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Northward Pathway Across the Tropical North Pacific Ocean Revealed by Surface Salinity: How do El Niño Anomalies Reach Hawaii?

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► **To cite this version:**

Audrey Hasson, Martin Puy, Jacqueline Boutin, Éric Guilyardi, Rosemary Morrow. Northward Pathway Across the Tropical North Pacific Ocean Revealed by Surface Salinity: How do El Niño Anomalies Reach Hawaii?. *Journal of Geophysical Research. Oceans*, 2018, 123 (4), pp.2697-2715. 10.1002/2017JC013423 . hal-01835837

HAL Id: hal-01835837

<https://hal.science/hal-01835837>

Submitted on 21 Sep 2018

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Abstract (236 words)

Using the unprecedented 7-year monitoring of sea surface salinity (SSS) from the Soil Moisture Ocean Salinity (SMOS) satellite mission, an unexpected large-scale anomaly at 20°N is studied in the tropical Pacific Ocean following the 2015-2016 extreme El Niño event. This basin-wide negative anomaly (below -0.3) is present in October 2015 between 15 and 25°N, reaching the Hawaiian archipelago. It has not been previously observed during El Niño events. It is accompanied by a negative equatorial SSS anomaly at the dateline (below -0.5) which has been previously described as an El Niño-associated SSS anomaly. A wide range of observations (in situ and space-borne) and a state-of-the-art ocean model simulation are used together to characterize and understand the mechanisms leading to this singular SSS signal. The extra-equatorial negative SSS anomaly is found to be a superposition of a persisting SSS anomaly due to the 2014 weak El Niño and of the larger 2015-2016 El Niño SSS anomaly. Both were advected northward in the tropical current system by the mean Ekman currents and hypothetically by instabilities in the zonal currents patterns. An analysis of analogous structures in the past 20 years shows that this northward displacement of SSS anomalies is not El Niño specific, even if their advection is enhanced during El Niño events. This study shows that when surface freshwater fluxes are weak SSS, unlike sea surface temperature, can be used to trace water mass displacement for up to 20 months.

1. Introduction

The tropical Pacific Ocean is characterized by a large band of low sea surface salinity (SSS) centered around 10°N, with freshpools on each side of the Pacific Ocean: The West-Pacific fresh-pool (WFPF) (Delcroix and Picaut, 1998) and East-Pacific fresh-pool (EPFP) (Alory et al. 2012) respectively (Fig. 1a). Higher salinities on the poleward sides of the low SSS band belong to the sub-tropical salinity maximums described by Hasson et al. (2013a) and Gordon et al. (2015). If the mean SSS field is mainly due to the surface freshwater fluxes, as indicated by its agreement with the 0 and -1.5 m.yr⁻¹ isohyets (Fig. 1a), the meridional shift between the two structures reveals the importance of ocean dynamics (Yu et al. 2011, Hasson et al., 2013b, Tchilibou et al. 2015, Sena-Martins and Stammer, 2015). The spatial distribution of

59 the tropical Pacific SSS is characterized by longitudinal gradients along the Equator and 20°N
60 with strong seasonal and interannual variations in their amplitude and zonal location (Fig.
61 2ac, Maes et al., 2014, Kao and Lagerloef, 2014). At the Equator, the mean seasonal cycle
62 consists of an extension and intensification of the WPFP towards the east in the second half of
63 the year and an extension of the EPFP to the west from November to June each year. At 20°N,
64 the low SSS zonal variations are synchronous with the equatorial WPFP in the west. In the
65 east, they are shifted with respect to the equatorial EPFP cycle by a few months: their
66 extending phase occurs between June and January. This is consistent with the latitudinal
67 displacement of the seasonal SSS anomaly (SSSA) associated with the Intertropical Pacific
68 Convergence Zone (ITCZ) seasonality (Yu et al. 2015 and Sena-Martins and Stammer, 2015).
69 Figure 2 also shows large year-to-year variations, following the El Niño Southern Oscillation
70 (ENSO) phase, the leading mode of interannual variability in the Tropical Pacific. ENSO has
71 both local and global impacts on the oceanic and atmospheric circulations and leads to
72 many environmental impacts and societal havoc (Wang and Picaut 2004, McPhaden et al.
73 2006 and Sarachik and Cane, 2010). It includes a warm phase, El Niño, and a cold phase, La
74 Niña (see Philander, 1989) which intensity are usually measured by the Niño 3.4 index
75 (surface temperature anomaly within the 3.4 region – 5°S-5°N, 170°-120°W) shown on Figure
76 2. The relationship between ENSO and the sea surface temperature (SST) is well described in
77 the literature. At the equator, ENSO is associated with the zonal displacement of the western
78 Pacific warm pool (WPWP, Fig. 2bd). The WPWP plays a key role in the zonal basin-scale
79 atmospheric circulation called the Walker Circulation which is greatly perturbed during
80 ENSO events.

