

1 **Role of the Amazon outflow on the barotropic tide on the** 2 **Amazonian shelf**

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10 11 **Highlights**

12 - A numerical study of the impact of the Amazon discharge on the magnitude of the tide
13 at its mouth

14 - The discharge induces a rise of tidal amplitude of ten centimeters at the coast

15 - This rise is associated to a rise of mean sea level also of ten centimeters

16 - This tidal amplification is partly attributable to the rise of mean sea level

17 - It is also partly attributable to the vertical density stratification of the Amazon plume

18 - Profound impacts of future sea level rise can be expected on tidal flooding and on
19 socio-economic dynamics of the Amazon delta

20 21 **Abstract**

22
23 The Amazon yields the largest freshwater discharge to the world ocean,
24 outflowing on a shallow, macro-tidal shelf. Its plume dynamics is complex and the
25 impact of the discharge on the tidal properties on the adjoining shelf remains poorly
26 understood. Through a series of numerical modelling experiment, we investigate the
27 interaction between the Amazon discharge and the tide over the Amazonian shelf. We
28 find that the runoff is responsible for a rise of the M2 tidal amplitude of ten cm in the
29 embayment between Cabo Norte and Cabo Cassipore. The runoff also induces a rise of
30 the mean sea level there, of ten cm as well. Such a one-to-one sensitivity of the tidal
31 amplitude and of the mean sea level over this region is quite unique among the world
32 coastline. The modulation of the bottom friction by the thickness of the water column as
33 well as by the vertical density stratification in the Amazon plume appears to be the main
34 forcing factor of this response. Our numerical sensitivity experiments suggest that the
35 seasonal variability of the Amazon discharge has little impact on the temporal variability
36 of the tidal characteristics over the Amazonian shelf.

37

38 **1. Introduction**

39

40 The Amazon, draining most of the northern part of South America, yields the
41 largest river discharge on Earth. It outflows on a broad, shallow shelf (Fig. 1),
42 characterized by a macrotidal regime (Beardsley et al., 1995). Its discharge shows
43 marked seasonal variations, lowest in December (100'000 - 150'000 m³/s), and highest
44 in May (300'000 m³/s) (Fig. 2). Several factors make the Amazon outflow unique.
45 Because of its magnitude, the classical estuarine salinity frontal structure is pushed far
46 offshore, out of the estuary, in the open ocean (Fontes et al., 2008). The location of the
47 outflow right at the equator makes the plume dynamics peculiar. The freshwater plume
48 dispersal is governed by an intricate physics, involving the large-scale North Brazil
49 Current, the local wind, and the tidal currents (Nikiema et al., 2007; Fontes et al., 2008;
50 Molinas et al., 2014; Ruault et al., 2020). The Amazon freshwater outflow is known to
51 impact both the local and the remote mean sea level, through the combination of its
52 mass and halosteric effects (Giffard et al., 2019; Durand et al., 2019). On account of the
53 strength of the tide and of the shallow depth of the near-shore Amazonian shelf (Fig. 1),
54 the tide is prone to generate strong shallow-water overtides and compound tides there
55 (Gallo and Vinzon, 2005). Being bordered by a sharp continental slope, with strong
56 vertical stratification of the water column in all seasons, the barotropic tide was found to
57 be instrumental in the sedimentary faciology of the Amazon shelf, through the internal
58 tide it radiates (Molinas et al., 2020).

59 Over the Amazonian shelf, the impact of the ocean tide on the spatial structure of
60 the Amazon plume has been well established (Molinas et al., 2014; Ruault et al., 2020).
61 On the other hand, the tide is known to be significantly impacted by the river flow in
62 various estuarine systems worldwide (see e.g. Haigh et al 2019 for a review of the past
63 studies). In the Amazon, the tide was shown to vary seasonally inside the estuary, as a
64 response to the seasonal variability of the river discharge (Gallo and Vinzon, 2005;
65 Kosuth et al., 2009). However, up to date little is known about the role of the Amazon
66 outflow on the characteristics of the tide on the adjoining oceanic shelf. There are
67 various processes through which discharge can influence the tide in large, shallow
68 deltaic systems or semi-enclosed basins. First, by modulating the mean sea level, the
69 river discharge can linearly modulate the vertical dilution/concentration of the tidal

70 energy flux, via the so-called shoaling effect (Haigh et al., 2019). This effect competes
71 with the barotropic modulation of the bottom friction, which tends to induce higher tidal
72 amplitude in conditions when the mean sea level is higher (see Talke and Jay, 2020, for a
73 review). Baroclinic modulation of the bottom friction can also be a prominent factor: the
74 freshwater discharge can induce a vertical stability of the water column at subsurface,
75 which in turn is less prone to turbulent mixing and momentum dissipation at the bottom
76 of the ocean (Kang et al., 2002; Muller et al., 2014). The specific geology of large river
77 outflows can also impact the tide. Wide parts of the Amazonian shelf are consistently
78 covered by fluid mud banks deposited by the river plume (Nittrouer et al., 2021).
79 Gabioux et al. (2005) and Fontes et al. (2008) analyzed the impact of these specific
80 sedimentary features on the bottom friction. They concluded that the fluid mud induces
81 a weak momentum dissipation of the barotropic tide, hereby favouring large tidal
82 amplitude at the coast.

83 The strength of the freshwater discharge, the magnitude of the tide and the broad,
84 shallow shelf altogether make this region a relevant case-study of the impact of the river
85 discharge on the coastal tide off the delta mouths. The current period of history tends to
86 be considered as the last epoch when the Amazon hydrodynamics remains primarily
87 unaffected by anthropogenic influences (Latrubesse et al., 2017; Nittrouer et al., 2021).
88 It is important to understand the water level variability at the mouth of the Amazon over
89 a broad range of timescales, in the 21st century context of ongoing sea level rise (Church
90 and White, 2011) and of profound changes in the hydrology of the Amazon watershed
91 (Latrubesse et al., 2017), where several large coastal cities of the Amazon delta are
92 already massively exposed to coastal flooding (Mansur et al., 2016; Szabo et al., 2016).
93 Hence it appears timely to decipher the interactions between the Amazon outflow and
94 the tide.

