearized hydrodynamics (Talke and Jay, 2020). Our numerical model, as it
446 explicitly accounts for all the processes mentioned above and their interactions,
447 offers an unprecedented opportunity to investigate the seasonal modulation of the
448 tidal characteristics.

449

450 **4.1 Tidal influence along the estuary**

451 The water level evolution at Óbidos, Almeirim, and Escola do Igarapé Grande
452 stations are presented in Figure 3, along with the water level profile along the river
453 and its tidal envelope computed separately for the high flow period (May 2018) and
454 the low flow period (October 2018). The tidal envelope is here again defined as the
455 syzygy amplitude, and a proxy of it was computed in the classical way from the sum
456 of S2 and M2 amplitudes (Pugh and Woodworth, 2014), as these constituents are the
457 main contributing components of the tide in our region.

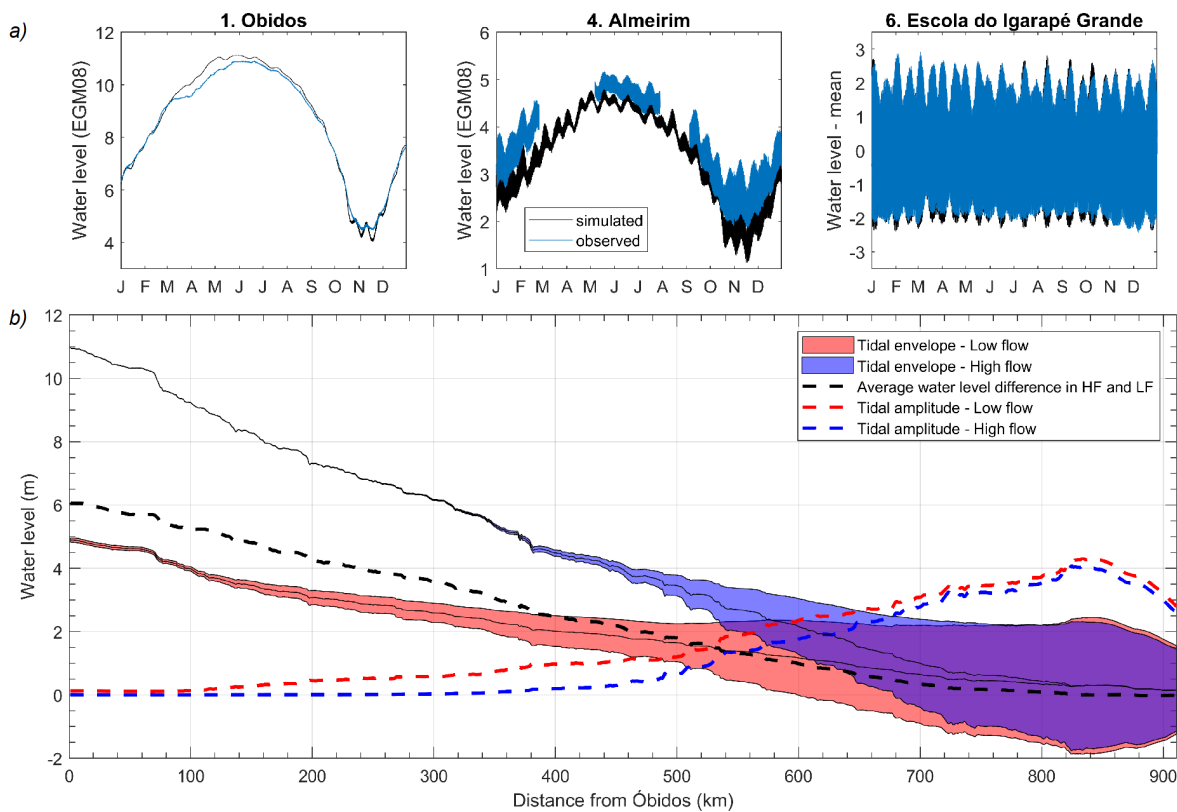
458 While the seasonal pulse of the river flow induces annually a 6 m change in
459 water level at Óbidos, this pulse decays downstream down to negligible values at the
460 mouth (Figure 3). Conversely, the tidal amplitude amounts to 3 m at the mouth in
461 Escola do Igarapé Grande, it decays upstream inside the estuary, with a tidal
462 amplitude two orders of magnitude inferior in Óbidos. Hence the intermediate part of
463 the estuary lies under the combined influence of both forcing factors. For instance, in
464 Almeirim, located 397 km downstream of Óbidos in the middle reach of the estuary,
465 the annual variation in water level due to the Amazon discharge is 4 m while the tidal
466 range varies from 40 cm (May) to 90 cm (October) (Figure 3).

467 Figure 3b shows that the semi-diurnal tide is highly variable at seasonal
468 timescales across the Amazon estuary. The reduction and increase of the Amazon
469 River discharge cause an increase and reduction of the tidal amplitude, respectively.
470 This variability implies that the extent of the tidal influence is itself highly variable
471 along the seasonal cycle. It is seen that in high flow, the upstream limit of the tidal
472 part of the estuary lies around 300 km from Óbidos; further upstream, the tidal
473 signature virtually disappears. In contrast, in the low flow season, this limit is shifted
474 towards upstream, up to Óbidos, where the open boundary of our model domain sits.
475 Around 535 km from Óbidos, the range of the seasonal variability of the water level is

476 similar to the tidal range. Upstream of this limit, the water level variability is
 477 dominated by the annual hydrologic cycle, whereas downstream of it, it is dominated
 478 by the tide. Figure 4 shows that, at a given distance upstream of the mouth, the
 479 mean water level is quite alike among the various tributaries of the delta, so that it
 480 can be largely seen as primarily dependent on the distance from the mouth. It is seen
 481 that the mean slope of the water line is not constant, as it is steeper over the
 482 upstream part of the estuary. This reflects the complex, spatially variable geometry of
 483 the riverbed from upstream to downstream (Fricke et al., 2019; Fassoni-Andrade et
 484 al., 2021).