81

82 A number of studies have explored the connection between salinity and ENSO (e.g. Delcroix
83 and Picaut, 1998, Picaut et al., 2001, Gouriou and Delcroix, 2002, Bosc et al. 2009, Qu et al.,
84 2014, Qu and Yu, 2014). Deep atmospheric convection, associated with the ascending branch
85 of the Walker circulation over the WPWP, induces precipitation above 10 mm/day on average
86 in the area (<https://pmm.nasa.gov/TRMM/TRMM-based-climatology>). At 140°W, the
87 interannual SSS signal amplitude reaches 1, which is twice the seasonal signal. Interannual
88 SSS changes are due to variations of the surface freshwater fluxes but also of the ocean
89 dynamics. Both horizontal and vertical processes have been shown to play an important role
90 (Vialard et al. 2002 and Hasson et al., 2013ab, 2014, Gasparin et al. 2016, Qu et al., 2014).
91 SSS was shown to be a robust tracer for ENSO (Delcroix and Picaut, 1998, Singh et al., 2011,
92 Qu and Yu, 2014). Unlike SST, the ENSO signature in SSS is not only located within a few

93 degrees of the equator but reaches higher latitudes (Delcroix et al. 1998, Hasson et al. 2014).
94 This allows us to track the ENSO-related signal away from the Equator, something not
95 possible with SST because of the strong thermal air-sea coupling.
96 Studies have also underlined the active role of salinity in the tropical ocean dynamics through
97 its effect on the vertical density stratification. The presence of a haline stratification in the
98 WPPF, shallower than the thermal one, controls the mixed layer (ML) depth and creates
99 barrier layers (Lukas and Lindstrom, 1991, Sprintall and Tomczak, 1992, Qu et al., 2014).
100 The ocean responds to this salinity-controlled density stratification by decreasing entrainment
101 cooling and by intensifying the local response to wind stress. The westward South Equatorial
102 Current (SEC) brings saline water under the WPPF from the equatorial upwelling and
103 reinforces the barrier layer (Cronin and McPhaden, 2002). As the SEC is modulated by
104 ENSO, it induces a strong interannual variability of the barrier layer strength (Vialard and
105 Delecluse, 1998). SSS is found to play an active role in ENSO evolution (Ballabrera-Poy et
106 al., 2002, Vialard et al. 2002, Zhu et al. 2014) and a recent study found that the assimilation of
107 SSS in coupled forecasts yields longer ENSO predictability (Hackert et al., 2014).

108

109 Salinity is thus a unique tracer for tracking water mass displacement and as a rain gauge for
110 high rainfall areas (such as the ITCZ) but is also able to modulate sea-air interactions through
111 the formation of barrier layers.

112 Salinity has been extensively observed since the 2000s by the Argo program, with vertical
113 profiles from 5 to 2000 m depth (Roemmich et al., 2009). Since 2010, SSS is monitored at an
114 unprecedented resolution from space by the European satellite mission Soil Moisture Ocean
115 Salinity (SMOS), by the Argentinian-American satellite mission Aquarius and by the
116 American satellite mission Soil Moisture Active Passive (SMAP). These missions enable the
117 observation of SSS globally at a resolution between 50x50km² and 150x150km² every 3 to 8
118 days. More details on these are given in the Data/Methods Section of the present paper. This
119 suite of observations provides a unique opportunity for studying the interannual variability of
120 the upper ocean salinity with unprecedented details.

121

122 During the SMOS time period (2010-present), the Niño3.4 index reveals 2 distinct ENSO
123 phases (colored line, Fig. 2): one La Niña event (mid 2010-2011), a terminating El Niño event
124 (early 2010), a full El Niño event (mid 2015-mid 2016) and almost 3 years in a “neutral state”
125 (2012-2014). Indeed, SMOS started measuring surface salinity in 2010, just as a moderate El

126 Niño was finishing. Following this event, La Niña developed and lasted for about two years.
127 SMOS observations of the 2010-2011 La Niña event show a strengthened WPFP eastern front
128 and high salinity waters (above 35) reaching 150°E at the equator (Fig. 2a). The strongest part
129 of the signal is however found south of the equator in the SPCZ as was shown in a previous
130 study by Hasson et al. 2013b.