95 The aim of the present study is to assess the impact of the Amazon outflow on the
96 tidal characteristics on the Amazonian shelf, through a set of dedicated ocean numerical
97 modeling experiments. Section 2 presents our modelling approach and the various
98 datasets we utilized. In Section 3, we present the model validation. Our results are
99 shown in Section 4, followed by a discussion in Section 5 and concluding remarks in
100 Section 6. Note that our focus is not on the Amazon mouth but rather on the continental
101 shelf situated to the North of it, as our model domain does not extend within the Amazon
102 delta per se.

103

104 **2. Data and methods**

105

106 *2.1 Model*

107

108 We use a regional configuration of the NEMO 3.6 ocean general circulation model
109 (Madec et al., 2014). It consists of a 3-level, two-way nested set of grids, with varying
110 resolution from $1/4^\circ$ (over the whole tropical Atlantic) to $1/12^\circ$ (over the western
111 tropical Atlantic) and $1/36^\circ$ (over the Amazonian shelf and slope region). The three
112 embedded domains are displayed in Figure 1. The model is strictly identical to the one
113 used by Ruault et al. (2020), and largely derived from the one used in Hernandez et al.
114 (2016), Giffard et al. (2020) and Gévaudan et al. (2021). We refer to these past papers
115 for extensive validation of the model. For the sake of conciseness in the present paper
116 we will focus mostly on the tidal validation. The model has a vertical grid of 75 levels,
117 identical across the three subdomains, with 12 levels in the upper 20 m. The three
118 domains are coupled online through AGRIF library (Blayo and Debreu, 1999; Debreu et
119 al., 2008). The motivation for this nesting strategy is to allow simultaneously the
120 resolution of the fine spatial scales that are expected to be instrumental for capturing
121 the hydrodynamics of the Amazonian shelf, as well as the basin-scale three-dimensional
122 thermohaline dynamics, which is known to be important in the vertical stratification of
123 the western equatorial Atlantic (e.g. Hernandez et al., 2016). The AGRIF algorithm
124 allows a seamless, numerically consistent exchange of information among the various
125 sub-domains (Blayo and Debreu, 1999; Debreu et al., 2008). The coarse resolution of the
126 outer domain ensures a tractable numerical cost overall. The vertical turbulence closure
127 uses a generic-length-scale scheme (Umlauf and Burchard 2003) with k-epsilon
128 formulation (see Reffray et al. 2015 for a description of its implementation in NEMO). In
129 the bottom boundary layer the friction is quadratic, with a drag coefficient of 10^{-3} . The
130 free-surface formulation follows a time-splitting scheme, solving separately the fast
131 barotropic transients (among which is the tide) and the lower frequencies. The
132 bathymetry was taken from GEBCO atlas (Weatherall et al., 2015). The river discharge of
133 the Amazon system (comprising the contributions of the Amazon itself, as well as
134 Tapajos and Xingu rivers) and Para/Tocantins system are injected in the model as mass
135 sources with zero salinity, through the open boundaries located at the estuaries mouths.

136 We use the discharge estimates provided by HYBAM (2018) hydrological observatory.
137 The atmospheric forcing (wind, heat and freshwater fluxes) is taken from DFS5.2
138 product (Dussin et al., 2016). The model tide is forced by the astronomical potential of
139 all major high frequency tidal constituents (M2, S2, N2, K2, K1, O1, Q1, and P1), and the
140 same constituents are applied at the boundaries of the outer domain, from FES 2012
141 tidal atlas (Carrère et al., 2012). The period of simulation is 2005-2015 and only the
142 period 2014-2015 is considered in the present study. We performed various sensitivity
143 experiments to decipher the mechanism of discharge-tide interaction, by switching on
144 and off the discharge forcing and/or the ocean vertical density stratification. The set of
145 model experiments we performed is summarized in Table 1.

146

147 *2.2 Observations*

148

149 To validate the large-scale patterns of the tide, we relied on FES2014 tidal atlas
150 (Carrère et al., 2016). As the quality of global tidal atlases in poorly-documented coastal
151 regions such as the mouths of the Amazon is largely unknown, we complemented the
152 tidal atlas with all historical tide-gauge records we could access over the region of
153 interest. They were obtained from the Brazilian Navy
154 (www.marinha.mil.br/chm/estacoes-maregraficas; last accessed 17/5/2021). They
155 amount to five records in total, with a duration limited to one month for most of them
156 (Table 2). The records have a hourly frequency. Their locations are displayed on Figure
157 1b. Each record was visually inspected and inconsistent values were discarded. Both
158 model outputs (at hourly frequency) and in situ records were subjected to harmonic
159 analysis, through the Tidal Toolbox (Allain, 2016).

160

161 **3. Model validation**

162

163 The model performance was successfully assessed for the regional circulation
164 patterns as well as for its thermohaline three-dimensional structure over the western
165 tropical Atlantic in the past studies of Hernandez et al. (2016), Giffard et al. (2020) and
166 Ruault et al. (2020). In the present paper we will thus primarily restrict our validation to
167 our specific features of interest, namely the tidal variability in the Amazonian shelf

168 region (Sections 3.1 and 3.2). A validation of the vertical stratification in the region off
169 the Amazonian shelf is provided in Section 3.3.

170

171 *3.1 Large-scale tidal patterns*

172

173 The tide over the Amazonian shelf is semi-diurnal, dominated by M2 and S2
174 constituents (Gallo and Vinzon, 2005; LeBars et al., 2010). Figure 3 compares the
175 amplitude of these constituents between our model and FES2014. It is seen that the
176 model successfully captures the two coastal maxima of M2 and S2 amplitude, located to
177 the north-west and to the south-east of the mouths of the Amazon. Beardsley et al.
178 (1995) identified the north-western region, between the two capes Cabo Norte and Cabo
179 Cassipore, as an embayment which cross-shore length is close to the resonant length for
180 semi-diurnal tidal constituents. In addition, they suggested that the bending of the
181 coastline around Cabo Norte precludes leakage of tidal energy from this region towards
182 the mouth of the Amazon, hereby favouring maximal tidal range there. For both M2 and
183 S2, the model shows an under-estimation of the amplitude in the core of this north-
184 western maximum (2°N, 50.5°W), typically by 30 cm and 10 cm respectively. In contrast,
185 the model shows an over-estimation of both M2 and S2 amplitudes along the south-
186 eastern coastal maximum (1°S-2°S, 44°W-48°W), by 30 cm and 20 cm respectively. We
187 remind that our model was not especially calibrated for the tide, in the sense that we did
188 not carry out any regional tuning of the bottom roughness, nor of the bathymetry, unlike
189 the past numerical modeling studies over the region specifically dedicated to the tidal
190 dynamics (Gallo and Vinzon, 2005; Fontes et al., 2008; LeBars et al., 2010; Molinas et al.,
191 2014). We remind that the objective of this study is not to produce a novel reference
192 tidal atlas of the area, but to study the river outflow – tide interaction. In that
193 perspective, the broad agreement between the model and FES2014 atlas appears
194 satisfactory.

