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► **To cite this version:**

Marta Martín-Rey, Irene Polo, Belén Rodríguez-Fonseca, Alban Lazar, Teresa Losada. Ocean dynamics shapes the structure and timing of Atlantic equatorial modes. *Journal of Geophysical Research. Oceans*, 2019, 124 (11), pp.7529-7544. 10.1029/2019JC015030 . hal-02408951

HAL Id: hal-02408951

<https://hal.sorbonne-universite.fr/hal-02408951v1>

Submitted on 13 Dec 2019

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1 **Ocean dynamics shapes the structure and timing**
2 **of Atlantic Equatorial Modes**

3
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19

20
21 **Key points**

- 22
- 23 ● Ocean waves determine the distinct timing of the Equatorial Modes under negative
24 AMV phases
- 25
- 26 ● Equatorial Kelvin waves favour the development of Equatorial Modes, while a
27 remotely-excited Rossby wave damps the equatorial SST anomalies
- 28
- 29 ● Diverse ocean dynamics activated during negative AMV phases modulate the
30 development of different Equatorial Modes
- 31

32 **Abstract**

33 A recent study has brought to light the co-existence of two distinct Atlantic Equatorial
34 Modes during negative phases of the Atlantic Multidecadal Variability: the Atlantic Niño
35 and Horse-Shoe (HS) mode. Nevertheless, the associated air-sea interactions for HS mode
36 have not been explored so far and the prevailing dynamic view of the Atlantic Niño has
37 been questioned. Here, using forced ocean model simulations, we find that for both
38 modes, ocean dynamics is essential to explain the equatorial SST variations, while air-
39 sea fluxes control the off-equatorial SST anomalies. Moreover, we demonstrate the key
40 role played by ocean waves in shaping their distinct structure and timing. For the positive
41 phase of both Atlantic Niño and HS, anomalous westerly winds trigger a set of equatorial
42 downwelling Kelvin waves (KW) during spring-summer. These dKWs deepen the
43 thermocline, favouring the equatorial warming through vertical diffusion and horizontal
44 advection. Remarkably, for the HS, an anomalous north-equatorial wind stress curl

45 excites an upwelling Rossby wave (RW), which propagates westward and is reflected at
46 the western boundary becoming an equatorial upwelling KW. The uKW propagates to
47 the east, activating the thermocline feedbacks responsible to cool the sea surface during
48 summer months. This RW-reflected mechanism acts as a negative feedback causing the
49 early termination of the HS mode. Our results provide an improvement in the
50 understanding of the TAV modes and emphasize the importance of ocean wave activity
51 to modulate the equatorial SST variability. These findings could be very useful to improve
52 the prediction of the Equatorial Modes.

53

54 **Plain Language Summary**

55

56 A recent study has found how the inter-annual variations of sea surface temperature (SST)
57 in the tropical Atlantic, are organized in two different equatorial modes during negative
58 phases of the Atlantic Multidecadal Variability. These modes, which illustrate a particular
59 and distinct spatial structure, are denoted as Atlantic Niño and Horse-Shoe mode. Here
60 we show that, for both patterns, ocean dynamics is key to generate equatorial SSTs, while
61 the off-equatorial SST anomalies are mainly explained by thermodynamic processes (heat
62 fluxes exchanges). Outstandingly, we demonstrate that ocean waves have a substantial
63 impact in the development and decay of Atlantic Niño and Horse-Shoe modes, shaping
64 their distinct spatial configuration and timing. Our results bring to light the importance of
65 ocean wave activity to explain the modulation of the equatorial Atlantic SST variability,
66 which could be relevant to improve its predictability and associated climatic impacts.

67 **1. Introduction**

68

69 The Atlantic Niño, also named as Equatorial Mode, is an air-sea coupled mode that
70 dominates the inter-annual tropical Atlantic variability (TAV) during boreal summer
71 (Zebiak 1993; Lübbecke et al. 2018). Its positive phase is characterized by a relaxation
72 of climatological trades and an anomalous warming in the eastern equatorial Atlantic.
73 The Atlantic Niño significantly influences the precipitation regime of remote and adjacent
74 areas (Kucharski et al. 2008; Polo et al. 2008a; Losada et al. 2012a; 2012b), causing
75 important socio-economic impacts (Rodríguez-Fonseca et al. 2015; Lübbecke et al.
76 2018). Thus, a complete understanding of the role of atmospheric forcings, as well as the
77 associated air-sea mechanisms and ocean dynamics, is necessary to anticipate these
78 phenomena. Remarkably, a recent study by Martín-Rey et al. (2018) has demonstrated a
79 modulation of the tropical Atlantic variability (TAV) modes under different phases of the
80 Atlantic Multidecadal Variability (AMV, Knight et al. (2006)). In particular, these
81 authors have brought to light a new overlooked equatorial mode, the so-called Horse-
82 Shoe (HS) mode, which coexists with the Atlantic Niño during negative AMV phases.
83 The HS pattern emerges as the second TAV mode during boreal summer, and is forced
84 by an ENSO event from previous winter (Martín-Rey et al. 2018). The positive phase of
85 HS is referred, hereinafter, to an anomalous equatorial warming surrounded by negative
86 SST anomalies in north and south-western TA (Figure S1b).

87 The co-existence of Atlantic Niño and HS during negative AMV phases, is understood in
88 terms of a distinct contribution of the Subtropical Highs acting under shallow mean
89 thermocline conditions in the eastern equatorial Atlantic. This could imply a more
90 effective Bjerknes feedback (Bjerknes 1969), enhancing the equatorial SST variability
91 and making the TA more receptive to external forcings (Martín-Rey et al. 2018). The
92 emergence of different configurations of the Equatorial Mode is a key element to
93 understand the multidecadal changes experienced by TAV, since different Atlantic Niño
94 structures have been associated with a modification of its climate impacts (Losada et al.
95 2012b; Martín-Rey et al. 2014; Losada and Rodríguez-Fonseca 2016; Martín-Rey et al.
96 2018).

97
98 Recent studies have questioned the air-sea interactions and ocean mechanisms
99 responsible to develop the Atlantic Niño, becoming a controversial topic (Lübbecke et al.
100 2010; Brandt et al. 2011; Richter et al. 2013; Nnamchi et al. 2015, 2016; Jouanno et al.
101 2017; Planton et al. 2018). Traditionally, it has been established that a relaxation of south-
102 easterly trades related to an anomalous weakening of the South Atlantic Anticyclone
103 (SAA), leads the generation of the Atlantic Niño (Polo et al. 2008a; Lübbecke et al. 2010).
104 These anomalous winds activate the dynamical Bjerknes feedback (Bjerknes 1969),
105 which drives the development of Atlantic Niño pattern and makes it self-sustaining
106 (Keenlyside and Latif 2007; Lübbecke and McPhaden 2013; Polo et al. 2015a). The
107 Bjerknes mechanism implies the propagation of equatorial Kelvin waves (Keenlyside and
108 Latif 2007), which can contribute to generate equatorial SST anomalies (Carton and
109 Huang 1994; Hormann and Brandt 2009; Lübbecke et al. 2010; Planton et al. 2018). The
110 ocean responds to the surface wind forcing through an adjustment of the vertical
111 stratification, giving rise to baroclinic (mode) Kelvin (KW) and Rossby waves (RW)
112 (Illig et al. 2004). These baroclinic ocean modes are characterized by opposite-sign
113 anomalies of sea surface height and thermocline depth and propagate with different phase
114 speeds (high-order modes are the slower ones, Illig et al. (2004)). Illig et al. (2004) and
115 Polo et al. (2008b) proposed an active contribution of the three first baroclinic modes
116 (ranging from 0.9 to 2.8 m/s and 0.28 to 0.89 m/s for KW and RW respectively) in the
117 equatorial Atlantic variability. In particular, these authors reported the existence of ocean
118 wave activity in the development and decay of the Atlantic Niño (Polo et al. 2008a;
119 Lübbecke et al. 2010). Nevertheless, other studies showed pronounced discrepancies
120 between events (Carton and Huang 1994; Hormann and Brandt 2009). Recent findings
121 have suggested alternative mechanisms to generate the equatorial Atlantic SST
122 variability, as equatorward advection of north tropical Atlantic subsurface temperature
123 anomalies (Richter et al. 2013) or equatorial deep jets (Brandt et al. 2011). Moreover,
124 Nnamchi et al. (2015); (2016) have argued that thermodynamic processes are enough to
125 create equatorial ocean variability, opening the debate about the dynamic prevailing view
126 of the Atlantic Niño.

127
128 In this context, the present study aims to clarify the air-sea interactions and oceanic
129 mechanisms responsible to generate the equatorial Atlantic variability. The co-existence
130 of two distinct Equatorial Modes (Atlantic Niño and HS) during negative AMV phases,

131 provides a favourable framework to investigate in detail the processes underlying their
132 development and decay. In particular, we will determine for the first time the air-sea
133 mechanisms and wave activity associated with the recently discovered HS mode, and
134 compare it with the Atlantic Niño pattern. For this purpose, an inter-annual simulation
135 with a forced ocean model has been performed and analysed for a negative AMV period
136 (1968-1995). Although coupled models suffer from strong and persistent biases in the TA
137 (Richter and Xie 2008; Richter et al. 2014; Wang et al. 2014), sensitivity experiments
138 correcting the surface winds reveal a considerably improvement in the simulation of the
139 TA climate (Goubanova et al. 2018). Thus, ocean simulations forced with observed
140 atmospheric fields, represent a good alternative to explore the TAV. Moreover, the ocean
141 model used in the present study, is able to compute interactively a closed heat budget in
142 the tropical Atlantic mixed layer. This allows us to investigate the different air-sea
143 processes and feedbacks involved in the development of the HS and Atlantic Niño modes.