485

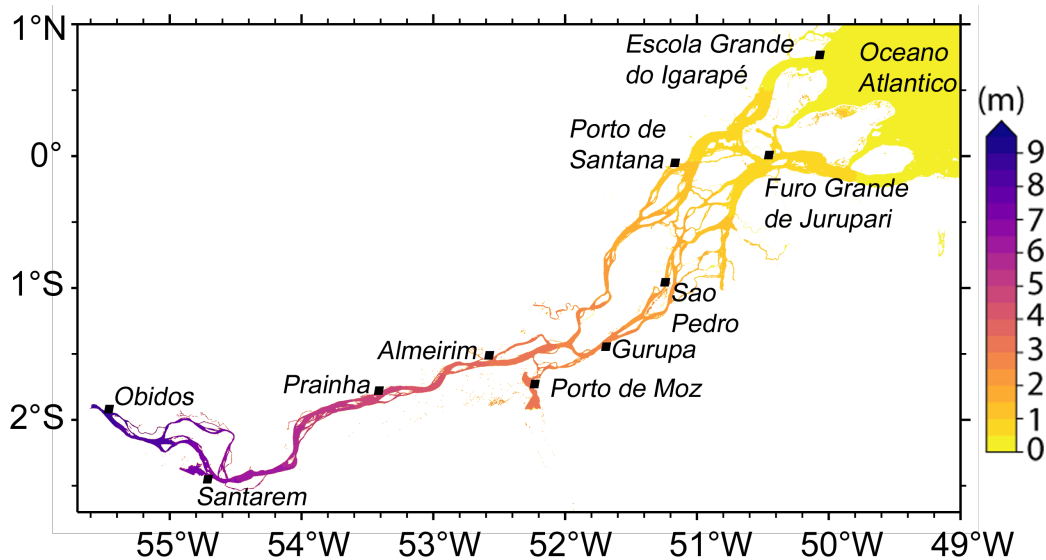
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487

488 Figure 3. a) Evolution of the simulated and observed water level in Óbidos, Almeirim,
 489 and Escola Igarapé Grande over 2018; b) Simulated mean water level and tidal
 490 envelope along the Amazon River during May 2018 (high flow) and October 2018
 491 (low flow).

492



493

494 Figure 4. Simulated mean water level over 2018.

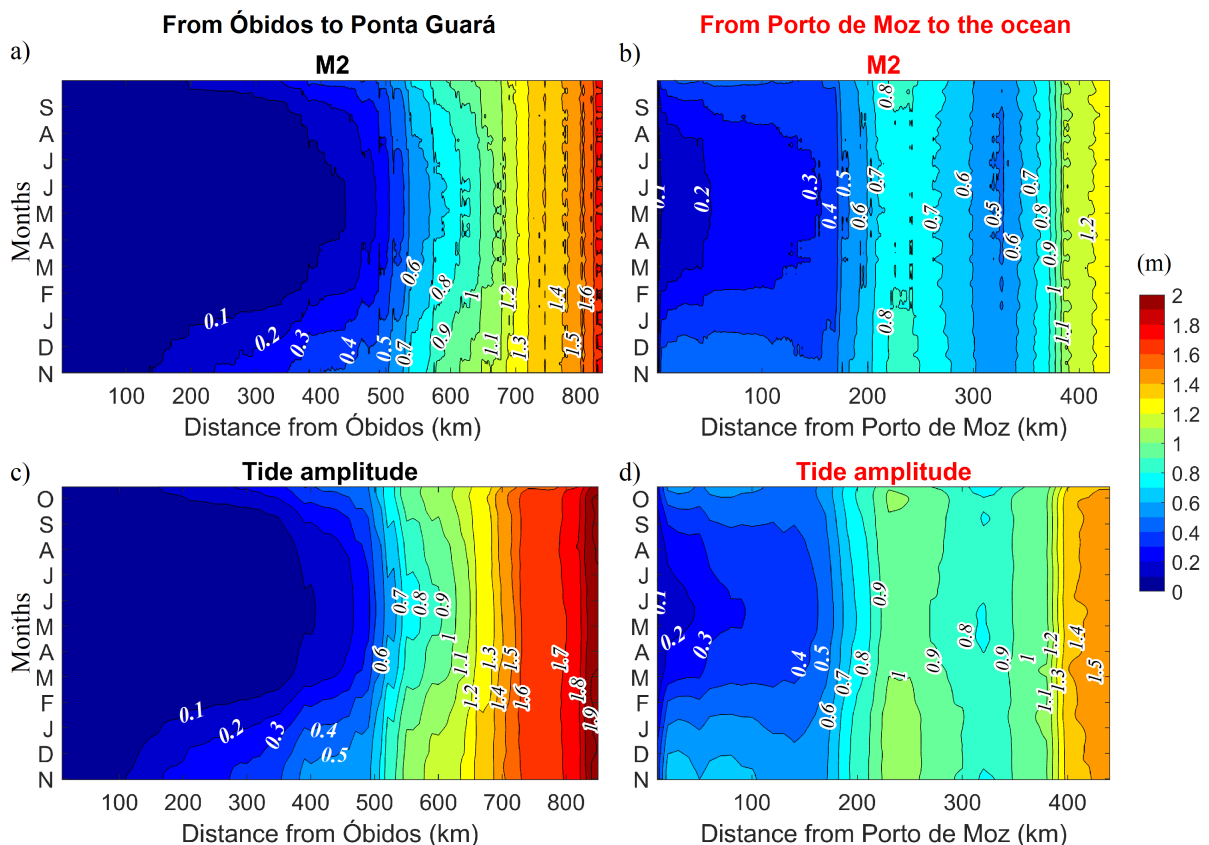
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496 **4.2 Tide amplitude**

497 Figure 5 shows the seasonal evolution of M2 constituent and the tidal
 498 amplitude obtained along the river for 2018. The tidal amplitude in the reach between
 499 Óbidos and Porto de Santana (station 5) is prominently influenced by the Amazon
 500 River variability, with higher tidal amplitude during the low flow season (Oct/Nov) and
 501 conversely lower tidal amplitude during the high flow season (May/Jun). There does
 502 not appear to be any appreciable time lag between the variability of the tidal
 503 amplitude and the river discharge or river stage, which reveals the dominant role of
 504 three combined effects, among the various processes listed above: interaction
 505 between tide and river flow, interaction between tide and floodplains, and shoaling
 506 effect on the tidal waves. First, during the high flow season, over a given reach, the
 507 tidal wave propagates against a stronger counter-current, which induces a larger
 508 energy dissipation through bottom friction in the course of the propagation (Godin,
 509 1999). Second, during the high flow season the river largely extends over the
 510 adjoining shallow floodplains, inducing additional sinks of energy of the tidal waves
 511 through bottom friction. Third, the linear shoaling effect may also contribute to
 512 reduced tidal amplitude when the water column is thicker. However, assessing the
 513 respective role of each of these three processes is beyond our scope.