195

196 *3.2 Tidal validation in the vicinity of the Amazon mouths*

197

198 In order to quantify the degree of realism of our model at the river mouth we
199 assessed the tide using the five available tide gauges (Fig. 1). Because our regional focus
200 lies in the vicinity of the Amazon mouths, it is necessary to assess specifically the realism

201 of the modeled tide there. We considered the two dominant tidal constituents, M2 and
 202 S2, which altogether capture the majority of the total tidal signal over the region
 203 (Beardsley et al., 1995). For each tide gauge station, we computed the error of the model
 204 tide as the modulus of the complex difference for these two constituents together,
 205 following the method by Andersen et al. (1995), used in numerous past studies (e.g.
 206 Krien et al., 2016;):

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

207
 208 The total error at a given station is:

$$\sigma = \sqrt{\frac{1}{2} \sum_{N_{constituents}} |\Delta z|^2}$$

209
 210 Table 2 shows our results. The modeled tide appears in good agreement with the
 211 observed values for the two northernmost tide gauge stations (Ponta do Céu and Ponta
 212 Guara), with complex errors of 8 cm and 9 cm respectively. These values are in line with
 213 the typical performance of regionally-tuned high-resolution tidal models, such as
 214 Molinas et al. (2014). In contrast, the realism of the modeled tide appears significantly
 215 worse when we get closer to the Amazon mouths, with errors of order 40 cm and above,
 216 that is about twice worse than Molinas et al. (2014). This can be explained by the poor
 217 numerical formulation of the open boundary of the Amazon outflow (where no radiative
 218 condition could be implemented, which could induce spurious reflection of the tidal
 219 energy there), by the poor quality of GEBCO bathymetry in this region of narrow
 220 channels (Le Bars et al., 2010; Fassoni-Andrade et al., 2021), as well as by the too coarse
 221 horizontal resolution of the model grid. As a result, we will refrain from analyzing our
 222 model outputs in the immediate vicinity of the mouths of Amazon delta, in the present
 223 study. Overall, the good quality of the modeled tide to the North of the equator gives us
 224 confidence in the subsequent analysis of the tide-discharge interactions there, as we
 225 shall see in Section 4.

226

227 *3.3 Vertical stratification of temperature and salinity off the Amazon mouth*

228

229 As we shall see in the following section, the vertical density stratification is an
 230 important ingredient of the plume-tide interaction on the Amazon shelf. A thorough
 231 validation of the model stratification there is challenging though, on account of the poor
 232 coverage of observational atlases there. Figure 4 presents a comparison between the

233 model temperature and salinity vertical structure and World Ocean Atlas climatology
234 (Locarnini et al 2013, Zweng et al 2013), along the north-south section off the Amazon
235 mouth in its area closest to the shore documented in the atlas (hence starting at 4°N). It
236 is seen that the model successfully captures the upper ocean temperature field, as well
237 as the thermocline structure, with a 20°C isotherm gently sloping upwards from about
238 150 m in the slope region to about 135 m at 10°N. The model shows a warm bias of
239 about 1°C over the upper 50 m. Such a bias is largely in line with state-of-the-art
240 numerical models of the area (Gévaudan et al., 2021). The structure of the halocline is
241 also decently captured by the model, with a 36 PSU isohaline sloping downwards from
242 about 15 m at 5°N to about 30 m at 10°N. Shoreward of 5°N, the model clearly shows the
243 signature of the Amazon freshwater plume in the upper 10 m, which is not seen in the
244 observations, most probably on account of the very poor observational coverage there.
245 However we investigated the vertical structure of the model salinity in the shelf region
246 within the salt wedge by comparing with the handful of hydrographic sections carried
247 out during AMASSEDS program (Lentz and Limeburner, 1995) and we could concluded
248 to a good consistency of the model and the *in situ* profiles (see Ruault et al., 2020).

249

250 **4. Results**

251

252 *4.1 Mean picture*

253

254 The model mean tidal range is displayed in Figure 5a. It was computed as the
255 long-term mean of the difference between maximum water level and minimum water
256 level, considered over a 24 hour-long moving window centered on every time step of the
257 model outputs. In line with the patterns of M2 and S2 amplitude, we find again the two
258 regional maxima lying on either side of the mouths of the Amazon. The maximum range,
259 in excess of 5 m, is seen in the coastal embayment immediately to the North of Cabo
260 Norte (50°W, 2°N). Figure 5b shows the difference in tidal range between the REF
261 simulation and the NoAMZ sensitivity experiment, which results from discarding the
262 Amazon freshwater discharge from the model forcing. It is seen that the Amazon outflow
263 induces a rise of the tidal range of about 14 cm in the region of Cabo Norte, reaching a
264 maximum value of 22 cm at the coast. Over the rest of the domain, the influence of the
265 Amazon outflow is modest, typically less than 6 cm in absolute values. One exception is

266 the immediate vicinity of the Amazon mouths around (50.5°W, 0.5°N) and around
267 (49°W, 2°S), where we will refrain from attempting any further analysis on account of
268 the doubtful quality of the modeled tide there (see Section 3). At this point, it is
269 interesting to investigate which tidal constituent is responsible for the differences
270 between REF and NOAMZ. Fig. 5c shows the difference of M2 amplitude between REF
271 and NOAMZ. We remind that the tidal amplitude amounts to half of the tidal range, by
272 definition. It is seen that the rise of tidal range induced by the Amazon discharge is
273 primarily due to the increase of M2 amplitude (note that the range of the color bar in Fig.
274 5b is exactly double that of Fig 5c, for convenience). Hence in the following we will
275 restrict our analyses to M2 tidal constituent. Aside from this rise in tidal range, the
276 Amazon outflow is also responsible for a rise of the mean sea level (Fig. 5d), as
277 intuitively expected from such a mighty discharge. It exceeds 30 cm in the immediate
278 vicinity of the mouths of the Amazon. In the region of Cabo Norte where we observed
279 the maximal difference in tidal amplitude between the two simulations, it amounts to
280 around 12 cm. In other words, when the Amazon outflow is activated in the model, the
281 rise in mean sea level there is of the same order of magnitude as the rise in tidal
282 amplitude. As a result, in this embayment the inclusion of the Amazon outflow induces a
283 twofold rise of the level of the high waters, through the combined effect of the increase
284 of mean sea level and increase of the tidal amplitude.