144

145 The paper is organized as follows. The model description and methodology used are
146 detailed in Section 2. The results are explained in Section 3: the simulated TAV is
147 described in Section 3.1; Section 3.2 assesses the wave activity associated with the
148 development of the Atlantic Niño and HS patterns, while a closed heat budget analysis is
149 carried out in Section 3.3. Finally, the main findings and discussion are presented in
150 Section 4.

151

152 **2. Data and Methods**

153

154 ***2.1 Model description***

155

156 A tropical Atlantic configuration of the ocean NEMO model (Madec 2008), named
157 ATLTROP025 (Faye et al. 2015), has been used. The horizontal resolution is $\frac{1}{4}^\circ$ with a
158 tripolar grid and 46 z-levels. The ocean model has been forced by inter-annual air-sea
159 fluxes from the DRAKKAR forcing set, version DFS4.4 (Brodeau et al. 2010), for the
160 period 1958-2011. This inter-annual simulation, hereinafter INTER simulation, starts
161 from stable conditions taken from a stabilized climatological run. Nevertheless, to avoid
162 the initial shock of the model, the first two years of the experiment have been dismissed.
163 Thus, INTER covers the period 1960-2011 and reproduces quite well the TA seasonal
164 cycle and variance, although standard warm SST biases appear in the upwelling regions
165 (up to 1.5°C, Figure 1a). A cold bias is also shown in the western equatorial Atlantic
166 (Figure 1a), accompanied by a shallower mixed layer (not shown), reduced sea surface
167 height (SSH, Figure 1b) and a reduction of the east-west thermocline slope (Figure 1c).

168

169 Observations from HadISST (Rayner et al. 2003) and version 2.2.4 of SODA reanalysis
170 (Giese and Ray 2011) have been used to validate the modelled SST, thermocline depth
171 and SSH. The simulation of mixed layer depth (not shown) has been evaluated using the
172 observational climatology from de Boyer Montegut et al. (2004). Despite its persistent
173 biases, the tropical Atlantic variability is quite well simulated by INTER simulation
174 (Figure 2 and Figure S1).

175 The modelled variables used throughout the manuscript are: wind stress, SSH, SST and
176 the depth of the isotherm of 18°C as a proxy of thermocline depth (D18). In this study,
177 we consider D18 instead of the commonly used isotherm of 20°C, to assure a complete
178 representation of the tropical Atlantic subsurface, including the equatorial and coastal
179 upwellings. According to the results from Martín-Rey et al. (2018), the negative AMV
180 period 1968-1995 is analysed in the present study.

181

182 **2.2 Methods**

183 Inter-annual anomalies were computed by subtracting the climatological seasonal cycle
184 of the whole period (1960-2011). This calculation has been done for each 4-month season,
185 from JFMA to DJFM for the space-time fields. The amplitude interannual SST anomalies,
186 and thus the interannual modes, are strongly influenced by low-frequency variability
187 associated with natural decadal patterns (i.e: Atlantic Multidecadal Variability; Pacific
188 Decadal variability) or the anthropogenic forcing (Tokinaga and Xie 2011; Martín-Rey
189 et al. 2018). These low-frequency signals can modulate the amplitude and structure of the
190 SST anomalies in the tropical Atlantic, giving rise to the decadal modulation of the
191 interannual modes (Losada and Rodríguez-Fonseca 2016; Martín-Rey et al. 2018).
192 However, in the present study we focus on the interannual variability modes that emerge
193 during a negative AMV period. In order to isolate the inter-annual variability and subtract
194 the low-frequency signal and the global warming trend, a 7-year cut-off Butterworth filter
195 (Butterworth 1930) has been applied to the seasonal (4-month) anomalies. Focusing on
196 Atl3 index, as a proxy for the equatorial SST variability, we have verified that the
197 Butterworth filter used here has a very satisfactory response, retaining only those
198 frequencies between 2-7 years (not shown). Therefore, the Atl3 index does not contain
199 GW trend or the low-frequencies associated with natural decadal variability, which
200 exhibit a strong decadal peak (not shown). To better visualize the wave propagation, a
201 band-pass Butterworth filter that retains the frequencies between 60-days and 540-days,
202 has been applied to the 5-day mean data of wind stress and SSH anomalies.

203

204 We computed the dominant modes of TA SST variability using the principal component
205 analysis (PCA). PCA has been applied to the interannually filtered boreal summer (June-
206 July-August-September) SST anomalies in the tropical Atlantic region limited by the
207 model boundaries: [58°W-18°E, 31°S-30°N]. PCA technique provides the Empirical
208 orthogonal functions (EOFs) and associated time series (principal components, PC),
209 together with the percentage of explained variance (von Storch and Zwiers 2001). The
210 independence of the modes has been evaluated using the North criterion (North et al.
211 1982).

212

213 Most of the results of the present study are based on lagged regression maps. Seasonal
214 anomalies, for each 4-month season from JFMA to DJFM (shifting one month in each
215 consecutive season) are regressed onto the boreal summer (JJAS) PC of the Atlantic Niño
216 and HS mode. Similarly, 5-day SSH and wind stress anomalies, for each 5-day time step
217 from January to December, are regressed onto the Atlantic Niño and HS time series (PC).
218 Two transects along 2°N-4°N and along the equator, have been selected for the time-

219 longitude hövmoller diagrams. Statistical significance is assessed according to a t-test
220 with 95% confidence level.
221

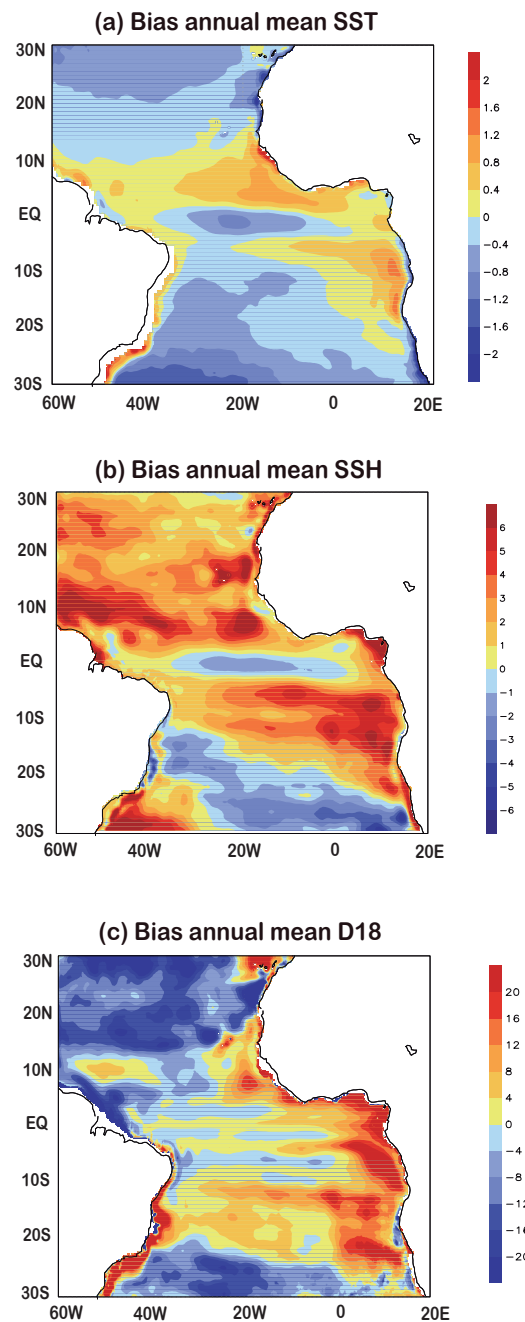


Figure 1. Validation of INTER simulation. Bias of the annual SST(a), SSH (b) and thermocline depth (D18, c) of INTER simulation with respect to SODA reanalysis for the period the period 1960-2008.

222

223 *2.3 Heat Budget analysis*

224

225 To determine the air-sea processes underlying the development of the HS and Atlantic
226 Niño mode, a closed heat budget analysis has been computed interactively by NEMO-
227 ATL TROP025 model in the TA mixed layer (ML). The temporal variations of the ML

228 temperature are given by a balance of atmospheric (a) and oceanic terms (b-c), according
 229 to the equation (Faye et al. 2015; Polo et al. 2015a):

230

$$231 \quad \partial_t \langle T \rangle = \underbrace{\frac{Q_s (1 - F_{z=h}) + Q^*}{\rho C_p h}}_a - \underbrace{\langle \overline{U_h} \cdot \overline{\partial_h T} \rangle + \langle D_l(T) \rangle}_b - \underbrace{\langle w \cdot \partial_t T \rangle - \frac{1}{h} (K_z \partial_z T)_{z=h}}_c + res \quad [1]$$

232

233

234

235

236 with $\langle \cdot \rangle = \frac{1}{h} \int_{-h}^0 \cdot dz$. The brackets denote the vertical integration over the ML with T and
 237 h representing the temperature and depth of the ML respectively; $\overline{U_h}$ and w are the
 238 horizontal and vertical currents; $D_l(T)$ is the lateral diffusion operator and K_z the vertical
 239 mixing coefficient. The *res* term has been calculated as a residual and is associated with
 240 the entrainment in the base of the ML. Thus, *res* term represents the upwelling of deep
 241 cold waters into the mixed layer. The net heat flux, Q_{net} , is divided in solar (Q_s) and non-
 242 solar (Q^*) components, and $F_{z=-h}$ is the exponential function that describes the fraction of
 243 shortwave fluxes penetrating in the ML. Finally, ρ is the seawater density and C_p is the
 244 seawater specific heat capacity coefficient.