514 The seasonal range of modulation of the tide is higher in the upstream reach.
 515 For example, considering the 20 cm isoline, the tidal amplitude gets shifted
 516 downstream by 290 km between November and May (Figure 5c). This variability
 517 reduces to the location where the Amazon River discharge no longer significantly
 518 influences the tidal amplitude (~700 km from Óbidos). This behavior implies that the
 519 frequent floods reported in Macapá (e.g., Mansur et al., 2016), the capital city of
 520 Amapá state located ~720 km from Óbidos nearby Porto de Santana (Figure 1) may
 521 not be related to the river floods, but rather to the tide and/or other oceanic influences.
 522 It is seen that the total tidal amplitude consistently presents a spatio-temporal pattern
 523 very similar to the sole M2 amplitude, M2 typically amounting to about 80% of the
 524 tidal range in the lower part of the Amazon. In the central part, the relative share of
 525 M2 decreases to about 60-70%. This is in line with the known dominance of M2 in
 526 the lower estuary, and its subsequent decay further upstream where M4 constituent
 527 picks up (Table A1; Gallo and Vinzon, 2005).

528



529

530 Figure 5. Tidal amplitude variability along the river in 2018. In (a) and (b), the
 531 amplitude of M2 (the dominant tidal constituent) is shown. In (c) and (d), the tidal
 532 amplitude is defined as the difference between daily maximum level and daily

533 minimum level (in a 25-hr moving window), subsequently low-pass-filtered with 28-
534 day cutoff period to discard the spring-neap cycle that does not form our focus. The
535 left plots correspond to the reach between Óbidos and the ocean, and the right plots
536 to the stretch between Porto de Moz and the ocean.

537

538 The amplitude of M2 monotonically decays in the Northern channel (Figure 5a
539 and c). In contrast, in the Southern channel, a second section appears, between 220
540 km and 310 km from Porto de Moz, where the amplitude of M2 increases again
541 (Figure 5b). This pattern is also seen in the total tidal amplitude (Figure 5d). This
542 reach comprises the Breves Channel confluence, connecting the Amazon River to
543 the Para-Tocantins estuary (Figure 1). Since we have no observations in this region,
544 it is not possible to confirm the realism of this tidal amplitude pattern. In addition, we
545 remind that we impose an outflowing boundary condition through the Breves Channel,
546 amounting to 1% of the Amazon discharge injected at Óbidos at any time. The
547 seasonal pattern of this boundary condition is the same as in Óbidos (minimum in
548 October and maximum in May). In the absence of any temporal record of this
549 throughflow (apart from the minimal data of Callède et al., 2010), the accuracy of this
550 boundary condition is also questionable. In our model, however, this Breves Channel
551 is subject to the tidal resonance of the semi-diurnal constituents, with an amplification
552 of 25% of M2 amplitude, for instance, between the entrance and the head of the
553 channel (not shown). This resonance of semi-diurnal constituents is consistent with
554 the 30% amplification foreseen by the idealized model of Talke and Jay (2020), given
555 the geometry of this channel. In turn, this resonance appears to induce leakage of
556 tidal energy in the confluence of the Breves Channel and the Southern Channel of
557 the Amazon, hereby inducing this secondary maximum located 220 km downstream
558 of Porto de Moz in our model (Figure 5b and d). To confirm the realism of this feature,
559 it would require assessing the water flow through the Breves Channel and the profile
560 of tidal amplitude along its course.

561

562 **4.3 Tidal wave celerity**

563 The upstream propagation of the tidal wave along the estuary is expected to
564 show a variable phase speed, depending on the seasonal variability of river level and

	7.Ponta Guar	6.Escola Igarap Grande	65.00	1.38	1.32	13.05	13.69	4.67
	7.Ponta Guar	4.Almeirim	495.03	12.31	11.25	11.17	12.22	8.59
From Porto de Moz to the ocean	9.Gurup	8.Porto de Moz	73.56	2.05	1.37	9.98	14.96	33.30
	10.So Pedro	9.Gurup	84.07	1.97	1.89	11.87	12.34	3.81
	11.Furo Grande de Jurupari	10.So Pedro	134.27	4.13	3.88	9.02	9.60	6.00
	12.Camaro Tuba	11.Furo Grande de Jurupari	63.24	4.13	4.03	4.25	4.36	2.47
	13.Chaves	12.Camaro Tuba	49.93	-0.95	-0.98	-14.56	-14.18	-2.70
	14.Cabo Maguari	13.Chaves	130.00	3.65	3.67	9.88	9.84	-0.36
	14.Cabo Maguari	8.Porto de Moz	535.07	14.98	13.86	9.92	10.72	7.47