285

286 *4.2 Seasonal variability*

287

288 As the Amazon discharge is variable along the seasonal cycle (Fig. 2), it is
289 interesting to assess the temporal variability of the pattern revealed in Section 4.1. To do
290 so, we performed a moving-window harmonic analysis over the 2 years of the model
291 simulations, considering temporal windows of 32 days, as in Tazkia et al. (2017). This
292 duration of 32 days is known to be long enough to separate the main semi-diurnal tidal
293 constituents dominating the tidal signal over our area (Pugh and Woodworth, 2014). We
294 spatially averaged the tidal amplitude over the "Cabo Norte" box (hereafter noted "CN"),
295 displayed in Figure 5c. Indeed, this box encompasses the area of maximum impact of the
296 Amazon discharge. Figure 6 shows the time evolution of M2 amplitude averaged over CN
297 box for the REF simulation (in blue) and for the NOAMZ ("no Amazon runoff") sensitivity
298 experiment (in red). It is seen that both curves vary in concert, keeping a roughly

299 constant offset of 10-15 cm. This means that the impact of the Amazon outflow on the
300 M2 amplitude is primarily independent of the seasonality of the discharge. However, it is
301 seen that M2 amplitude does show a very distinct seasonal cycle similar in both
302 simulations, with highest amplitude in boreal fall and lowest amplitude in boreal spring
303 in both years we simulated. The peak-to-peak difference of this seasonal variability of
304 M2 amplitude is of order 10-15 cm, which is comparable with the mean impact of the
305 Amazon outflow on M2 amplitude there.

306 Although a detailed analysis of the mechanisms responsible of this seasonal
307 variability of the tide over CN box is out of the scope of the present study, we performed
308 two additional sensitivity experiments to acquire some insights in the underlying
309 dynamics. These experiments are named BRTP (for "barotropic") and BRTPnoAMZ (for
310 "barotropic without Amazon runoff"). In both these experiments, we imposed a uniform
311 density throughout the model domain. This was done by imposing at each model time
312 step a constant, uniform value to the model temperature and salinity 3D fields, of 28°C
313 and 38 units (in the practical salinity scale) respectively. We similarly analyzed the
314 temporal variability of the tide in BRTP and BRTPnoAMZ experiments over CN box
315 (respectively dark green curve and light green curve in Fig. 6). It is seen that both
316 barotropic simulations show a very similar seasonal evolution of M2 amplitude,
317 consistently within 1 cm one from the other. Both barotropic simulations show a M2
318 amplitude consistently between that of REF and that of NoAMZ. It is also interesting to
319 see that their seasonal evolution of M2 amplitude is similar to REF and NOAMZ
320 simulations, with minimum amplitude in spring, maximum amplitude in fall. The peak-
321 to-peak range of seasonal variability amounts to about 8 cm, comparable with (but
322 somewhat smaller than) the two vertically-stratified simulations REF and NOAMZ.

323 To understand the key parameter responsible for the difference of tidal
324 amplitude between REF and NOAMZ, we computed the monthly de-tided sea level over
325 CN box (Fig. 7a). In both simulations, no clear seasonal variability can be seen. Rather,
326 some marked intra-seasonal fluctuations of the sea level appear, with typical magnitude
327 of 5 cm. The offset between the two simulations consistently remains around 10-15 cm,
328 in line with the difference of long-term mean sea level we have seen in Figure 5d. In
329 particular, none of the simulations exhibits a seasonality of the sea level correlated with
330 the evolution of M2 amplitude seen there. However, if we consider an offshore box
331 encompassing the outer continental shelf and slope region (displayed in Figure 5c), both

332 simulations show a prominent seasonal variability of the de-tided sea level, minimum in
333 boreal spring and maximum in boreal fall, with peak-to-peak amplitude of about 15 cm,
334 and in phase with the evolution of the tidal amplitude in the CN box.

335

336 **5. Discussion**

337

338 As we have seen in the previous section, the impact of the Amazon discharge on
339 the tidal characteristics appears maximal at the coast, in the embayment located
340 immediately to the North of Cabo Norte, in the core of maximal tidal range observed
341 over the Amazonian shelf. This impact appears largely independent of the time. There,
342 the Amazon outflow induces a ten cm increase of the mean sea level, as well as a ten cm
343 increase of tidal amplitude. As a result, the level of high tide water shows a twofold
344 increase, viz. twenty cm (not shown), compared to a numerical modeling framework not
345 accounting for the Amazon discharge. This very large sensitivity of the tidal amplitude
346 change in Cabo Norte region with regards to the local sea level change, amounting to a
347 ratio of about 1:1, appears quite unique among the world coastlines, based on the global
348 studies of Pickering et al. (2017) or Schindelegger et al. (2018). Indeed, both these
349 studies concluded to a much smaller sensitivity of the tide to the regional mean sea level
350 in the coastal ocean. Based on a comprehensive, worldwide observational dataset as
351 well as on global modeling of future sea level rise scenarios, they reported typical ratio
352 values of about 1:10 to 1:5, i.e. a rise in tidal amplitude of order one-tenth to one-fifth of
353 the corresponding rise in regional sea level. As said in the introduction, the sensitivity of
354 the tidal amplitude to the sea level in the shallow regions (such as the Amazonian shelf)
355 involves several competing effects (Haigh et al., 2019; Talke and Jay, 2020). The first one
356 is a linear shoaling/deepening effect, yielding increased tidal amplitude when the water
357 depth decreases. It is simply explained by the vertical convergence/divergence of the
358 tidal energy flux radiated shoreward from the deep ocean towards the shallow coastal
359 domain. This effect is not consistent with the tidal amplification seen in REF simulation
360 with regards to NoAMZ. The second effect is frictional: the higher the mean sea level, the
361 lower is the magnitude of the momentum dissipation at the bottom. This effect thus
362 favours increased tidal amplitude when the water depth increases. In the region of Cabo
363 Norte, this frictional effect appears consistent with our model experiments: the increase
364 in mean sea level induced by the Amazon outflow is associated with an increase of the