131

132 The presence of El Niño precursors in early-2014 (McPhaden et al., 2015), suggested the
133 development of a strong El Niño at the end of the year. However, the absence of sustained
134 westerly wind events and unusually strong easterly winds in summer 2014 are thought to have
135 halted the ongoing El Niño (McPhaden et al., 2015, Levine and McPhaden, 2016, Puy et al.
136 2016b, Zhu et al., 2016). Instead of shifting eastward, the WPWP remained west of the
137 dateline and the lack of atmosphere-ocean coupling stalled the developing El Niño. During
138 the following year, a major El Niño developed, to become one of the 3 strongest events ever
139 measured since 1950 (Blunden and Arndt, 2016, Paek et al. 2017). The state of the tropical
140 Pacific ocean at the end of 2014 has been suggested to have favored the outcome of this
141 unusually strong El Niño event (Levine and McPhaden, 2016) even though the random
142 occurrence of westward wind bursts can also explain its uniqueness (Puy et al. 2016b). By
143 spring 2015, the SST increased in the central and eastern equatorial Pacific with a strong
144 response of winds and atmospheric convection, leading to global atmospheric modifications
145 (Palmeiro et al. 2017). Negative SSSA were observed between 0 and 15°N around 170°W
146 from mid 2014 to mid 2015 (Boutin et al. 2016). This period was then followed by an
147 acceleration of the El Niño development till early 2016. The atmospheric convection
148 associated with the WPWP (i.e. the ascending branch of the Walker circulation) expanded
149 east of the dateline and well above average precipitation were found in the central equatorial
150 Pacific and south of the ITCZ, and below average near Indonesia.

151 By October 2015, and as expected, low salinities (below 35) and high temperatures were
152 found around the equator east of the dateline (Fig. 2ab and 4) highlighting the El Niño
153 eastward shift of the WPWP and WPFP described by Gasparin et al. (2016) and Corbett et al.,
154 (2017).

155

156 Additionally, significant freshening was observed around 20°N (Fig. 2b and 4) accompanied
157 with a slight increase in SST (Fig. 2d). While the equatorial SSS anomalies associated with
158 past El Niño have been well documented, thanks, in particular, to the SSS observations of the
159 TOGA/TAO network, the extra-equatorial anomalies less well known. This double anomalous

160 negative SSS feature appears to be specific to 2015. The extra-equatorial SSS anomaly is
161 indeed not represented by the canonical SSS patterns associated with either the Central or
162 Eastern Pacific El Niño events, as described by Singh et al. (2011) with 30 years of in situ
163 observations (their Figure 5). The negative SSS anomaly associated with El Niño events of
164 the observed period is located between 10°N and 20°S.

165

166 The 2015-2016 El Niño is the first event fully captured by the SMOS satellite mission, giving
167 us an unprecedented opportunity to investigate the associated extra-equatorial SSSA. It is also
168 the most powerful El Niño monitored by the fully deployed Argo program (Gasparin et al.,
169 2016, Corbett et al., 2017). Guimbard et al. (2017) observed the extent of the EPFP (less than
170 34.5 in their study) to be 20% larger in 2015 than the climatology and to reach the dateline by
171 the end of 2015. During the previous rainy season the preconditioning in 2014 of the zonal
172 extension of the EPFP was found to be an essential factor enabling the development of the
173 2015 maxima.

174

175 In this paper we combine the analysis of satellite observations with a numerical simulation in
176 order to investigate the unexpected 2015 northern tropical Pacific ocean SSS signal and the
177 processes driving it. Data and methodology are presented in section 2. Section 3 presents the
178 observation and analysis of the 2015 SSSA followed by the presentation of the mechanisms
179 revealed from observation and modeling. Analogous events during the 1996-2014 period are
180 also discussed. A discussion, conclusions and perspectives are given in section 4.

181

182 **2. Data / Methods**

183 This study is based on the combined use of observations (satellite, in situ) and a numerical
184 simulation. All datasets and relevant characteristics are presented in this section.

185

186 **2.1. Observational Datasets**

187 SMOS satellite salinity and an optimal interpolation of Argo float salinity measurement
188 datasets are at the center of our investigation.