245

246 The oceanic component includes horizontal (b, zonal and meridional advection and lateral
 247 diffusion) and vertical processes (c, turbulent mixing or vertical diffusion, vertical
 248 advection and entrainment). All terms from equation [1] are provided as outputs by
 249 INTER simulation for the period 1968-1995. The calculation of seasonal (4-month)
 250 anomalies for the different heat budget terms has been performed in a similar way than
 251 for the rest of the atmospheric and oceanic variables. This approach is a useful method to
 252 understand the oceanic processes related to the formation of ENSO (Vialard et al. 2001)
 253 and Atlantic Niño (Polo et al. 2015a).

254

3. Results

255

3.1 Simulated boreal summer tropical Atlantic variability

256

257 INTER simulation reproduces the observational results of Martín-Rey et al. (2018),
 258 hereinafter MR18, for the 1968-1995 period (Figure 2a-b). The Atlantic Niño and HS
 259 emerge as the first two leading modes, exhibiting significant equatorial SST anomalies.
 260 It is worth mentioning that the commonly used Atl3 index [20°W-0°,3°N-3°S],
 261 previously filtered, is a good indicator for both phenomena (Figure S1d). However,
 262 during negative AMV periods, when both modes co-exist, we also need an additional
 263 index referred to the western-equatorial Atlantic, WEQ [50°W-30°W,3°N-3°S], to
 264 determine which equatorial mode is emerging in the tropical Atlantic basin. For Atlantic
 265 Niño pattern, same sign SST anomalies are found in WEQ and Atl3 (stars, Figure S1d),
 266 while opposite-sign ones are exhibited during the HS mode (dots, Figure S1d). Notice
 267 that there are some years in which mixed events occurred (i.e: 1971,1973 or 1986). In
 268 those cases, the resultant spatial pattern will fit better with the Atlantic Niño or HS mode
 269 depending on the combination of the loadings of each PC (Figure 2c). The observed

270 explained variance and inter-annual variability are also well captured by the model
271 (Figure 2a-c and Figure S1a-b). This result confirms the important finding of MR18: the
272 existence of two distinct Equatorial Modes during negative AMV phases.

273 The basin-wide Atlantic Niño pattern described in MR18 for negative AMV phases is
274 well reproduced by INTER (Figure 2a and Figure S1a). INTER also simulates the general
275 reduction of tropical trades during previous winter-spring (Figure 5b,f), caused by a
276 simultaneous weakening of the Subtropical Highs (Martín-Rey et al. 2018). Interestingly,
277 The Atlantic Niño during negative AMV exhibits an early development, starting from
278 previous fall-winter (Figure 2d) and it is characterized by a westward extension of its
279 equatorial warm tongue (Figure 2a), compared with the canonical Atlantic Niño (see
280 Figure 5 in (Losada and Rodríguez-Fonseca 2016; Martín-Rey et al. 2018). The reduced
281 equatorial winds are accompanied by an elevation of the SSH in the eastern equatorial
282 Atlantic (purple contours, Figure 2a), in agreement with previous studies (Polo et al.
283 2008a; Lübbecke et al. 2010).

284
285 The emergence of the overlooked HS pattern during negative AMV phases is well
286 captured by INTER simulation (Figure 2b and Figure S1b). Moreover, the modelled
287 evolution of HS agrees with MR18: intensified northern and southern trades during
288 winter-spring and anomalous equatorial westerlies (Figure 6b,f), related to the ENSO-
289 induced atmospheric forcing (Martín-Rey et al. 2018). The weakened surface winds along
290 the equatorial band originate a zonal SSH gradient with positive anomalies in the central-
291 east and negative ones in the west (purple contours, Figure 2b). This SSH configuration
292 resembles the Kelvin and Rossby wave footprint, representative of the delayed-oscillator
293 mechanism (Battisti 1988; Schopf and Suarez 1988).

294
295 The spectrum analysis of these modes reveals that both modes own similar inter-annual
296 peaks (Figure S1c), although HS exhibits larger periodicity (~3.8 years) than the Atlantic
297 Niño (~2.3 years). It implies a higher frequency of occurrence of Atlantic Niño events
298 during the negative AMV period (compared with HS), in agreement with its larger
299 explained variance (Figure 2 and Figure S1). Interestingly, the seasonal evolution of the
300 equatorial temperature tendency denotes a distinct timing for these equatorial modes
301 (Figure 2d). The Atlantic Niño starts to develop in late winter (NDJF) and persists until
302 boreal summer (JJAS, blue line in Figure 2d), while HS pattern illustrates a shorter
303 development, centred in boreal spring (purple line in Figure 2d). The early development
304 and long duration of the Atlantic Niño is a special feature that appears during negative
305 AMV phases and be related to changes in the mean state (Martín-Rey et al. 2018) or the
306 interaction with the boreal winter equatorial variability ('Atlantic Niño II' described by
307 Okumura and Xie (2006)).

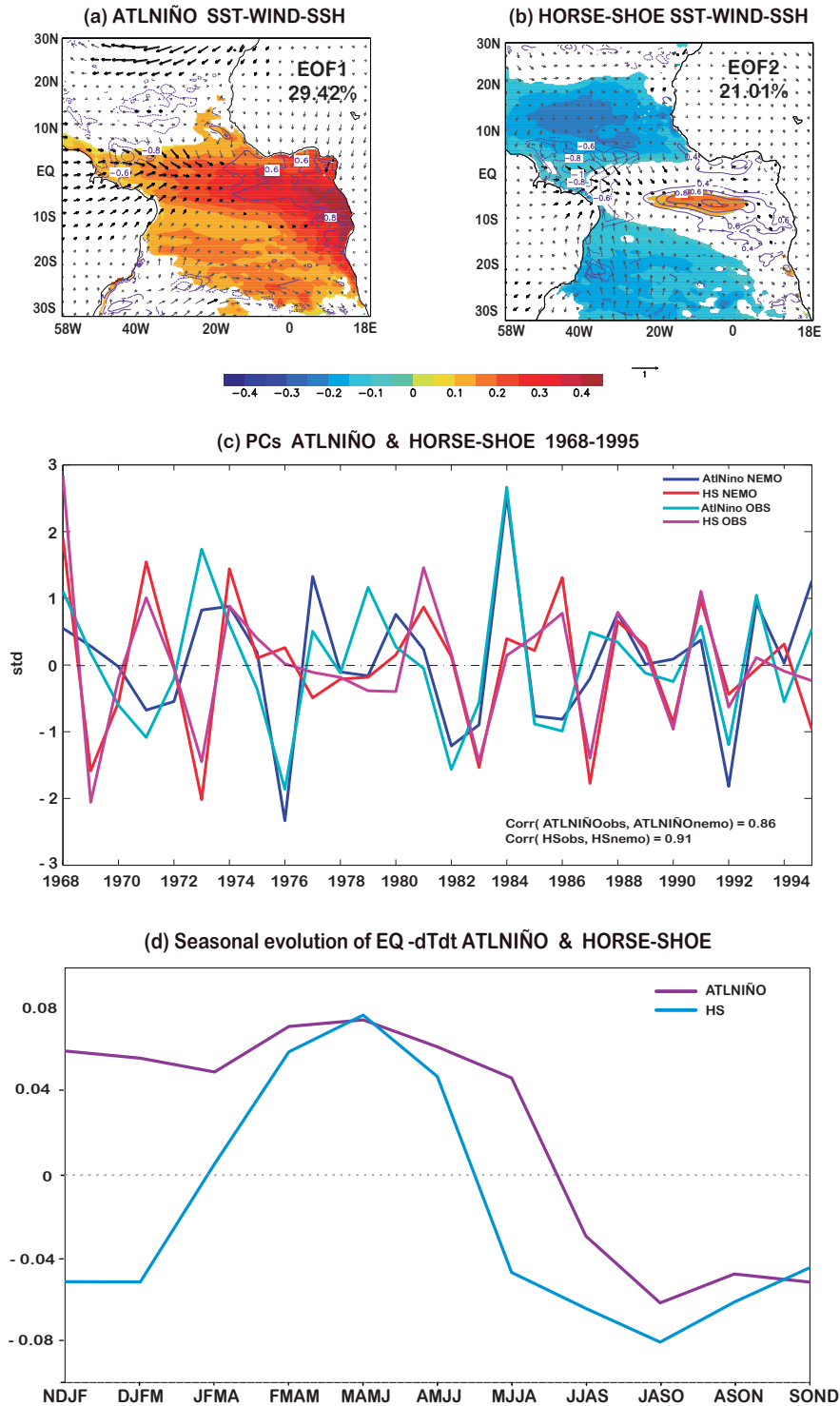


Figure 2. Simulated Atlantic Niño and HS mode. (a-b) Regression maps of anomalous simulated SST (shaded, °C), SSH (contours, cm) and observed surface wind (vectors, m/s) in boreal summer (JJAS) on the PC of the Atlantic Niño (a) and HS (b), also fixed in boreal summer (JJAS). Significant fields exceeding 95% confidence level according to a t-test are presented in shaded, black vectors and purple contours. (c) PCs of Atlantic Niño and HS for the negative AMV period 1968-1995 from model and observations. (d) Time evolution of seasonal temperature tendency in the ML averaged along the equatorial region [30°W-10°E, 5°N-5°S] for Atlantic Niño and HS from boreal winter (NDJF) to fall (SOND).