365 tidal amplitude. This finding appears in line with what was concluded in other powerful
366 estuarine systems adjacent broad, shallow shelves (Pickering et al., 2017; Tazkia et al.,
367 2017; van Maanen and Sottolichio, 2018; Schindelegger et al., 2017; Khan et al., 2020).
368 The origin of the higher sea level in the Cabo Norte region when the Amazon runoff is
369 accounted for (in REF) compared to the case when it is not (in NoAMZ), can be either
370 steric (linked to the lighter density of the plume waters) or manometric (linked to the
371 mass effect of the riverine water bulge) (Durand et al., 2019; Gregory et al., 2019). The
372 two barotropic experiments, carried out with and without the Amazon runoff forcing,
373 show a mean sea level roughly identical in the region of Cabo Norte (within 1 cm; not
374 shown). This implies that the difference in mean sea level between the two stratified
375 experiments (with vs. without the Amazon forcing) is essentially driven by steric effects.
376 The very strong sensitivity of the tide to the regional sea level suggested by our model
377 over the region of Cabo Norte is probably linked to the specific geometry of this
378 embayment, favouring the resonance of semi-diurnal tidal constituents (Beardsley et al.,
379 1995). The last effect through which tide can be altered in river plume regions is
380 through the inhibition of the bottom friction by the vertical density gradient underlying
381 the river plume (e.g. Kang et al. 2002). The lower M2 amplitude observed in our
382 barotropic experiment (BRTP) compared to REF experiment suggests that this
383 mechanism contributes to the higher M2 amplitude in REF, typically by half a dozen cm.

384 The seasonal variability of the tidal characteristics exhibited by our model
385 around Cabo Norte, with minimum amplitude in boreal spring and maximum amplitude
386 in fall, does not appear to be driven by the seasonal variability of the Amazon discharge.
387 Indeed, both the reference simulation and the Amazon-free NoAMZ sensitivity
388 experiment show a similar seasonal evolution. This echoes to the finding of Molinas et al.
389 (2014), who concluded that the variability of the position of the salinity front located at
390 the forehead of the Amazon freshwater plume on the continental shelf is primarily
391 driven by the variability of the tide and of the wind, much more than by the variability of
392 the river discharge. However the Amazon plume is known to present a marked seasonal
393 variability of the vertical density stratification at the basis of the Amazon fresh plume,
394 driven by the seasonal cycle of the runoff (Geyer and Kineke, 1995). Our model suggests
395 that the seasonal variability of the tidal amplitude over the Amazonian shelf is not
396 driven by the seasonal variability of the plume stratification, as this seasonal evolution
397 of the tide remains alike in the vertically-stratified and in the barotropic model

398 experiments. This stands in contrast with what was found in previous studies dealing
399 with other tropical shelves receiving massive, seasonally-varying freshwater discharges
400 such as the East China Sea (Kang et al., 2002). The characteristics of the tide over the
401 Amazonian shelf, as in any coastal region, integrate a variety of factors acting over a
402 broad range of spatial scales, from local to regional (Haigh et al., 2019). The seasonal
403 variability of the tidal characteristics around Cabo Norte reflects the seasonal variability
404 of the sea level in the outer shelf region, much more than the seasonal variability of the
405 local sea level. Similarly with the time-mean effect of the Amazon discharge, this
406 relationship is suggestive of a mechanism of seasonal modulation of the bottom friction
407 by the seasonal modulation of the water column thickness further offshore, the season
408 of highest sea level corresponding to the season of highest tidal amplitude. The seasonal
409 evolution of the offshore sea level is known to result from direct equatorial wind forcing
410 and contributions of waves generated by boundary reflection (Ding et al. 2009).

411

412 **6. Concluding remarks**

413

414 This study investigates the impact of the Amazon outflow on the tidal
415 characteristics over the adjacent continental shelf. The embayment located immediately
416 to the North of Cabo Norte, corresponding to the regional maximum of tidal range,
417 appears as the main zone of tidal impact of the Amazon discharge. There, we could
418 conclude to an overall increase of the tidal range by more than twenty cm, partly driven
419 by the reduced bottom friction effect of the steric sea level bulge associated with the
420 Amazon plume, and partly driven by the reduced bottom friction effect associated with
421 the density stratification at the bottom of the plume. This region is bordered by a low-
422 lying, flat coastal floodplain (Nittrouer et al., 2021; Fassoni-Andrade et al., 2021), and
423 exhibits a particularly energetic morphodynamics (Gensac et al., 2016; Santos et al.,
424 2018). Over the region, the impact of extreme water levels on the riparian societies and
425 ecosystems is well identified (Szabo et al., 2016; Mansur et al., 2016). In a social and
426 ecological context where every centimeter of water level counts, and keeping in mind
427 the dominance of the tide on the overall variability of the water level there, our study
428 calls for a careful consideration of the Amazon outflow in the next generation of tidal
429 models of the Northern coast of South America.

430 There are several limitations in the present study. Our model has a limited
431 horizontal resolution, it relies on a basic representation of the near-shore bathymetry, it
432 excludes the inner Amazon estuary, and we did not attempt any regional tuning of the
433 bottom friction. These limitations are probably largely responsible for the limited skills
434 of the modeled tide in the immediate vicinity of the mouths of the Amazon. A dedicated
435 revisit of the present study with a high-resolution hydrodynamic model explicitly
436 comprising the lower Amazon estuary, and regionally calibrated in terms of bottom
437 roughness, is certainly timely.