189 The SMOS satellite mission was launched in November 2009 as the second European Space
190 Agency (ESA) Earth Explorer (Kerr et al. 2010). It has been delivering space borne SSS since
191 January 2010. The level-3 SMOS product used here is developed by the CATDS CEC-
192 LOCEAN and known as debias_v2. This product is corrected for coastal biases following an
193 improved method described in Kolodziejczyk et al. (2016) and for latitudinal biases (Boutin et
194 al. 2017 in revision). This dataset is available on a $0.25 \times 0.25^\circ$ EASE grid, smoothed over 18
195 days and available every 4 days from January 2010 to the end of 2016. The accuracy of this
196 SMOS SSS dataset in the open ocean is estimated to be better than 0.2 and is specifically
197 assessed in our region in the present paper.

198 Numerous in situ SSS datasets are available. We use mooring datasets for their high temporal
199 resolution timeseries available from the mid 90s at specific locations and an optimal
200 interpolation of in situ observations (mainly Argo floats) for its synoptic coverage.

201 The TAO-TRITON array has been deployed in the tropical Pacific Ocean in order to study
202 ENSO and its predictability following the 1982-1983 event. Moorings provides many high
203 temporal resolution ocean and atmosphere measurements. Here, we use daily salinity and
204 temperature measurements at various depth (McPhaden, 2006). As many moorings have gaps
205 in their timeseries surface salinity and temperature data were also retrieved from the Woods
206 Hole Oceanographic Institution Hawaii Ocean Timeseries Site (WHOTS) mooring at 22°
207 $45'N$, $158^\circ W$. Mooring data is used in the present study for point-comparison of SSS and SST
208 in order to assess other data quality. Whenever available, measurements from sensors at 1m
209 depth were used and, when unavailable, the 10m depth sensor was used to get the longest
210 possible time series. Stratification in the first 10 m is assumed to be negligible at the
211 interannual time scale. Difference between the surface and 10m salinity can however
212 sometimes reach 1 locally but on average the vertical salinity differences are -0.03 in the
213 tropics (Drucker and Riser, 2014) No flag was used for the TAO data as they were found to

214 be not fully reliable as shown by Tang et al. (2017). This is further explained in section 2.4.
215 Only “Acceptable measurements” were used for WHOTS mooring.

216 The optimal interpolation “In Situ Analysis System” (ISAS) combines temperature and
217 salinity measurements mainly from Argo floats profiles, TAO-TRITON moorings and vessels
218 CTD casts. ISAS provides monthly fields of temperature and salinity from the surface ocean
219 down to 2000m and on a near global $.5^{\circ}\times.5^{\circ}$ horizontal mesh (Gaillard et al., 2016). In this
220 paper, we use the 5m depth level and version 6.2 of the ISAS algorithm applied in a delayed
221 mode (with careful in situ data evaluation) until 2012 (Gaillard et al., 2016) and in near real-
222 time data after 2012 (Brion et al., 2011). ISAS uses covariance scales of 300 km in longitude,
223 proportional to the Rossby radius of deformation in latitude, and 30-day in time. The
224 resolution of scales less than 300 km by the monthly gridded values is expected to be poor,
225 even though it is weighted by the number of nearby data and their location.

226 Additional observational data have been used in order to study the mechanisms behind the
227 observed salinity variations, amongst which the Sea Surface Temperature (SST) from the
228 National Climatic Data Center of the National Oceanic and Atmospheric Administration
229 (NODC/NOAA), the surface currents (U) from the Geostrophic and Ekman Current
230 Observatory (GEKCO), evaporation (E) from Ocean-Atmosphere (OA)Flux and precipitation
231 (P) from the Global Precipitation Climatology Project (GPCP).

232 The SST product is hereafter referred to as Reynolds SST (Reynolds et al., 2007). This
233 gridded $\frac{1}{4}$ -degree daily product (V2.0) is an optimal interpolation from combined datasets
234 derived from satellites and in-situ data (from ships and buoys). Reynolds SST is available
235 from 1981 till present. Based on satellite wind stress and altimeter sea level, GEKCO
236 provides daily geostrophic and Ekman currents at a $.25^{\circ}$ spatial resolution from 1992 to
237 present (Sudre et al. 2013). Currents within 2 degrees of the equator are discarded. GPCP
238 precipitation data are available in its version 2.1 from October 1996 to October 2015 in a
239 daily 2.5-degree resolution mesh (Huffman et al. 2009). The OAFlux project supplies
240 evaporation data on a monthly 1° spatial grid from 1958 to present (Yu et al. 2008). Niño 3.4
241 SST anomalies were retrieved from the NOAA Earth Sciences Research Laboratory (ESRL)
242 and subsequently smoothed by a 5-month moving average.