308 Our results provide further evidence about the differences between the Atlantic Niño and
309 HS modes, giving robustness to the co-existence of two distinct and independent
310 Equatorial Modes under negative AMV phases (Martín-Rey et al. 2018). It is worth
311 mentioning that, as pointed out by Losada and Rodríguez-Fonseca (2016), the classical
312 Atlantic Niño pattern has also changed during negative AMV periods. We have
313 demonstrated that, in addition to the basin-wide SST configuration, the stronger and
314 westward-shifted equatorial warm tongue, the Atlantic Niño also shows a longer
315 evolution during negative AMV phases (see Figure 5 in Martín-Rey et al. (2018)). All
316 these changes can be understood in terms of a modification in the tropical Atlantic mean
317 state during negative AMV periods. An enhanced thermocline slope could imply an
318 equatorial Atlantic more receptive to wind variations, favouring the activation of diverse
319 ocean dynamics and enhancing the SST variability (Martín-Rey et al. 2018). Under this
320 context, changes in the emergence and timing of the Equatorial Modes under different
321 AMV phases becomes reasonable. Furthermore, a potential interaction between the boreal
322 winter (Okumura and Xie 2006) and summer equatorial Atlantic variability can be also
323 explained the special evolution of the Atlantic Niño during those decades.

324

325 The realism of INTER simulation allows us to further investigate the ocean dynamics
326 involved in the development of HS and Atlantic Niño modes. The distribution of their
327 associated SSH anomalies (contours in Figure 2a-b) suggests a possible propagation of
328 oceanic waves. Thus, the wave activity is assessed in next section.

329

330 ***3.2 Wave activity during the Atlantic Niño and Horse-Shoe development***

331

332 The SSH footprint of HS and Atlantic Niño is also felt in the equatorial Atlantic
333 subsurface, illustrated by thermocline variations (Figure 3a and Figure 4a). The
334 simultaneous alteration of the SSH and thermocline depth suggests the excitation of
335 baroclinic ocean waves. To elucidate the wave activity, time-longitude diagrams of
336 regressed band-pass filtered 5-day SSH and wind stress anomalies onto the time series
337 (PC) of the Atlantic Niño and HS modes are displayed in Figure 3 and Figure 4.

338

339 For the Atlantic Niño, the decay of anomalous easterly winds in the western equatorial
340 Atlantic [50°W-40°W] in March originates an anomalous SSH elevation that propagates
341 eastward as a downwelling KW (dKW1_{AN}, Figure 3b). The dKW1_{AN} takes one month to
342 reach the African coast (yellow arrow, Figure 3b), consistent with a mix of first and
343 second baroclinic modes (~1.69m/s, Illig et al. (2004)). From April-May, an anomalous
344 wind burst in the western side of the basin triggers a secondary downwelling Kelvin wave,
345 dKW2_{AN} (~ 1.13m/s), propagating to the east as a mix of second and third baroclinic
346 modes (yellow arrow, Figure 3b). Both dKWs cause deeper thermocline conditions from
347 early spring to late summer (Figure 3a), allowing the Atlantic Niño warming to last up to
348 JJAS (Figure 2a, d).

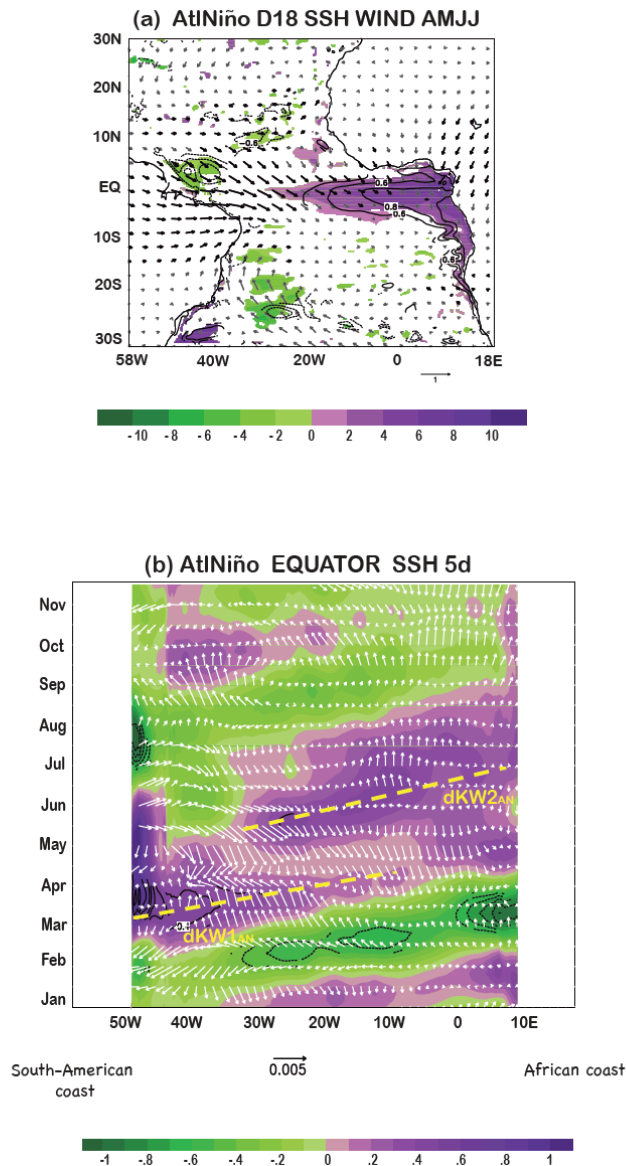


Figure 3. Wave activity involved in the development of Atlantic Niño. (a) Regression of the anomalous observed surface wind (vectors, m/s), thermocline depth (shaded, m) and SSH (contour, cm) in AMJJ onto the PC of Atlantic Niño fixed during boreal summer (JJAS). Significant values exceeding 95% confidence level according to a t-test are shown in shaded, black contours and vectors. (b) Time-longitude diagrams at the equator of the regressed 5-day SSH anomalies (shaded, cm) and wind stress (vectors, N/m^2) from January to December onto the PC of Atlantic Niño. Significant values exceeding 95% according to a t-test are shown in black contours. Downwelling KW are indicated by yellow arrows.

349 Our results corroborate the existence of Kelvin wave activity during the development of
 350 the Atlantic Niño, as proposed in previous studies (Carton and Huang 1994; Hormann
 351 and Brandt 2009; Lübbecke et al. 2010). Moreover, we demonstrate that a continuous
 352 Kelvin wave propagation occurs from spring to summer months (Figure 3b), pre-
 353 conditioning the equatorial band to generate strong and long Atlantic Niño events during
 354 negative AMV phases (Figure 2d and Figure 5 in Martín-Rey et al. (2018)). This has been
 355 confirmed using composite analysis (Figure S2a) and individual events (Figure S3).
 356 Moreover, our findings highlight the key role of ocean wave propagation in the generation
 357 of equatorial variability, in contrast with Nnamchi et al. (2015); (2016).