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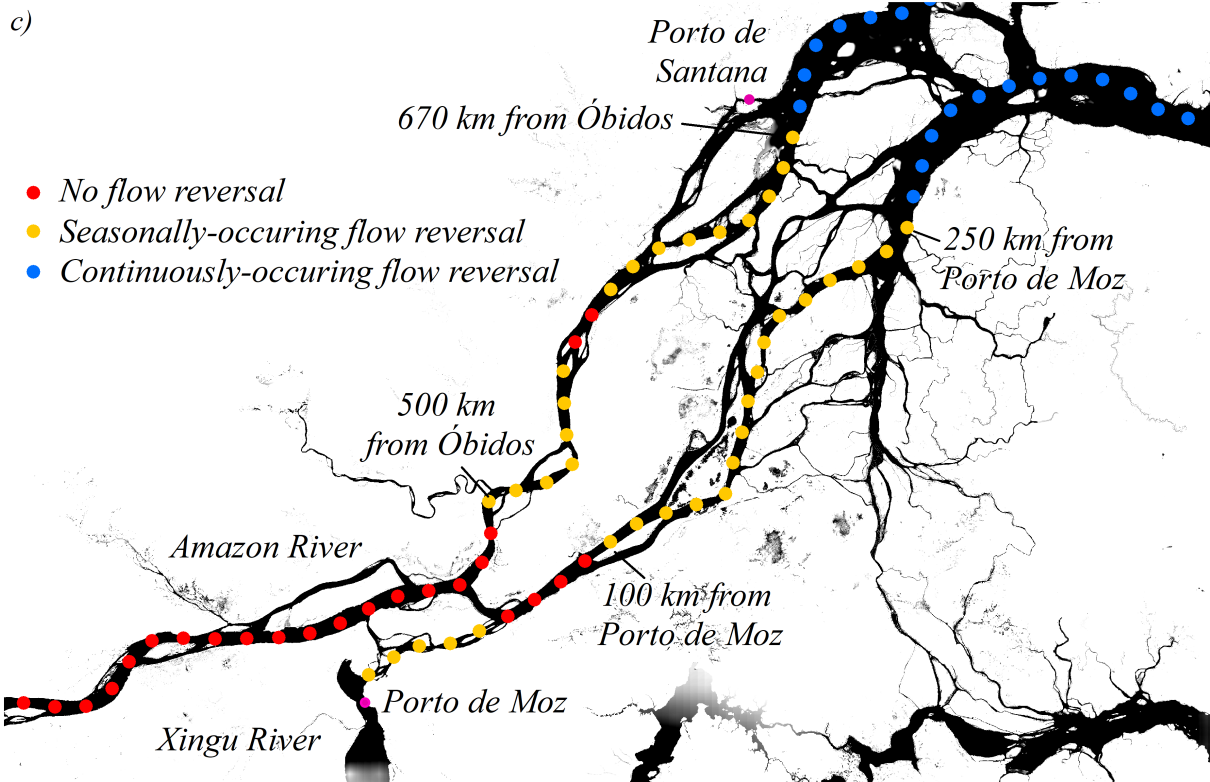
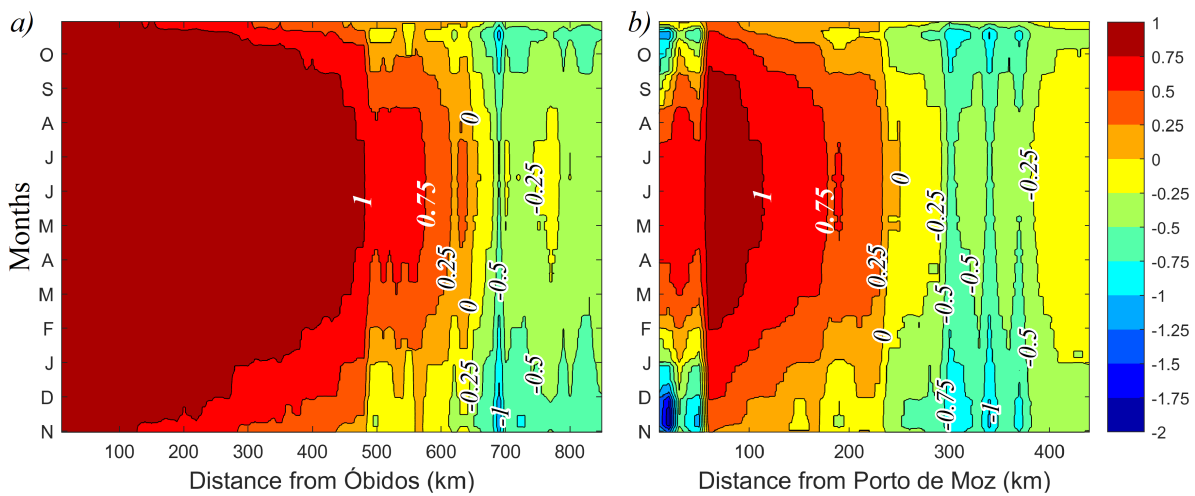
591 **4.4 Water flow reversal**

592 In the coastal ocean, a commonly known feature of the tide is the complete
593 reversal of the tidal flow between the rising tide and the falling tide (e.g., Pugh and
594 Woodworth, 2014). The picture is more complex in estuaries, as the tidal current is
595 superimposed on (and interacts with) the background river flow. Close to the Amazon
596 estuary mouth, where the river arms are typically broad and the semi-diurnal tide is
597 powerful, the tidal influence remains prominent on the flow, with consistent reversals
598 occurring twice daily throughout the seasonal cycle (Less et al., 2021). In contrast, in
599 the upstream part of the estuary, it can be expected that the tidal velocities are
600 overwhelmed by the background river velocity so that no reversal ever occurs
601 (Callede et al., 1996). As Kosuth et al. (2009) reported from a limited set of cross-
602 sectional ADCP surveys, the observed pattern of water flow along a tidal cycle is
603 highly dependent on the location considered along the Amazon estuary: whereas a
604 flow reversal is common in the downstream part of the estuary during the rising tide,
605 it is not always so in its intermediate portion (typically in the region of the confluence
606 at the beginning of the deltaic region, 500 km downstream of obidos), and it was
607 never observed some 100 km further upstream, around Almeirim (station 4). There,

608 they reported that the river flow velocity decreases during the rising tide, but not
609 enough to get reversed. The location of the boundary between the two regimes
610 (always flow towards downstream vs. flow alternately towards upstream and towards
611 downstream during the tidal cycle) and its displacements along the seasonal cycle
612 are unknown due to the limited number of current-meter sections existing in the
613 observational records. The knowledge of this boundary bears some relevance, for
614 the understanding of the sediment dynamics in the estuary, for characterization of the
615 spatial dynamics of the ecosystems of the area (such as transports of fish larvae), for
616 the understanding of the biogeochemistry, or more generally of the chemical cycles
617 in the water body, and more basically for navigation-related issues.