243 Nearly all in situ salinities are based on seawater conductivity providing Practical Salinity
244 measurements. Even though the difference is not noticeable at our scale of interest in the
245 tropical Pacific Ocean, all salinities have been converted into absolute salinities using the
246 Thermodynamic Equation of Seawater (TEOS-10) established by the Intergovernmental

247 Oceanographic Comity (IOC) and are expressed in g.kg^{-1} (IOC, SCOR and IAPSO, 2010).
248 Using absolute salinity allows a direct comparison of observations and model salinities
249 (Wright et al. 2011).

250

251 **2.2. Numerical simulation**

252 To further analyze the SSSA associated with ENSO in 2015, forced oceanic experiments were
253 performed. The NEMO v3.2 model (Nucleus for European Modelling of the Ocean, Madec et
254 al., 2008) was set up in a 1° resolution global configuration (ORCA1, Hewitt et al., 2011),
255 with local transformations in the tropics leading to a $1/3^\circ$ meridional resolution at the equator.
256 The model vertical resolution is 10m at the surface, 25m at 100m depth and 300m at 5000m
257 depth, resulting in 42 vertical levels. More details on the model configuration and assessment
258 can be found in Puy et al. (2016a). The numerical simulation provides daily outputs of all the
259 needed parameters for this study such as salinity, temperature and currents but also all the
260 terms of the mixed layer salinity budget equation (see Section 2.5).

261 The model is forced by the DRAKKAR Forcing Set v5.2 (DFS5.2, Dussin and Barnier 2013),
262 derived from ERA 40 (Uppala et al. 2005) until 2002 and ERA-Interim reanalysis (Dee et al.
263 2011) afterwards. The model is used in the present study to compute the salinity budget of the
264 mixed layer (ML) and therefore no direct SSS restoring can be used. In order to prevent the
265 salinity drift associated with the absence of restoring, a correcting term is computed as an
266 additional freshwater surface fluxes. This methodology was already used and described by
267 Vialard et al. (2002) and more recently by Hasson et al. (2013a, 2013b and 2014). The
268 computation of the correcting terms requires the run of a first simulation with a very strong
269 surface damping (i.e. 1000 mm/day). The 1985-2015 average correction on the freshwater
270 fluxes is computed from this first simulation and then added to the DFS5.2 forcing in the
271 second simulation. This way the simulation does not drift over time but keeps its dynamical
272 integrity for the time scales of interest. The correction corresponds to about 3.26% of the
273 average forcing field on our region of interest (10°S - 30°N , 140°E - 70°W). The ML salinity
274 budget is computed online at every model computation time step, the ML depth being defined
275 as the depth at which the density differs by 0.01 from the surface.

276 This model reproduces relatively well the interannual variability of the tropical Pacific Ocean
277 in 2014 and 2015 (Puy et al. 2016ab). The model is further assessed, especially in terms of
278 salinity, in Section 2.4.

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2.3. Filtering time series

All anomalies were computed as described below. The common period of all datasets i.e. 2010-2015 is used to build a monthly climatology. Given the short length of the period, filtering the time series without excluding data on either end is challenging. Our first solution is to construct a monthly climatology is built from 25-month Butterworth high-pass filtered data. The difference between the climatology over the 2010-2015 and the full record period of each dataset is small and does not impact the results of this paper. This high-passed monthly climatology is then subtracted from the original dataset to create a first estimation of the interannual anomalies and is referred to as the “limited” interannual filter. This filtering methodology preserves each end of all time-series but does not filter out the intraseasonal variability. This “limited” interannual filter is used when investigating events close to the end of the time-series. A second solution uses the same processing but adds an additional 13-month low-pass filter to remove the residual high frequency variability and preserve the interannual variability. This more “robust” protocol is used whenever possible (i.e. 6-month away from either end of the time-series). Figure 3 shows interannual anomalies from the “limited” and “robust” filters from the 2010-2015 monthly climatology at two mooring sites (stars on Fig. 1a). Both filters remove the seasonal cycle adequately. As expected the “limited” filter leaves out some intraseasonal variability. This signal appears to be associated with waves such as tropical instability waves and barotropic Rossby waves (Kessler et al. 2006; Farrar 2011).

301
302

2.4. SSS datasets assessment

303 Comparison of the in situ, space-borne and simulated salinity datasets were made both at
304 selected mooring positions and at the basin scale.