359 Noticeably, the development of the HS mode entails more complex wave activity than
360 the Atlantic Niño (Figure 4). An anomalous wind burst in the western equatorial Atlantic
361 [50°W-30°W] in April-May excites a dKW_{HS} , propagating as a mixed of first and second
362 baroclinic mode (~ 1.9 m/s) and reaching the African coast in June (yellow arrow, Figure
363 4c). As the dKW_{HS} displaces to the east, the SSH elevates and the thermocline deepens
364 (Figure 4a), favouring the development of the warm tongue (Figure 2b). The dKW is
365 reflected in the African coast, returning as an off-equatorial Rossby wave (yellow arrow,
366 Figure 4d). Interestingly, the wave activity in HS mode is not restricted to the local
367 excitation of equatorial Kelvin waves. The basin-scale wind stress field illustrates
368 intensified north-easterlies in NTA contrasting with westerly winds along the equatorial
369 band during boreal spring (purple vectors, Figure 4b). Consequently, an anomalous
370 positive wind stress curl appears north of the equator, associated with a downward Ekman
371 velocity (shaded, Figure 4b) that reduces the SSH in MAMJ (Figure 4d). This negative
372 SSH perturbation at 10°W-20°W propagates to the west as an upwelling RW (uRW_{HS})
373 from March- to July (blue arrow, Figure 4d), resembling a mix between second and third
374 baroclinic modes (~ 0.31 m/s). The uRW_{HS} is reflected at the western boundary in June,
375 becoming an equatorial $uKW1_{HS}$ (~ 2.33 m/s, mix between first and second baroclinic
376 modes; Figure 4e). The equatorial propagation of $uKW1_{HS}$ rises the thermocline in June-
377 July, allowing for the equatorial cooling (blue arrow, Figure 4e). This remotely-excited
378 $uKW1_{HS}$ acts as a negative feedback, causing the early termination of the equatorial
379 warming, and thus, the HS mode in boreal summer (Figure 2b,d). Notice that, a secondary
380 $uKW2_{HS}$ is triggered from August by anomalous local easterly winds in the western
381 equatorial Atlantic (blue arrow, Figure 4e). The $uKW2_{HS}$ supports the shallower
382 thermocline conditions created by $uKW1_{HS}$, maintaining the favourable scenario for the
383 surface cooling and also contributing to the damping of the HS mode (Figure 2b,d).
384 Additional calculations based on composite analysis (Figure S2c-d) and individual events
385 (Figure S4) confirm the key role of locally and remotely-excited oceanic waves in the
386 development and decay of the HS mode. It is worth mentioning that the RW-reflected
387 mechanism is clearer illustrated in individual HS events (Figure S4) than in the composite
388 map (Figure S2b-c) and regression analysis (Figure 4c-d). The RW-reflected mechanism
389 is found in all HS events, although several discrepancies are shown in the ocean wave
390 activity at the equator, being more active during certain years (i.e: 1981). Additional local
391 forcing, as anomalous wind burst in the western equatorial Atlantic can also trigger
392 equatorial KW that propagate eastward impacting in the SST anomalies, as described for
393 the Atlantic Niño events (Figure S2). Despite the expected differences, the coherent
394 results across diverse methodologies (i.e: regression maps, composites and individual
395 events) give robustness to the existence of the RW-mechanism during the HS mode.

396

397 Our results demonstrate the importance of ocean waves in shaping the structure and
398 timing of the Equatorial Modes. Indeed, they play a crucial role in the shorter
399 development of the HS pattern (Figure 4d-e). This RW-reflected mechanism was
400 previously reported as part of the interaction between the Meridional Mode (MM) and
401 the Atlantic Niño pattern (Foltz and McPhaden 2010a, 2010b). Foltz and McPhaden

402 (2010a) first identified the RW-reflected mechanism during the development of the
403 Meridional Mode acting as a negative delayed feedback for the generation of an Atlantic
404 Niño event during the following summer. Similar results were reported by Lübbecke and
405 McPhaden (2012) associated with the ENSO forcing over the tropical Atlantic variability.
406 These authors suggested that the RW-reflected mechanism is responsible for the
407 inconsistent equatorial Atlantic response to previous winter ENSO.

408

409 In addition, with those studies, recent findings have demonstrated that the RW-reflected
410 mechanism has a substantial contribution in generating equatorial SST variability during
411 summer months (Burmeister et al. 2016; Martín-Rey and Lazar 2019). Martín-Rey and
412 Lazar (2019) reveal that during the MM development, a competition between two
413 counteracting effects is established in the equatorial Atlantic: the RW-reflected
414 mechanism and the local wind forcing. Changes in the strength and persistence of each
415 forcing will determine the boreal summer equatorial SST anomalies following a
416 Meridional Mode event (Burmeister et al. 2016; Martín-Rey and Lazar 2019).

417

418 In summary, our results bring to light the ocean waves as a key element to modulate the
419 distinct Atlantic Equatorial Modes. In particular, the propagation of locally and remotely
420 excited ocean waves determine the equatorial vertical stratification, which shapes the
421 timing of the Equatorial Modes during negative AMV phases.

422

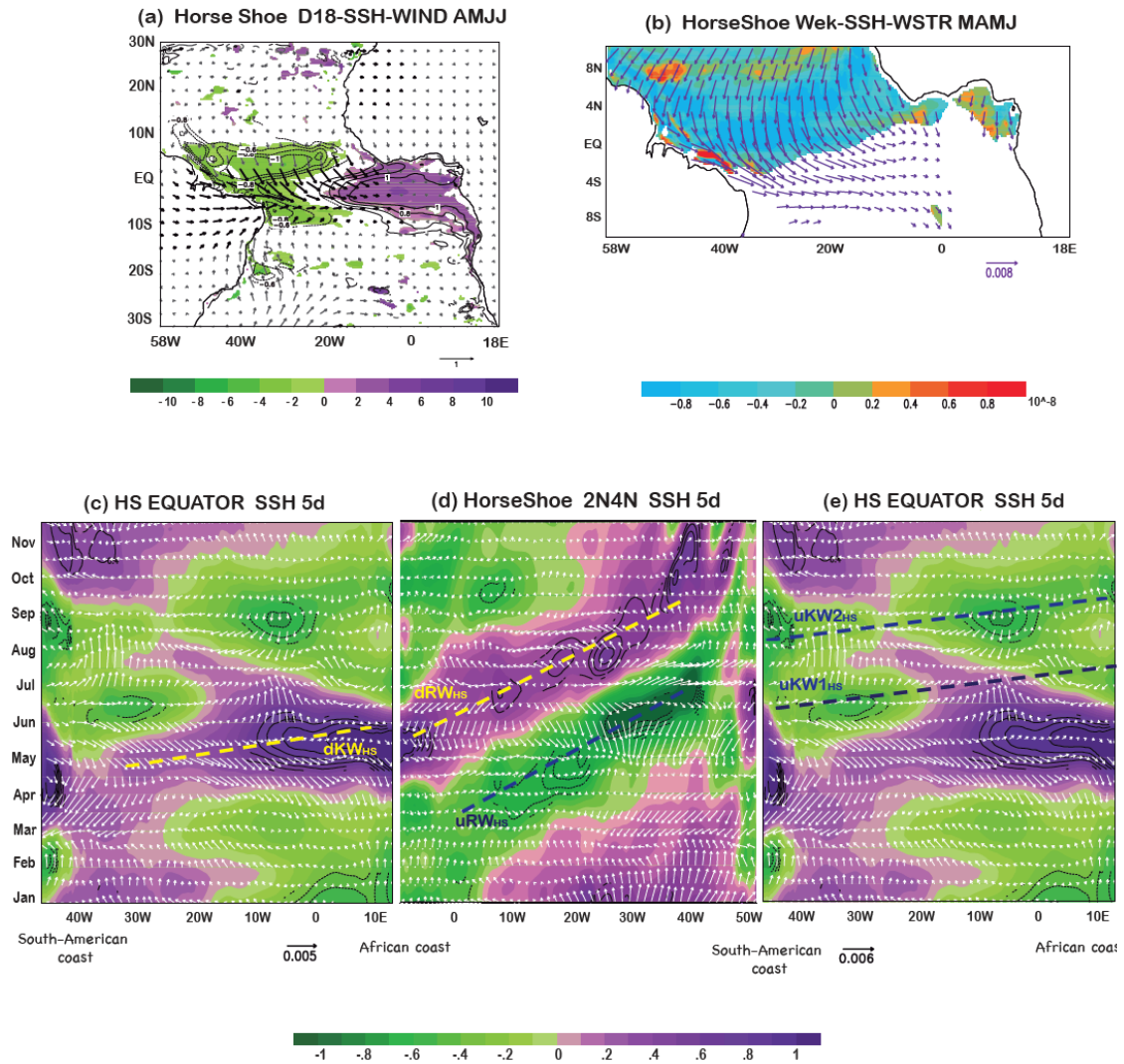


Figure 4. Wave activity involved in the development of HS. (a) Regression of the anomalous observed surface wind (vectors, m/s), thermocline depth (shaded, m) and SSH (contour, cm) in AMJJ onto the PC of the HS fixed during boreal summer (JJAS). Significant values exceeding 95% confidence level according to a t-test are shown in shaded, black and purple contours and vectors. (b) Regressed wind stress (vectors, N/m^2) and wind stress curl (shaded, N/m^3) in MAMJ onto the PC of HS fixed in boreal summer (JJAS). Significant values are shown in shaded, black contours and purple vectors. (c-e) Time-longitude diagrams at the equator (c,e) and $2^\circ N-4^\circ N$ (d) of the regressed 5-day SSH anomalies (shaded, cm) and wind stress (vectors, N/m^2) from January to December onto the PC of HS. Significant values exceeding 95% according to a t-test are shown in black contours. Downwelling (upwelling) KW and RW are indicated by yellow (blue) arrows.

423

424

3.3 Air-sea interactions in the Atlantic Niño and HS development

425

426

427

428

INTER reproduces quite well the observed TAV (Figure 2 and S1), providing a reliable ocean simulation to explore the ocean dynamics. To achieve a comprehensive understanding of the associated air-sea processes of Atlantic Niño and HS, a closed heat

429 budget analysis is carried out from previous winter to spring-summer months with INTER
430 simulation.