618 We analyzed this regime boundary by computing the ratio between the daily
619 maximum along-channel velocity at ebb and at flood. Such a ratio means that
620 wherever negative values are seen, flow inversion occurs; conversely, positive
621 values mean that the flow is consistently downstream across the tidal cycle. The ratio
622 magnitude indicates the residual flow dominance over the tidal flow. Figure 6a and b
623 display the ratio, after applying a 28-day moving average, and Figure 6c shows the
624 portion of the estuary subject to at least one current reversal occurring over a 28-day
625 tidal cycle. It is seen that the location of this regime shift (seen as the null isocontour)
626 lies around 500 km downstream of Óbidos on average (Figure 6a), consistently with
627 the observations reported by Kosuth et al. (2009). However, this boundary gets
628 markedly displaced between the high flow season and the low flow season, with
629 extreme positions some 500 km and 670 km downstream of Óbidos (almost in Porto
630 de Santana – station 5) during the low flow season and the high flow season,
631 respectively. A similar spatio-temporal pattern of the boundary of the velocity regime
632 is seen in the southern channel, with a flow reversal boundary shifting from 100 km
633 downstream of Porto de Moz during the low-flow season to 250 km from Porto de
634 Moz during the high flow season (Figure 6b). These displacements result from the
635 combined effect of stronger residual flow velocity of the Amazon River and weaker
636 tidal current during the high flow season at any given location along the estuary. The
637 reach located in the Xingu River, upstream of the confluence of Xingu River and the
638 Amazon (~50 km in length, from Porto de Moz), also experiences an extended flow
639 inversion period from July to February (Figure 6b), probably related to the
640 consistently weak Xingu River discharge (Figure 1) combined with the relatively

641 strong tide arriving there from the Amazon. A couple of isolated red dots (viz. no flow
 642 reversal) are seen within the stretch of seasonally-occurring flow reversal in the
 643 Northern channel, around 575km from Óbidos. These are related to the localized
 644 pattern of velocity ratio seen at this location in Figure 6a, that remains positive there,
 645 even during the peak low flow season in November-December. This feature is related
 646 to the local change in the river geometry, where a reduced cross-section induces an
 647 increased residual flow velocity of the river. However, the velocity ratio reaches
 648 values very close to zero in the low flow season there, so that the large-scale pattern
 649 we pictured from upstream to downstream of the estuary remains valid.



651 Figure 6. Space-time structure of the regime of the tidal flow reversal (ratio between
652 the daily maximum velocity at ebb and flood) of the Amazon estuary for (a) the
653 Northern channel and (b) the Southern channel. In yellow are the regions where the
654 flow is consistently towards downstream, whereas in blue are the regions where the
655 flow reverses towards upstream at least once during a 28-day tidal cycle. (c) Map of
656 the tidal flow regimes of the Amazon estuary. The locations where the river flow
657 reverses at least once over a 28-day tidal cycle are displayed in blue bullets (when
658 this occurs year-round) and yellow bullets (when this happens in some seasons only).
659 The locations where this reversal of the river flow never occurs are in red bullets.

660

661 **5. Characteristics of the tide during extreme years**

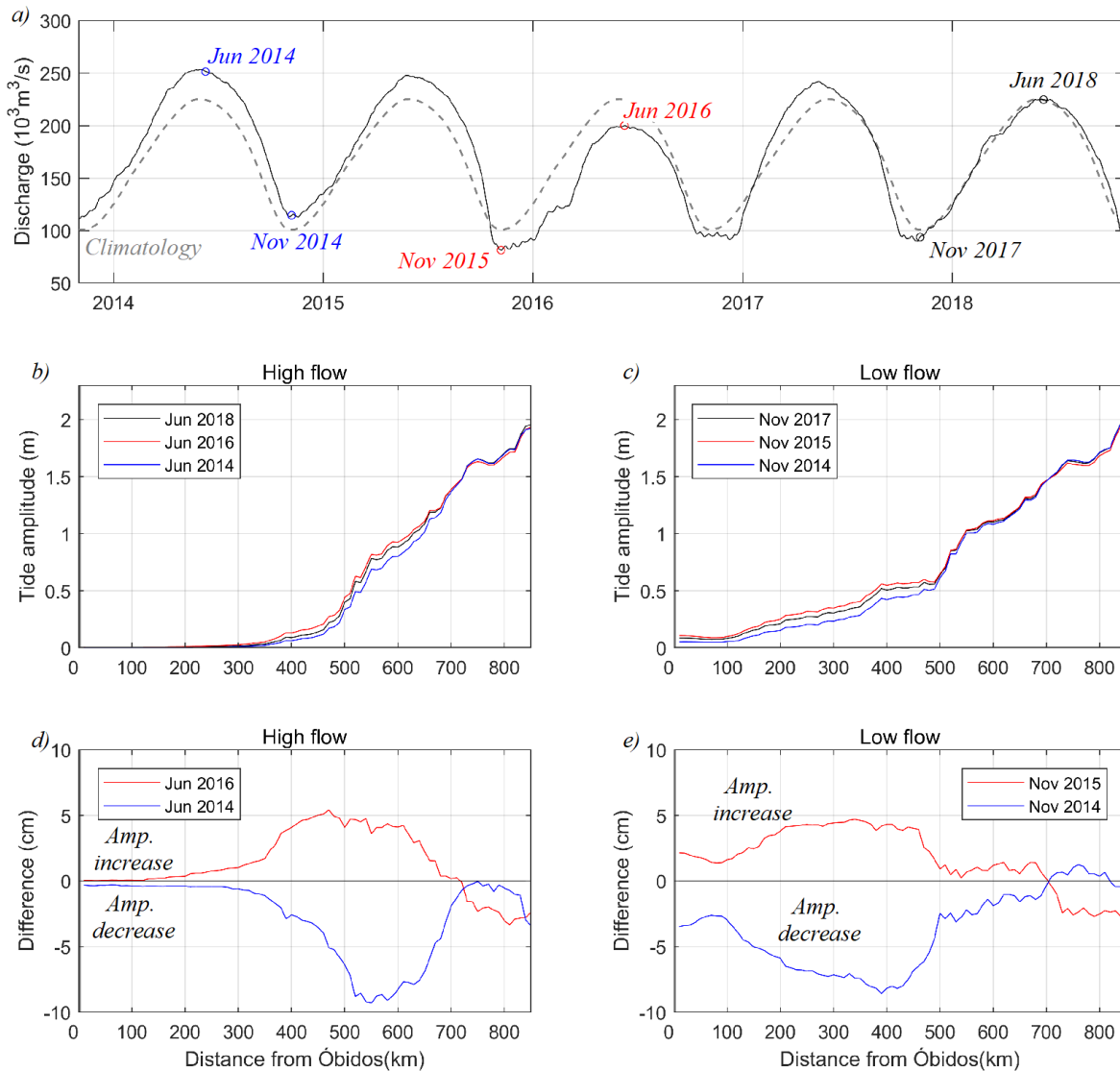
662 Beyond the seasonal timescale, it appears interesting to assess the impact of
663 the interannual variability on the characteristics of the tide in the Amazon estuary, as
664 the magnitude of the yearly freshwater discharge exhibited a marked interannual
665 variability over the past decade, particularly in the 2014-2016 period.