438 As a matter of fact, the sea level rise induced by the Amazon outflow around Cabo
439 Norte, analyzed in the present study, amounting to ten centimeters, is of comparable
440 magnitude to the global sea level rise observed along the 20th century (Church and
441 White 2011). In the context of the ongoing 21st century global sea level rise, and keeping
442 in mind that the rise expected by the end of this century is much larger than what
443 occurred during the past century (Oppenheimer et al., 2019), our study calls for a revisit
444 of the processes we identified, in conditions when the mean sea level will largely exceed
445 the level of today.

446

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448

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455 helped with the embedded numerical modeling setup.

456

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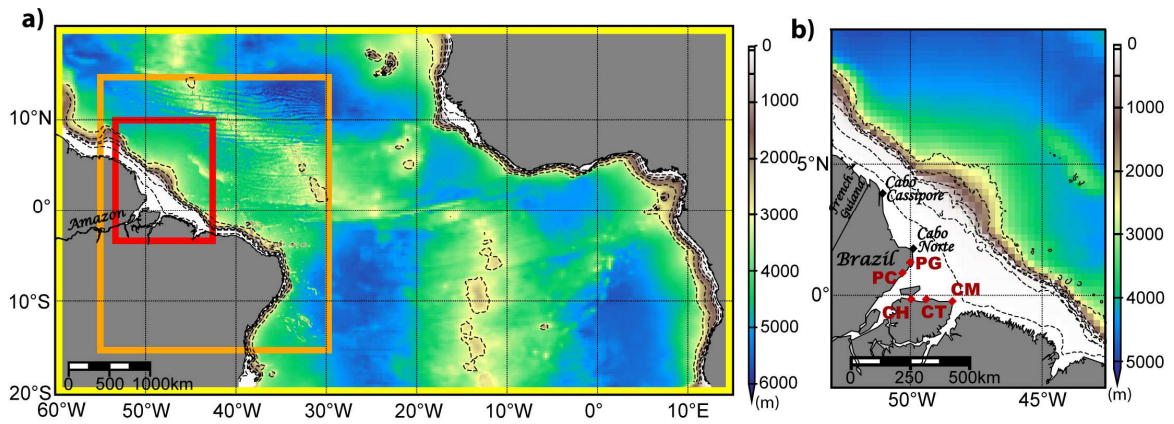
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Model simulation name	Tidal forcing	Wind forcing	Amazon discharge forcing	Density stratification	Period of the simulation
REF	✓	✓	✓	✓	2014-2015
NOAMZ	✓	✓		✓	2014-2015
B RTP	✓	✓	✓		2015
B RTPnoAMZ	✓	✓			2015

620 **Table 1.** Characteristics of the modeling experiments
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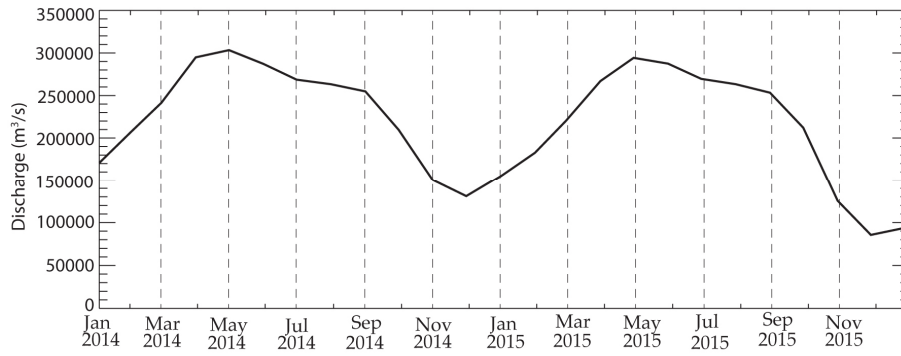
Station (record length)	Observation			Model		
		Ao (cm)	ϕ_o (degrees)	Am (cm)	ϕ_m (degrees)	Error (cm)
Cabo Maguari (48.41662°W,0.25298°S) (1 month)	M2	131	0°	164	-17°	54
	S2	38	18°	56	13°	18
	σ				40	
Camarão Tuba (49.51987°W,0.23006°S) (1 month)	M2	152	75°	89	82°	65
	S2	41	80°	26	99°	18
	σ				48	
Chaves (49.98383°W,0.1664°S) (1 month)	M2	117	94°	94	144°	92
	S2	21	137°	22	159°	8
	σ				65	
Ponta do Céu (50.11686°W,0.76510°N) (1 year)	M2	174	91°	172	94°	9
	S2	36	123°	43	126°	7
	σ				8	
Ponta Guara (49.88333°W,1.21667°N) (1 month)	M2	153	43°	143	40°	12
	S2	40	62°	35	69°	6
	σ				9	