431

432 *3.3.1 Heat Budget analysis of Atlantic Niño mode*

433

434 For the positive phase of the simulated Atlantic Niño, weakened south-easterlies during
435 previous winter reduce the evaporative heat loss, warming the underneath region (Figure
436 5a-b). In Angola-Benguela area, anomalous temperature advection by horizontal mean
437 currents generates the surface warming (Figure 5c). In addition, anomalous along-shore
438 winds blowing southward produce an anomalous eastward Ekman transport, inhibiting
439 the upwelling and warming the coastal region (Figure 5d). Notice that the model exhibits
440 an underestimation of the Angola current, with enhanced mean westward currents in the
441 Angola-Benguela area (not shown). This can originate an overestimation of the horizontal
442 advection contribution in this area during the development of the Atlantic Niño. The
443 propagation of coastal Kelvin waves remotely forced at the equator can be responsible of
444 a large part of Angola-Benguela SST variability (Florenchie et al. 2003; Rouault et al.
445 2007; Polo et al. 2008b; Lübbecke et al. 2010; Rouault et al. 2018). Anomalous SSH
446 anomalies appear along south African coast in April-May (not shown), coherent with the
447 coastal propagation of dKW_{HS} and dKW_{AN} waves. This gives robustness to the
448 importance of ocean waves to generate SST anomalies in Angola-Benguela region. A
449 recent study has proposed air-sea fluxes and river discharge as additional sources for
450 Angola-Benguela SST variability (Lübbecke et al. 2019).

451

452 Along the equator, weakened trades during boreal spring trigger a sequence of dKW s that
453 propagate eastward from March to June (Figure 3b), deepening the thermocline (Figure
454 3a). It allows the activation of vertical diffusion that warms up the equatorial band (Figure
455 5d,h). These SSTs are advected off-equator and along the south-African coast by
456 horizontal mean currents, shaping the Atlantic Niño warm tongue (Figure 5c,g). In the
457 eastern equatorial Atlantic, at both sides of the equator, the reduced evaporation and cloud
458 cover generates a surface warming through radiative and latent heat fluxes (Figure 5b,f).
459 Finally, the SST over the equatorial band is reduced by surface fluxes (not shown).

460

461 In summary, INTER indicates that the southwestern lobe of Atlantic Niño pattern is
462 mainly generated by thermodynamic (air-sea fluxes) mechanisms, while dynamical
463 (thermocline and advective) feedbacks, activated by ocean wave propagation, are
464 essential to develop the equatorial SST anomalies.

465

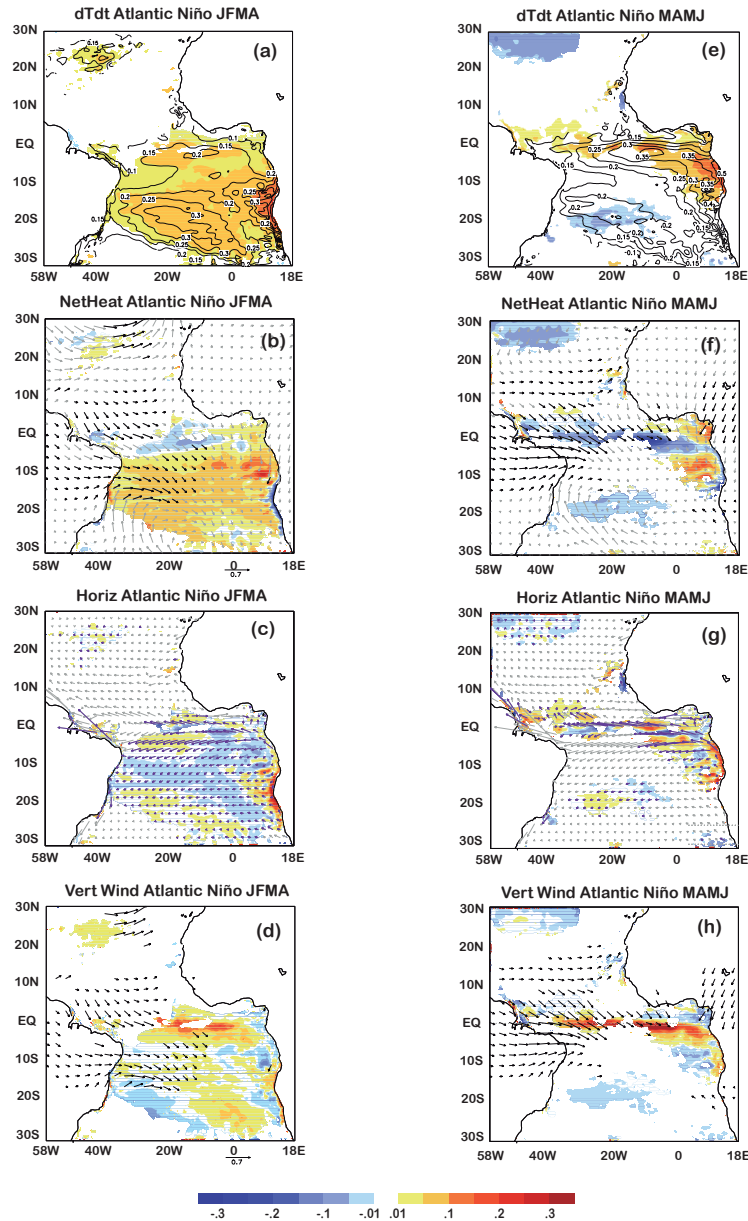


Figure 5. Heat budget analysis for Atlantic Niño. Regression maps of anomalous modeled heat budget terms (in $^{\circ}\text{C}/\text{month}$) in the ML and other variables in JFMA (left) and MAMJ (right) onto the PC of Atlantic Niño fixed in JJAS: (a,e) temperature trend (shaded) and SST (contour, $^{\circ}\text{C}$); (b,f) net surface heat fluxes (shaded) and surface wind (vectors, m/s); (c,g) horizontal terms (shaded) and mean currents (vectors, m/s); (d,h) vertical terms (shaded) and surface wind (vectors, m/s). Regressions for heat budget terms and mean currents are shown only when temperature tendency regression is significant. Significant fields exceeding 95% confidence level according to a t-test are shown in shaded, black and purple vectors and black contours.

466

467

3.3.2 Heat Budget analysis of Horse-Shoe mode

468

469

470

471

Regarding the simulated HS mode, intensified off-equatorial trades during boreal winter, increase the latent heat loss, cooling the sea surface and developing the HS branches (Figure 6a-b). At the equator, the locally wind-excited dKW_{HS} propagates eastward

472 during boreal spring (yellow arrow, Figure 4c), deepening the thermocline (Figure 4a)
473 and favouring the surface warming via vertical processes (i.e: vertical diffusion, Figure
474 6d,h). Horizontal advection illustrates an important contribution south of the equator and
475 along the West-African coast (Figure 6c,g). A significant contribution of surface heat
476 fluxes is also seen in MAMJ in the eastern equatorial warming, at both sides of the equator
477 (Figure 6f).

478

479 Interestingly, the excitation of uRW_{HS} , later reflected into uKW_{HS} (Figure 4d-e),
480 provides a negative feedback for the HS mode, causing its early termination in boreal
481 summer (Figure 2d). From June, as uKW_{HS} propagates to the east (Figure 4e), the
482 equatorial thermocline becomes shallower (Figure 4a), allowing the vertical diffusion of
483 deep cold waters and cooling the sea surface (Figure 6i,l). Anomalous temperature
484 advection by horizontal mean currents lead the off-equatorial cold SST anomalies (Figure
485 6k). This added to the substantial contribution of air-sea fluxes (Figure 6j), damps the HS
486 warm tongue in summer months (Figure 6i and Figure 2d).

487

488 Our results from the heat budget analysis, confirm that air-sea fluxes are the main drivers
489 of the HS branches and southwestern lobe of the Atlantic Niño mode. Furthermore, we
490 provide further evidence of the fundamental role of ocean dynamics to generate and
491 modulate the equatorial SST variability (Foltz et al. 2003; Polo et al. 2015a; Dippe et al.
492 2017; Jouanno et al. 2017). It is noteworthy that both thermocline and advective feedback
493 have a substantial contribution in the development of the Atlantic Niño warm tongue,
494 while thermocline feedback appears as dominant in the generation of the HS pattern. It is
495 can be understood by the continuous Kelvin wave propagation, dKW vs uKW , that
496 modify the vertical structure, activating the thermocline feedbacks. Thus, we conclude
497 that wave activity shapes the distinct timing and spatial configuration of the Equatorial
498 Modes during a negative AMV phase.

499

500 In the present study, the dynamical nature of the Atlantic Niño has been corroborated for
501 two distinct Equatorial Modes. Ocean dynamics based on vertical diffusion and horizontal
502 advection control the development of equatorial Atlantic SST variability, indicating that
503 thermodynamics are only important for the off-equatorial structure. This disagrees with
504 the results from Nnamchi et al. (2015); (2016), which claimed for the thermodynamic
505 origin of the Atlantic Niño. However, Nnamchi et al. (2015) findings are based on coupled
506 climate models that present a strong bias in their oceanic component (Wang et al. 2014),
507 causing an overestimation of the thermodynamic contribution (Jouanno et al. 2017). On
508 its part, Nnamchi et al. (2016) study of reanalysis datasets is based in an approximated
509 estimation of a not-closed heat budget analysis, in which the air-sea fluxes present a
510 significant but not unique contribution to the mixed layer temperature trend (Nnamchi et
511 al. 2016). Thus, those findings should be interpreted with caution.