666 Interannual variability of the tide due to non-astronomical factors has already
667 been reported in other regions (e.g., Haigh et al., 2020, and references therein). For
668 instance, Devlin et al. (2017) concluded that it could be significant indeed in several
669 regions along the Pacific Ocean shoreline for instance. Jay et al. (2011) investigated
670 the long-term changes of the tidal characteristics in the lower Columbia River (west
671 coast of the United States), in response to the changes in river regime (among other
672 factors). However, to the best of our knowledge, this issue has never been
673 investigated in the Amazon estuary. We considered our model hindcast of both
674 extreme floods and extreme drought periods that occurred between 2014 and 2016.
675 These were compared with the year 2018, a year of roughly normal discharge
676 conditions. The floods of June 2016 (discharge, $Q=200$ thousand $\text{m}^3.\text{s}^{-1}$) and June
677 2014 ($Q=250$ thousand $\text{m}^3.\text{s}^{-1}$) represent below and above average discharge
678 respectively (with Q in 2018 peaking at 225 thousand $\text{m}^3.\text{s}^{-1}$) (Figure 7a). The low
679 flow period of November 2014 ($Q=113$ thousand $\text{m}^3.\text{s}^{-1}$) and November 2015 ($Q=81$
680 thousand $\text{m}^3.\text{s}^{-1}$) represent above and below average discharge, respectively, the
681 climatological low flow value amounting to 100 thousand $\text{m}^3.\text{s}^{-1}$ (Figure 7a). The tidal

682 amplitude variations along the river and the tidal range difference between the
683 extreme years and the normal year (2018) are presented in Figure 7b-e.

684

685



686

687 Figure 7. a) Amazon discharge climatology (1968-2020, dashes) and interannual
688 evolution (solid) observed between 2014 and 2018; Profile of tidal amplitude along
689 the river in high flow season (b) and low flow season (c); Tidal amplitude difference
690 between the extreme years and the typical year (2018) in high flow season (d) and in
691 the low flow season.

692

693 The interannual pattern of year-to-year modulation of the tidal amplitude is in
694 line with the seasonal picture described in Section 4, with excess discharge yielding

695 lower tidal amplitude and vice-versa lower discharge associated with higher tidal
696 amplitude, both in low and high flow seasons. However, the influence of interannual
697 discharge anomaly on tidal amplitude strongly varies along the river course and
698 among the periods considered. In the high flow period, above-average (2014) and
699 below-average (2016) discharge affect the tidal amplitude mainly over the reach
700 located between 200 km and 720 km from Óbidos, with variations of up to 8 cm in
701 amplitude, in absolute values (Figure 7d). This maximum difference is seen between
702 500 km and 600 km and typically amounts to 10% of the tidal amplitude there.
703 Further downstream, the anomalies reduce until ~720 km from Óbidos, where they
704 virtually disappear. This implies that the tidal range in the downstream half of the
705 terminal delta (typically downstream of Porto de Santana – Station 5) is primarily
706 unaffected by the severe floods that occur interannually in the Amazon River. Above-
707 and below-average floods do not appear to affect tidal range in the upstream-most
708 reach, with tidal range variability being seen only 200 km downstream of Óbidos
709 (between Monte Alegre and Santarém cities) and further downstream, regardless of
710 flood magnitude (Figure 7d).

711 The anomalies of tidal amplitude in years with a lower (November 2015) and
712 higher (November 2014) low flow period mimic the response during extreme floods,
713 with excess low flow yielding negative tidal amplitude anomaly, and deficient low flow
714 yielding positive tidal amplitude anomaly. The anomalous patterns extend over a
715 longer reach than in the high flow period. The extent to which the Amazon River
716 discharge influences the tidal range amounts to ~700 km, from Óbidos to Porto de
717 Santana (station 5; Figure 7e). However, our model domain starts at Óbidos, where
718 the tidal amplitude ranges from 5 cm (Nov/2014) to 10 cm (Nov/2015). This implies
719 that the tidally-influenced river stretch extent may be even larger, extending to the
720 region upstream of Óbidos. The anomaly of tidal amplitude along the river can reach
721 7 cm in the surroundings of Almeirim (station 4, ~400 km from Óbidos), amounting to
722 20% of the tidal range there. In this region, apart from the interaction between the
723 tide and the anomalously low discharge, the river's connection with the extended
724 shallow floodplains may also be significantly altered during extreme droughts and, in
725 turn, may impact the tidal dynamics. However, the lack of tidal records in these
726 floodplains precludes us from further investigating this issue. Downstream of this

727 region, the discharge has less influence on the tidal range (and the anomalies even
728 reverse sign) downstream of Porto de Santana (~700 km from Óbidos).