624 **Table 2.** Comparison between the observed and model tidal constituents at the five in
625 situ stations displayed in Figure 1b. The error is defined as the modulus of the complex
626 difference. σ denotes the complex error.
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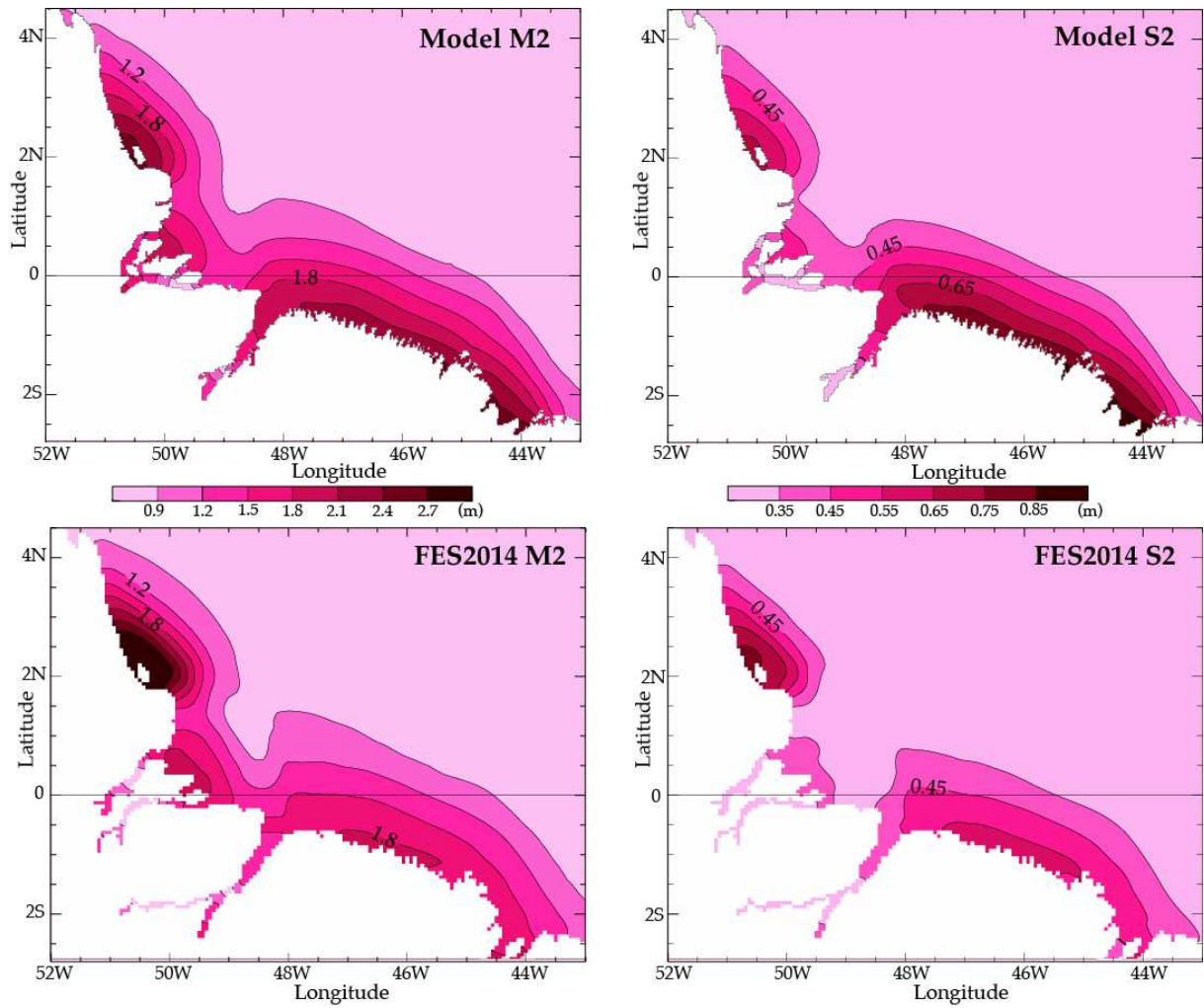
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Fig. 1. Study region with model bathymetry. Yellow = coarse model grid ($1/4^\circ$); Orange = intermediate grid ($1/12^\circ$); Red = fine grid ($1/36^\circ$). In (b), zoom on the domain of the fine grid, with the locations of the five tide gauge stations (CM = Cabo Maguari; CT = Camarão Tuba; CH = Chaves; PC = Ponta do Céu; PG = Ponta Guará). The 15m, 80m, 500m, 1000m, 2000m and 3000m isobaths are shown in dashes.



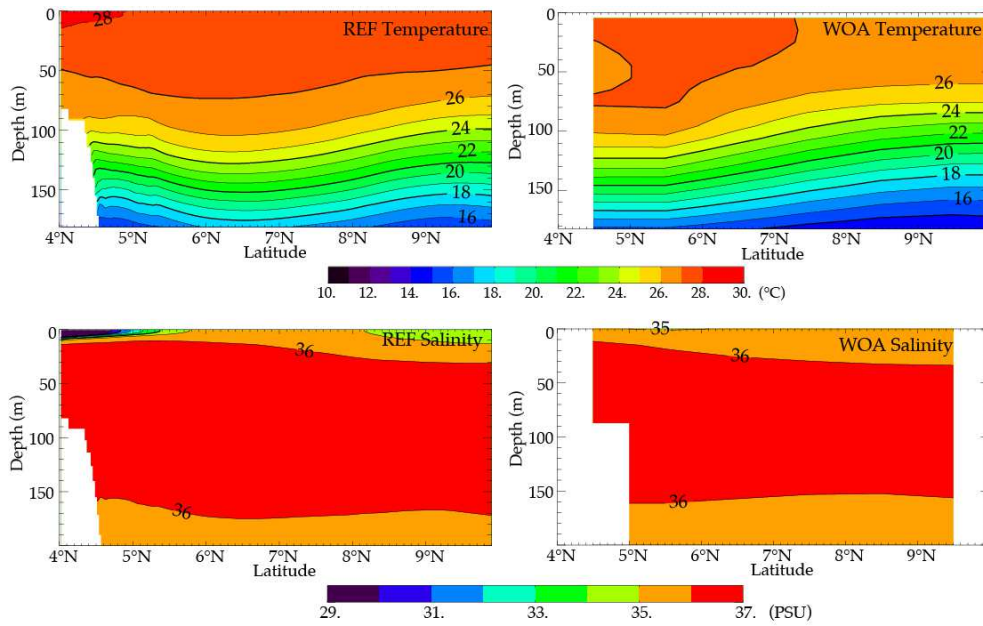
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Fig. 2. Evolution of the Amazon discharge from HYBAM (2018) in Óbidos station used to force the model (in m³/s).