512

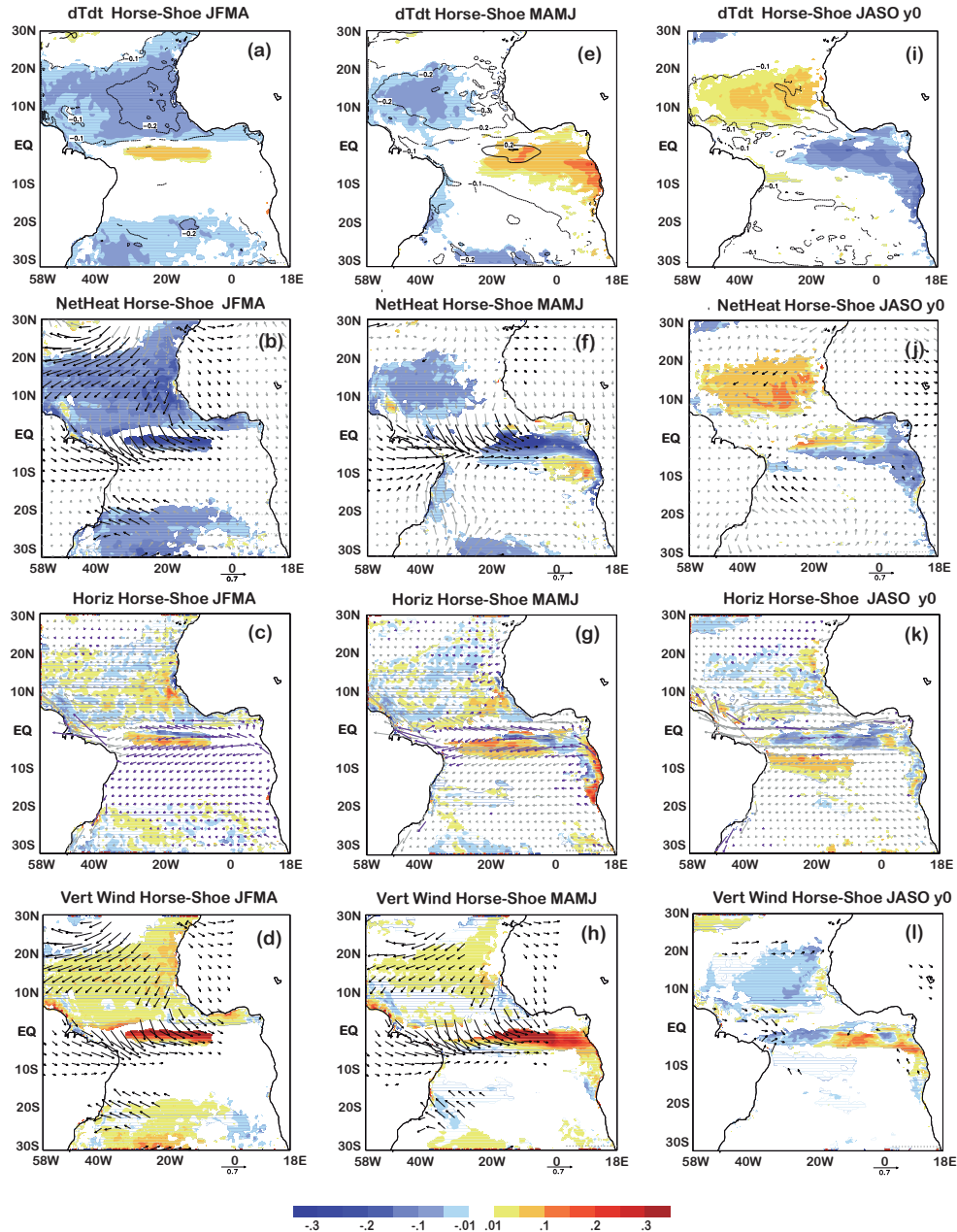


Figure 6. Heat budget analysis for HS. Similar than Figure 5 but for HS mode in JFMA, MAMJ and JASO.

513

514 4. Conclusions and Discussion

515

516 A previous study revealed the co-existence of two distinct Atlantic Equatorial Modes, the
 517 Atlantic Niño and Horse-Shoe, during negative AMV phases (Martín-Rey et al. 2018).
 518 During negative AMV, a shallower mean thermocline and enhanced SST in the eastern
 519 equatorial Atlantic provides a favourable scenario to investigate the processes that
 520 generate the Equatorial Modes. Moreover, the prevailing dynamic view of the Atlantic
 521 Niño has been recently questioned and additional mechanisms have been proposed to
 522 generate the equatorial Atlantic variability (Brandt et al. 2011; Richter et al. 2013;

523 Nnamchi et al. 2015, 2016). In this context, a better assessment of the air-sea processes
524 and wave activity responsible to generate the Atlantic Equatorial Modes is necessary.

525

526 The present study clarifies the mechanisms underlying the development of the Atlantic
527 Niño and HS mode. For this purpose, we have used an inter-annual forced ocean
528 simulation during a negative AMV period (1968-1995). The main conclusions achieved,
529 illustrated in Figure 7, are enumerated as follows:

530

531 ○ Atlantic Niño and HS modes (amplitude, structure and explained variance) are
532 well reproduced by the model. These two modes represent the inter-annual TAV
533 during the negative AMV period and exhibit different periodicity (~ 3.8 yr for HS
534 and ~ 2.3 yr for the Atlantic Niño).

535

536 ○ For both modes, locally and remotely-excited ocean waves play a fundamental
537 role in the modulation of their distinct structure and timing:

538

539 a) *Atlantic Niño*: anomalous equatorial westerlies in boreal spring and summer
540 trigger a sequence of downwelling KWs that deepen the thermocline, setting
541 up the favourable conditions to develop and sustain the Atlantic Niño warm
542 tongue.

543

544 b) *Horse-Shoe mode*: anomalous westerlies in spring excite a dKW_{HS} that
545 reduces the thermocline slope, favouring the warming of the equatorial band.
546 North-equatorial anomalous wind stress curl triggers an uRW_{HS} that propagates
547 westward during boreal spring. The uRW_{HS} is reflected at the western
548 boundary, becoming an upwelling KW_{HS} . The uKW_{HS} acts a negative
549 feedback causing the early termination of the HS mode during boreal summer.

550

551 ○ A closed heat budget analysis has been carried out and the main air-sea processes
552 responsible for Atlantic Niño and HS development have been identified:

553

554 ● a) *Atlantic Niño*: air-sea fluxes control the generation of southwestern TA
555 SST anomalies. The decelerated trades diminish the evaporative cooling,
556 warming the sea surface. At the equator, the propagation of the dKW_{HS}
557 activates the thermocline and advective feedbacks, responsible to develop
558 the Atlantic Niño warm tongue.

559

560 ● b) *Horse-Shoe mode*: intensified northern and southern trades enhance the
561 evaporative heat loss, cooling the sea surface and conforming the horse-
562 shoe branches. At the equator, the propagation of dKW_{HS} during boreal
563 spring decreases the thermocline slope, warming the mixed layer by
564 vertical processes (i.e: vertical diffusion). The remotely-excited uRW_{HS} is
565 western-boundary reflected into uKW_{HS} that causes the thermocline to

566 rise, activating the thermocline and advective feedbacks that cool the
567 equatorial band. This uKW_{HS} contributes to damp the initial equatorial
568 warming, causing the early termination of the HS.

569

570 Our results give robustness to the importance of ocean dynamics in the development and
571 decay of Equatorial Modes, clarifying its dynamical nature in contrast with the
572 thermodynamic's hypothesis. Especially noteworthy is the important role of the ocean
573 waves baroclinic modes in shaping the distinct structure and timing of Atlantic Niño and
574 HS modes during negative AMV. The RW-reflected mechanism is essential to understand
575 the early termination of the HS mode in boreal summer, and can be key to modulate the
576 connection between the Meridional Mode and Atlantic Niño (Foltz and McPhaden 2010a;
577 Burmeister et al. 2016; Martín-Rey and Lazar 2019).

578

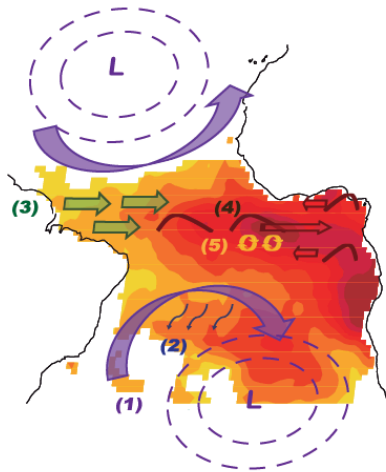
579 The present study provides an improvement in the current understanding of TA inter-
580 annual variability and its decadal changes. We have demonstrated, that during negative
581 AMV phases, the enhanced equatorial SST variability due to a favourable mean state
582 contribute to activate diverse ocean dynamics, creating distinct configurations of the
583 Equatorial Mode that co-exist in the tropical Atlantic basin. Figure 7 illustrates that the
584 Atlantic Niño equatorial SST anomalies are mainly generated by thermocline and
585 advective feedbacks (Figure 7a-b), while the enhanced ocean wave activity during HS
586 mode, implies a dominant role of thermocline feedback in the development of the
587 equatorial warm tongue (Figure 7c-d). It is worth mentioning the early beginning (Figure
588 2d) of the Atlantic Niño mode. This can be favoured by a more receptive tropical Atlantic
589 mean state, but can be also explained by a possible interaction with the so-called 'Atlantic
590 Niño II' peaking in boreal winter (Okumura and Xie 2006). During those decades, the
591 equatorial Atlantic SST variability from previous fall-winter to summer can be connected,
592 originating a longer and more intense Atlantic Niño. This deserves further research that
593 will be carried out by the authors in future studies.