305 The coherence among the different products is estimated at several mooring sites in terms of
306 SSS and SST. All datasets were compared to their closest neighbor and filtered using the
307 “limited” and “robust” filters described above. This comparison is illustrated for SSS at the
308 dateline-Equator TAO and the WHOTS moorings (stars on Fig. 1a; Fig. 3). All datasets in
309 Fig. 3a show coherent variability in SSSA at the equator. TAO mooring timeseries
310 suspiciously departs from other datasets by 0.5 in April 2003 highlighting possible issues with

311 the TAO data. Interannual SSS variations are however well represented, for instance during
312 ENSO phases (i.e. 1997, 2002, 2007, 2010 and 2015). Further north at WHOTS, observations
313 consistently show weaker variability than at lower latitude (Fig. 3b). SSS variations do not
314 show any apparent correlation with ENSO (Niño 3.4 index). We point out the strong
315 agreement between the mooring and SMOS SSS at both interannual and intraseasonal
316 timescales. The model shows stronger interannual variations. Moreover, the bathymetry
317 around the Hawaiian Islands, and thus currents, is very complex. The model is expected to
318 inaccurately represent the variability close to the islands.

319 In order to further assess the datasets, statistics at 18 moorings (stars and dots on Fig. 1a)
320 were computed (Table 1). Statistical comparisons were made for the TAO moorings Quality
321 Control (QC)'ed data and for the whole time-series regardless of the QC, and it was found 1)
322 that there were not enough QCed data points to compute significant comparisons at most
323 moorings and 2) the results presented below do not differ substantially whether non QCed
324 data is used or not. The TAO moorings measurement and the ISAS product are not strictly
325 independent but it is expected that the objective analysis of ISAS will smooth out large TAO
326 errors so it could be used to remove the largest errors in the TAO data. TAO minus ISAS SSS
327 Root Mean Square Deviation (RMSD) is used to test the TAO dataset. Wherever the TAO-
328 ISAS RMSD is larger than 0.3°C for SST and larger than 0.2 for SSS the TAO mooring
329 dataset is discarded. Filters described above are not used for this comparison. The mooring
330 data was averaged in time to reflect the other datasets time-resolution, leading to significant
331 differences in the number of points of comparison between datasets. Table 1 provides a
332 summary of the RMSD at the two moorings presented above (Fig. 3) and at all sites together.
333 NEMO- and Reynolds- TAO SST RMSD are below .5 and $.4^{\circ}\text{C}$ respectively showing a good
334 accuracy of both means of SST. NEMO and SMOS reproduce accurately TAO measurements
335 (RMSD both around 0.25) even though some dubious measurements are still present in the
336 TAO dataset.

337 In order to further validate the large scale features which are of particular interest for the
338 present study, the October 2015 SSA is shown for SMOS, ISAS and the model in Figure 4
339 using the “limited filter”. Patterns of the zonally-oriented basin-wide negative SSSA are
340 consistent amongst the products. Firstly, the structure of the strongest anomaly, centered
341 around the Equator and the dateline, is well simulated by the model when compared to both
342 observation datasets, although its eastward extent is slightly reduced. Secondly, a fresh tongue

343 extends eastwards from the first anomaly, centered around 8°N and 5° wide in latitude, as
 344 seen in SMOS observations and as reproduced well by the model. It is however very smooth
 345 and non-continuous in the ISAS optimal interpolation as expected from the product's
 346 effective resolution. Thirdly, the vast region of negative anomaly north of 10/15°N is
 347 consistently seen in the model and in the observations. Finally, the patches of positive SSSA
 348 bracketed by the negative ones west of the dateline are also very coherent from one product to
 349 another. These features will be further described in the Results Section. The good agreement
 350 between in situ and SMOS SSS datasets is well known. Since satellites only measure the first
 351 cm of the water column and Argo top measurement is on average 5 m, stratification in the
 352 tropical areas can be substantial (see Boutin et al., 2016 for a review). It was however shown
 353 that at the large scale the impact of stratification is reduced (Druker and Riser, 2014).
 354 Differences in measurement methods must hence be kept in mind.

355 This assessment gives us confidence in the consistency of all datasets to reproduce the SSS
 356 interannual variability in the tropical Pacific Ocean, as described by the TAO moorings. It
 357 further shows the particular capacity of SMOS observations and model simulations to
 358 reproduce observed detailed structures such as the sharp frontal features that optimal
 359 interpolations, such as ISAS, struggle to represent.