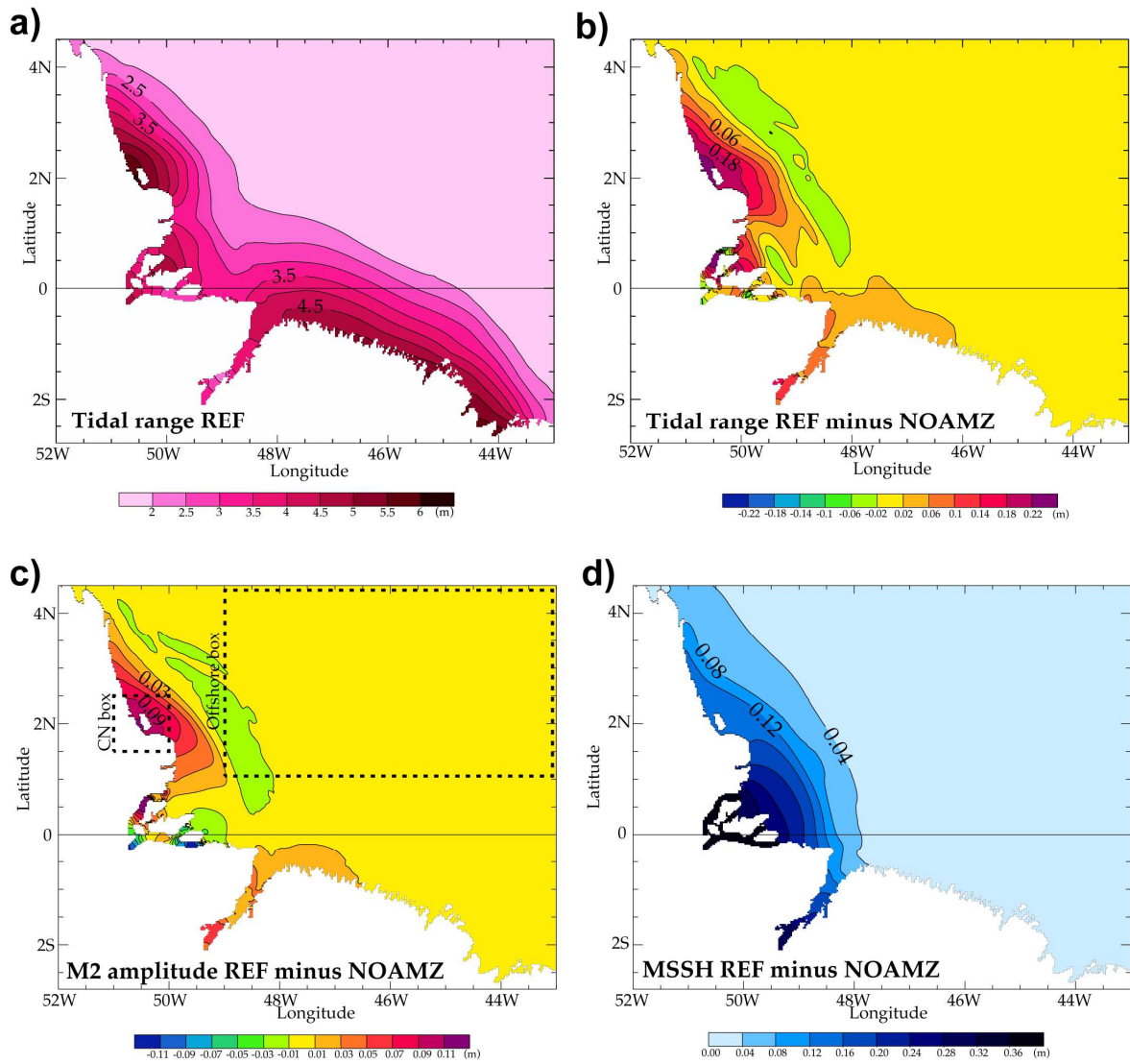
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Fig. 3. Tidal amplitudes from the model (REF experiment) and FES2014 tidal atlas, for M2 and S2 tidal constituents (in m).



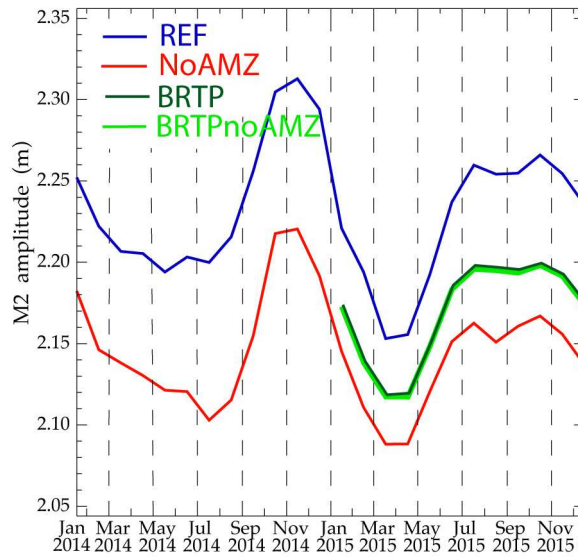
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Fig. 4. Meridional sections of climatological modelled (from REF simulation, left column) and observed (from World Ocean Atlas, right column) temperature and salinity in the upper 200 m along 50°W, off the Amazon mouth.



652 **Fig. 5.** (a) Mean tidal range in the model (REF experiment). (b) Difference of mean tidal range between
 653 REF and NoAMZ experiments. (c) Difference of amplitude of M2 tide between REF and NoAMZ
 654 experiments. (d) Difference of mean sea surface height between REF and NoAMZ experiments (in m).
 655 Figure (c) shows the limits of boxes around Cabo Norte ("CN box") (50°W-51°W;1.5°N-2.5°N) and
 656 offshore ("Offshore Box") (43°W-49°W;1°N-4.5°N) used for subsequent analyses.
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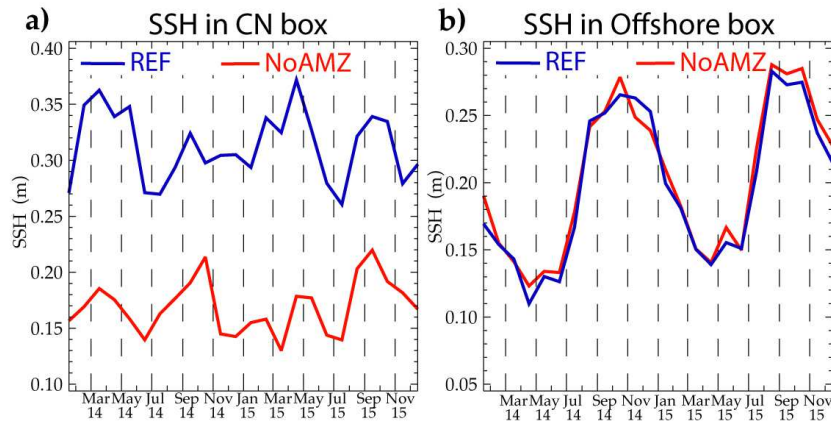
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Fig. 6. Monthly evolution of M2 tide amplitude of the various model experiments, averaged over the box "Cabo Norte"

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Fig. 7. (a) Monthly evolution of the sea surface height over the box "Cabo Norte", for the REF experiment (blue) and for the NoAMZ experiment (red). (b) same as (a), over the box "Offshore".