729

730 **6. Conclusion**

731 This study investigated the seasonal and interannual variability of the tide
732 along the Amazon River estuary through a novel, cross-scale, high resolution
733 hydrodynamic numerical modeling platform duly validated against the available
734 observations. Our findings show that the variability of the Amazon discharge has a
735 significant influence on the magnitude and extent of the tidal propagation, on the tidal
736 wave celerity, and the occurrence and magnitude of tidal flow reversal. This concerns
737 the seasonal cycle as well as the year-to-year variability, both in the high flow season
738 and in the low flow season.

739 The Amazon is the river with the largest discharge so that the monomodal
740 flood pulse continuously affects the extent of tidal influence along the estuary. Our
741 findings allow us to divide the estuary into the three following stretches: first, between
742 Óbidos and 300 km downstream of Óbidos, a stretch where the water level is
743 primarily influenced by the upstream watershed and only seasonally by the tide;
744 second, between 300 km and 700 km from Óbidos (close by Prainha and Porto de
745 Santana, respectively), a stretch where the water level is influenced by the river and
746 by the tide throughout the year; third, a downstream stretch that is primarily
747 influenced by the tide, between 700 km from Óbidos (around Porto de Santana) and
748 the ocean.

749 The amplitude of M2 constituent decays from the vicinity of the mouths
750 towards upstream, from a maximum reached about 100 km upstream of the oceanic
751 outlets to a practically null value far upstream. The seasonal change follows the
752 discharge pattern, with maximum values in October/November and minimum values
753 in May/June.

754 At interannual timescales, the tidal amplitude varies significantly, by typically
755 10% during anomalous floods and up to 20-25% during anomalous droughts,
756 primarily in the central reach of the estuary (from 300 km to 700 km upstream of the
757 mouths). Nevertheless, the spatial extent of tidal anomalies along the Amazon River
758 appears quite consistent among the various anomalous events of discharge we

759 considered. Indeed, regardless of the sign of the discharge anomaly, the influence on
760 the tidal range in June is limited to a reach of about 500 km length, starting 200 km
761 downstream of Óbidos and vanishing 700 km downstream of Óbidos. Similarly,
762 during the anomalous droughts (November), the imprint on the tidal range extends
763 from Óbidos to 700 km downstream of Óbidos, irrespective of the sign of the drought
764 anomaly.

765 The present description of the tidal characteristics of the Amazon may help to
766 understand the dynamics of the extreme events of water level and of the associated
767 spatio-temporal structure of the dryings and floodings, which have profound impacts
768 on the socio-economy of the riparian population (e.g., Mansur et al., 2016).
769 Furthermore, we believe our modeling study also contributes to paving the way for a
770 better understanding of the sediments dynamics as well as of the biogeochemical
771 cycles over the region.

772 As described in section 3, our modeling platform is not free of limitations. A re-
773 visit of the present conclusions once the various limitations can be alleviated will
774 certainly be timely.

775 A key issue in understanding the hydrodynamics of the Amazon estuary is the
776 lack of a dense-enough, high-quality, operational monitoring network of the water
777 level. The existing in situ monitoring stations used thoroughly in the present study are
778 few and the available records suffer from frequent data gaps and observational
779 issues, both on account of the enormity of the area and its difficult access.

780 Further analysis is needed to evaluate the estuary extent in the extreme low
781 flow periods, since our model domain is limited to the region from Óbidos to the
782 ocean. However, there are indications that the tide affects the water level in the
783 region upstream of Óbidos in such extreme drought periods, even if the tidal
784 amplitudes remain very small there (<4 cm). In this sense, a further upstream
785 extension of our model domain appears appropriate.

786 Finally, the Amazon estuary is probably currently experiencing its last epoch of
787 pristine hydrodynamical regime. Indeed the Amazon watershed faces anthropogenic
788 changes in its upstream parts that may impact its hydrological budget (Latrubesse et
789 al., 2017). Moreover, the Amazon basin is affected by climate variability, with 7 of the
790 latest 10 strongest floods since 1903 recorded in the past 13 years (Chevuturi et al.,

791 2022). The estuary is also subject to the ongoing sea level rise. Bearing in mind the
792 very significant tidal modulation reported here at annual to interannual timescales, it
793 is expected that the ongoing long-term changes of oceanic water level will also exert
794 significant impacts on the tidal characteristics. Therefore, it will be essential to
795 monitor and assess this long-term evolution and the associated water level extremes.
796

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804

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997

998 **Appendix**

999 Table A.1. Amplitudes of the dominant constituents modeled in high and low flow

		Amplitude (cm)									
		Mm		Msf		M2		S2		M4	
		sim	obs	sim	obs	sim	obs	sim	obs	sim	obs
High flow	Óbidos	6.27	10.54	1.93	2.20	0.20	0.15	0.12	0.30	0.02	0.08
	Santarém	5.68	8.85	3.10	0.47	0.07	0.23	0.01	0.14	0.01	0.04
	Prainha	5.44	2.99	5.01	4.24	0.95	5.68	0.27	1.10	0.16	0.98