360

361 **2.5. Salinity Budget Processes**

362 The ML salinity budget equation can be written as below (e.g. Hasson et al., 2013).

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$$364 \quad \underbrace{\partial_t \mathbf{S}}_I = \underbrace{(E - P) \frac{\mathbf{S}}{H}}_{II} + \underbrace{-\vec{u} \cdot \vec{\nabla} \mathbf{S}}_{III} + \underbrace{\vec{\nabla} (K_h \cdot \vec{\nabla} \mathbf{S})}_{IV} + \underbrace{(w + \partial_t H) \frac{1}{H} \delta \mathbf{S}}_V + \underbrace{\partial_z (K_z \cdot \delta \mathbf{S}) \frac{1}{H}}_{VI} \quad (1)$$

365

366 Term *I* (g.kg⁻¹.year⁻¹) denotes the rate of change of salinity within the ML. The salinity
 367 averaged within the ML is denoted by \mathbf{S} . The terms on the right-hand side of the equation
 368 describes the budget. Term *II* represents the freshwater forcing from the atmosphere onto the
 369 ML of depth *H*. The land freshwater contribution to the budget can be neglected in the
 370 tropical Pacific Ocean at the scales of interest. The horizontal processes are described by
 371 terms *III* and *IV*, which represent the advection by the ML horizontal currents and the
 372 horizontal mixing, respectively. Terms *V* and *VI* describe the vertical processes at the bottom

373 of the ML. The vertical advection and entrainment are represented by term V . Term VI
 374 corresponds to the vertical mixing. K_h and K_z are the horizontal and vertical diffusion
 375 coefficients, and δS the vertical salinity gradient across the ML base.

376

377 Even though the processes at fine scales are parameterized by the diffusion coefficients, it is
 378 not possible to close this budget from observations only, given its complexity. All terms of
 379 the full salinity budget (Eq. 1) can be computed from the NEMO numerical simulation at
 380 every iteration step (online) except for the entrainment (residual). They are then averaged and
 381 archived daily.

382 Aside from the fine scales, the processes at depth within the ocean (e.g. at the bottom of the
 383 ML) are too complex to account for with in situ observations as shown by various studies
 384 (Hasson et al. 2013, Sommer et al 2015, Gasparin et al. 2016, Guimbard et al. 2017). The
 385 observation-based budget is therefore simplified as:

$$386 \quad \underbrace{\partial_t SSS}_I = \underbrace{(E - P) \frac{SSS}{H}}_{II} + \underbrace{-\vec{u} \cdot \vec{\nabla} SSS}_{III} + \text{residuals} \quad (2)$$

387 Where the SSS and the surface currents (u) are assumed to be representative of the ML. All of
 388 the vertical and fine scale terms are included in the residuals (IV , V , VI of Equation 1) and
 389 only the SSS tendency (I), freshwater fluxes (II) and horizontal advection (III) are
 390 represented. Following the SMOS product resolution, the observation based budget is
 391 computed from 18-day low pass filtered data from which the median is computed within 2.5°
 392 of latitude and 5° of longitude to force all datasets to have the most consistent resolution and
 393 to smooth out the noise.

394

395 **3. Results**

396 **3.1. The October 2015 20°N SSS anomaly**

397 **3.1.1. Description**

398

399 By the end of 2015, significant freshening is observed around 20°N (Fig. 2c, Fig. 4). SSS
 400 decreases across the basin at this latitude from mid-2014 to 2016 (Fig. 2c). The EPFP edge,
 401 denoted by the “eastern” 35 isohaline, reaches the dateline. This basin-wide freshening is
 402 represented in all SSS observations and the model (Fig. 3b and 4) and has an amplitude
 403 greater than 0.5 between 10 and 25°N. This feature is hereafter referred to as the 20°N
 404 anomaly. It is accompanied by a large equatorial freshening of about 1 in the western part of

405 the basin, centered around the dateline (Fig. 2a and 4). Fresh waters (below 35) are found east
406 of the dateline from mid 2015 to mid 2016 and the two freshpools join one another (Fig. 2a).
407 As described in the introduction, the equatorial SSS decrease is associated with the eastward
408 shift of the WFPF associated with El Niño and was described by Gasparin et al. (2016) and
409 Corbett et al. (2017). The large equatorial negative SSSA (below -0.5) lies between 160°E-
410 160°W and 8°S-8°N with an extension spreading all the way to 90°W and 10°N, forming a
411 “sigma-shaped” pattern.