594

595 Our findings provide useful information to improve the predictability of the Equatorial
596 Modes. Nevertheless, open questions still remain, aimed to clarify the connection
597 between the Meridional Mode and Equatorial Mode, as well as the contribution of
598 positive AMV background state or Global Warming in the development of TAV. Further
599 research is being carried out by the authors, in the framework of the H2020-EU
600 FESTIVAL project (ref. 797236) to clarify the precursor role of boreal spring variability
601 in generate the equatorial SST anomalies.

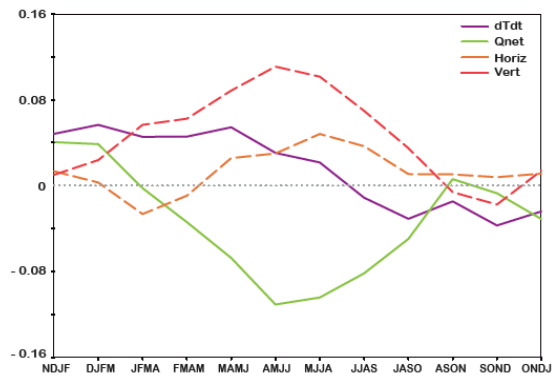
602

(a) Development of Atlantic Niño in AMO neg

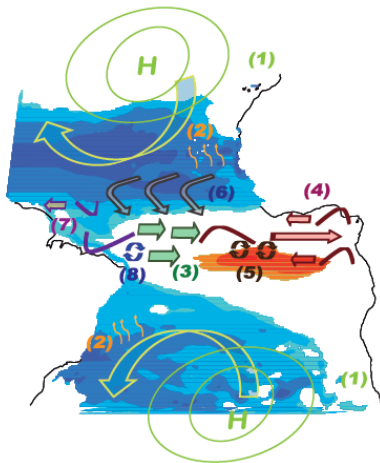


- (1) Weakened Subtropical Highs: reduced trades
- (2) Net heat fluxes warm the STA
- (3) Westerlies along the EQ
- (4) dKW's propagating eastward and reflected into dRW's
- (5) Vertical diffusion creates the equatorial warm tongue

(b) HB Atl3 [20W-0,3N-3S] Atlantic Niño



(c) Development of Horse-Shoe in AMO neg



- (1) Strengthened Subtropical Highs, Intensified trades
- (2) Net heat fluxes cool the NTA and STA
- (3) Westerlies along the EQ
- (4) dKWHs propagates eastward and is reflected into dRW at 5N and 5S
- (5) Vertical diffusion creates the equatorial warm tongue
- (6) Cross-equatorial winds create a negative Ekman pumping north of EQ
- (7) uRW at 2N-5N is boundary reflected into equatorial uKW
- (8) Vertical diffusion cools the mixed layer, damping the warm tongue

(d) HB Atl3 [20W-0,3N-3S] HS

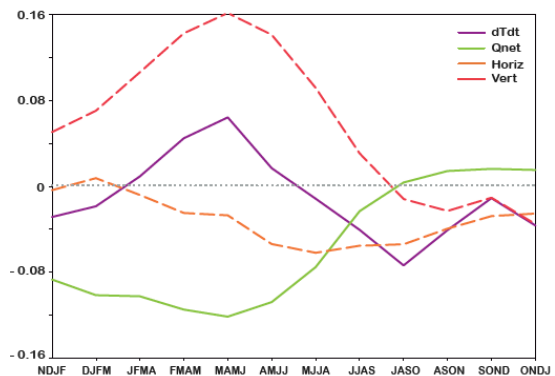


Figure 7. Mechanisms responsible for the development of Atlantic Niño and HS mode. Schematic of the Atlantic Niño (a) and HS (c) development during a negative AMV period. Time evolution of the heat budget terms in the Atl3 [20W-0,3N-3S] region for the Atlantic Niño (b) and HS mode (d) during the negative AMV period 1968-1995.

603 **Acknowledgements:** We would like to thank Jean-Marc Molines for his strong support
604 to perform the simulations with the NEMO model. The research leading to these results
605 received funding from the EU FP7/2007-2013 under Grant Agreement 603521
606 (PREFACE project), the MORDICUS grant under contract ANR-13-SENV-0002-01, the
607 PRE-4CAST (CGL2017-86415-R), CNES/EUMETSAT (CNES - DIA/TEC-2016.8595,
608 EUM/LEO-JAS3/DOC/16/852054), the MSCA-IF-EF-ST FESTIVAL (H2020-EU
609 project 797236) and the EU-TRIATLAS (ref. 817578). The observed SSTs from
610 HadISST dataset were provided by the MetOffice Hadley Centre, from its website
611 at <https://www.metoffice.gov.uk/hadobs/hadisst/>. The data from the INTER simulation
612 are available from the authors upon request.

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739

740 **Figure Caption**

741

742 **Figure 1. Validation of INTER simulation.** Bias of the annual SST(a), SSH (b) and thermocline
743 depth (D18, c) of INTER simulation with respect to SODA reanalysis for the period the period
744 1960-2008.

745

746 **Figure 2. Simulated Atlantic Niño and HS mode.** (a-b) Regression maps of anomalous
747 simulated SST (shaded, °C), SSH (contours, cm) and observed surface wind (vectors,

748 m/s) in boreal summer (JJAS) on the PC of the Atlantic Niño (a) and HS (b), also fixed
749 in boreal summer (JJAS). Significant fields exceeding 95% confidence level according to
750 a t-test are presented in shaded, black vectors and purple contours. (c) PCs of Atlantic
751 Niño and HS for the negative AMV period 1968-1995 from model and observations. (d)
752 Time evolution of seasonal temperature tendency in the ML averaged along the equatorial
753 region [30°W-10°E, 5°N-5°S] for Atlantic Niño and HS from boreal winter (NDJF) to
754 fall (SOND).

755

756 **Figure 3. Wave activity involved in the development of Atlantic Niño.** (a) Regression
757 of the anomalous observed surface wind (vectors, m/s), thermocline depth (shaded, m)
758 and SSH (contour, cm) in AMJJ onto the PC of Atlantic Niño fixed during boreal summer
759 (JJAS). Significant values exceeding 95% confidence level according to a t-test are shown
760 in shaded, black contours and vectors. (b) Time-longitude diagrams at the equator of the
761 regressed 5-day SSH anomalies (shaded, cm) and wind stress (vectors, N/m²) from
762 January to December onto the PC of Atlantic Niño. Significant values exceeding 95%
763 according to a t-test are shown in black contours. Downwelling KW are indicated by
764 yellow arrows.

765

766 **Figure 4. Wave activity involved in the development of HS.** (a) Regression of the
767 anomalous observed surface wind (vectors, m/s), thermocline depth (shaded, m) and SSH
768 (contour, cm) in AMJJ onto the PC of the HS fixed during boreal summer (JJAS).
769 Significant values exceeding 95% confidence level according to a t-test are shown in
770 shaded, black and purple contours and vectors. (b) Regressed wind stress (vectors, N/m²)
771 and wind stress curl (shaded, N/m³) in MAMJ onto the PC of HS fixed in boreal summer
772 (JJAS). Significant values are shown in shaded, black contours and purple vectors. (c-e)
773 Time-longitude diagrams at the equator (c,e) and 2°N-4°N (d) of the regressed 5-day SSH
774 anomalies (shaded, cm) and wind stress (vectors, N/m²) from January to December onto
775 the PC of HS. Significant values exceeding 95% according to a t-test are shown in black
776 contours. Downwelling (upwelling) KW and RW are indicated by yellow (blue) arrows.

777

778 **Figure 5. Heat budget analysis for Atlantic Niño.** Regression maps of anomalous
779 modelled heat budget terms (in °C/month) in the ML and other variables in JFMA (left)
780 and MAMJ (right) onto the PC of Atlantic Niño fixed in JJAS: (a,e) temperature trend
781 (shaded) and SST (contour, °C); (b,f) net surface heat fluxes (shaded) and surface wind
782 (vectors, m/s); (c,g) horizontal terms (shaded) and mean currents (vectors, m/s); (d,h)
783 vertical terms (shaded) and surface wind (vectors, m/s). Regressions for heat budget terms
784 and mean currents are shown only when temperature tendency regression is significant.
785 Significant fields exceeding 95% confidence level according to a t-test are shown in
786 shaded, black and purple vectors and black contours.

787

788 **Figure 6. Heat budget analysis for HS.** Similar than Figure 5 but for HS mode in JFMA,
789 MAMJ and JASO.

790

791 **Figure 7. Mechanisms responsible for the development of Atlantic Niño and HS**

792 **mode.** Schematic of the Atlantic Niño (a) and HS (c) development during a negative
793 AMV period. Time evolution of the heat budget terms in the Atl3 [20W-0,3N-3S]
794 region for the Atlantic Niño (b) and HS mode (d) during the negative AMV period
795 1968-1995
796
797
798