	Almeirim	7.54	5.43	9.11	4.47	7.60	16.96	2.11	2.88	1.74	3.94
	Porto de Santana	14.14	4.96	18.49	10.00	100.00	117.45	23.86	19.53	23.51	23.92
	Escola Igarapé Grande	6.28	12.07	8.58	13.05	165.24	170.60	41.43	35.11	19.33	20.28
	Ponta Guar	4.22	3.23	6.14	-	124.52	153.37	31.39	39.84	22.94	25.86
	Porto de Moz	8.52	10.60	11.14	10.07	10.20	4.04	2.84	0.62	2.67	1.46
	Gurup	10.56	7.69	13.09	11.12	21.94	45.04	6.17	7.89	4.37	8.00
	So Pedro	9.74	12.53	12.85	18.07	22.16	62.76	5.75	9.03	4.48	11.44
	Furo Grande de Jurupari	12.64	10.36	16.47	-	59.26	90.92	16.05	29.54	17.20	19.26
	Camaro Tuba	8.06	9.55	10.03	-	114.11	152.12	34.11	40.94	27.17	27.79
	Chaves	10.91	8.29	13.93	-	64.24	116.98	20.45	20.65	29.64	30.29
	Cabo Maguari	5.20	23.99	6.02	-	147.25	131.40	40.78	37.82	24.56	22.15
	Low flow	bidos	72.76	64.98	9.98	16.70	3.97	3.14	1.90	1.38	0.88
Santarm		59.64	52.75	10.43	9.77	6.15	3.89	0.87	1.34	1.53	1.44
Prainha		45.06	14.66	15.78	9.34	18.38	12.96	6.54	4.08	4.33	3.04
Almeirim		34.18	20.54	19.42	6.40	34.09	37.06	10.88	9.51	9.45	10.65
Porto de Santana		15.70	12.06	17.53	14.48	115.51	108.05	30.83	26.77	22.26	17.18
Escola Igarap Grande		5.37	3.56	8.91	10.04	175.01	169.60	50.85	38.16	20.07	14.81
Ponta Guar		3.55	3.23	6.11	-	133.63	153.37	39.23	39.84	24.02	25.86
Porto de Moz		30.41	11.72	19.34	11.54	39.73	10.09	12.10	2.67	12.66	4.67
Gurup		27.14	6.26	21.46	15.98	43.98	58.48	13.14	13.51	8.95	9.55
So Pedro		31.64	12.53	12.88	18.07	42.94	62.76	14.06	9.03	8.86	11.44
Furo Grande de Jurupari		12.48	10.36	16.33	-	66.06	90.92	21.31	29.54	15.44	19.26
Camaro Tuba		7.12	9.55	11.22	-	120.69	152.12	43.36	40.94	25.42	27.79
Chaves	10.24	8.29	14.78	-	70.85	116.98	26.87	20.65	27.59	30.29	
Cabo Maguari	3.91	23.99	8.34	-	154.81	131.40	51.13	37.82	21.97	22.15	

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1001 Table A.2. Phases of the dominant constituents modeled in high and low flow

		Phase									
		Mm		Msf		M2		S2		M4	
		sim	obs	sim	obs	sim	obs	sim	obs	sim	obs
High flow	bidos	464.33	430.43	549.34	656.86	580.43	540.92	603.89	595.05	611.47	542.02
	Santarm	483.50	440.27	517.39	590.90	667.63	597.02	683.04	633.62	542.72	630.73
	Prainha	451.92	438.77	466.74	459.53	530.40	478.43	540.15	492.87	552.42	463.44
	Almeirim	415.26	374.53	433.89	475.62	423.37	403.84	433.39	423.29	379.69	713.99
	Porto de Santana	25.08	41.99	39.34	20.43	232.21	210.59	248.26	232.08	14.52	348.83

Low flow	Escola Igarapé Grande	6.48	21.86	39.60	48.35	106.55	93.57	120.51	116.73	111.52	111.85
	Ponta Guará	10.76	149.31	41.88	-	66.43	43.71	76.86	61.83	343.80	309.79
	Porto de Moz	408.74	407.73	431.03	438.92	411.41	389.33	418.38	406.64	361.10	686.70
	Gurupá	38.15	34.35	55.72	51.15	352.02	323.98	0.71	334.82	260.80	182.43
	São Pedro	24.75	43.00	44.79	31.36	294.98	278.13	306.06	301.83	111.718	87.99
	Furo Grande de Jurupari	19.05	14.70	37.03	-	175.16	165.68	183.08	192.40	231.40	265.40
	Camarão Tuba	6.73	26.21	34.36	-	55.38	74.97	73.10	79.88	83.87	80.95
	Chaves	13.60	332.59	35.71	-	83.00	93.62	98.98	136.51	137.96	121.88
	Cabo Maguari	-7.06	-10.45	-336.57	-	-22.96	0.64	-7.58	-341.55	-108.46	-60.11
	Óbidos	431.93	437.80	703.13	644.30	659.84	615.04	414.62	434.74	529.78	467.19
	Santarém	429.78	436.84	376.65	654.62	577.15	551.18	540.24	492.31	672.56	636.06
	Prainha	425.76	550.70	390.41	489.44	467.26	446.53	483.77	472.80	478.95	434.13
	Almeirim	421.23	416.14	391.18	360.64	389.56	378.66	411.48	406.62	708.28	700.97
	Porto de Santana	49.79	36.72	21.66	40.68	224.98	197.42	248.59	224.04	354.04	329.99
	Escola Igarapé Grande	42.35	7.06	6.05	29.90	101.52	88.96	122.65	113.69	105.31	108.90
	Ponta Guará	42.97	149.31	357.01	-	63.27	43.71	78.61	61.83	346.80	309.79
	Porto de Moz	420.62	401.97	393.25	408.69	376.20	368.52	394.86	380.46	684.98	670.68
	Gurupá	56.27	47.00	29.26	45.05	336.59	319.90	353.50	347.78	237.20	185.50
	São Pedro	41.3066	43.00	41.7019	31.36	281.722	278.13	298.02	301.83	83.4821	87.99
Furo Grande de Jurupari	44.83	14.70	19.48	-	169.09	165.68	184.10	192.40	223.19	265.40	
Camarão Tuba	38.92	26.21	11.58	-	52.27	74.97	77.82	79.88	78.37	80.95	
Chaves	41.62	332.59	16.44	-	80.64	93.62	104.70	136.51	129.64	121.88	
Cabo Maguari	-320.36	-10.45	-352.39	-	-25.71	0.64	-3.85	-341.55	-112.50	-60.11	

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1003 Table A.3. Complex error of the modeled tide at each station in high and low flow
 1004 season (in cm)

Station	High flow	Low flow
Óbidos	4.52	7.72
Santarém	4.32	7.31
Prainha	4.20	39.24
Almeirim	8.18	11.22
Porto de Santana	33.28	39.80
Escola Igarapé Grande	27.89	29.14
Ponta Guará	45.90	39.83
Porto de Moz	5.30	26.75
Gurupá	20.68	21.62

São Pedro	23.13	16.47
Furo Grande de Jurupari	27.09	21.55
Camarão Tuba	42.03	43.91
Chaves	40.83	38.03
Cabo Maguari	47.61	55.19

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