412

413 The two large-scale SSSAs are separated by a band of weaker anomalously fresh waters
414 centered around 10°N. A positive +0.3 anomaly extends east from north of Papua New
415 Guinea to 170°E (Fig. 4). This is consistent with Singh et al. (2011) analysis of El Niño
416 composite patterns of SSS.

417 This anomalous negative interannual SSS double-pattern (i.e. equatorial and extra-equatorial)
418 is specific to the year 2015. Singh et al. (2011) found SSSA associated with El Niño events to
419 be concentrated south of 10°N. During the 2002-2003 and 2009-2010 El Niño events, no
420 freshening is found around 20°N, both in ISAS, SMOS (2010 only) and modelling datasets
421 (Fig. 3b). In addition, the model does not show any significant freshening around 20°N for any
422 of the simulated El Niño events during 1985-2013 (Fig. 3b).

423 In the present study, we show how the October 2015 20°N SSS anomaly was generated and
424 how the equatorial and extra-equatorial anomaly are related.

425

426 **3.1.2. Build-up of the 20°N SSS anomaly**

427 The 20°N SSS anomaly first appears in 2014 as shown by observation and modelling (Fig. 3b
428 and Fig. 2c). SSS decreases consistently amongst products at WHOTS mooring from early
429 2014 to the end of 2015 (Fig. 3b). The analysis of SMOS interannual monthly SSSA shows
430 that the 20°N SSS anomaly appears to originate west of the dateline in the equatorial region in
431 early 2014 (Fig. 5a-d). The model simulation shows gradual build-up over 2014-2015 (Fig.
432 5e-h). The evolution of the April 2014 negative anomaly can be described from observations
433 and modelling as follows.

434 In April 2014, an equatorial negative interannual SSS anomaly of below -0.3 is present west of
435 the dateline (Fig 5ae). From April to October 2014, SSS decreases across a large band,
436 roughly from 5 to 10°N and from the dateline to the American coast. A zonal bipolar anomaly
437 is in place around the equator in October 2014 with an anomaly of -0.3 west of 170°E and

438 +0.3 to the east (Fig. 5 bf). This “sigma shaped” anomaly resembles the canonical SSS signal
439 associated with ENSO described by Singh et al. (2011), even if El Niño is not developing in
440 2014. By April 2015, the equatorial anomaly starts its eastward shift expected from the 2015
441 El Niño event development (Fig 5cg). North of 5°N, the anomaly is intensified and spreads all
442 the way to 20°N. From April to October 2015, the negative equatorial anomaly intensifies to
443 be well over -0.5 and reaches the dateline (Fig. 5dh). Similar to October 2014, the anomaly
444 becomes “sigma shaped” as a narrow 5°-10°N less fresh anomaly band develops. By October
445 2014, the positive anomaly centered on 5°S and the dateline has nearly disappeared to the
446 east. The 20°N anomaly (<-0.5) is distinct and spans from 10 to 25°N (Fig. 5dh). The model
447 shows a weaker anomaly than the observations but has consistent salinity patterns and timing.
448 This discrepancy could be explained by very near surface stratification as the model averages
449 salinity over the mixed layer (with a minimal depth of 10m, corresponding to the 1st level of
450 the model) whereas SMOS measures the first centimeter. Moreover, this discrepancy can also
451 be due to imprecision in the model’s mixing parametrization and its coarser resolution north
452 of 10°N. Note that the equatorial Pacific Ocean is in a very similar state in April 2014 and
453 April 2015 in terms of SSS (Fig. 5aecg). By October the difference between 2014 and 2015 is
454 substantial. In 2015, the “sigma-shaped” anomaly fully develops and is seconded by the wide-
455 spread 20°N anomaly (Fig. 5dh). In early 2016, both anomalies weaken, even though the
456 northward extension is still apparent (not shown).

457

458 During this period, saltier than usual waters occur off Baja California. This anomaly lasted all
459 through 2014 and 2015 (Fig. 5a-d), which seems consistent with the warmer than usual waters
460 found in this region at that time and called “the Blob” (Di Lorenzo and Mantua, 2016,
461 Gentemann et al. 2017, Hu et al. 2017). Further exploration of this SSS anomaly and its
462 relation to the “Blob” temperature anomaly are needed, but are beyond the scope of this
463 study.

464

465 These strong interannual SSS variations are driven by freshwater fluxes (evaporation and
466 precipitation) and the ocean currents and mixing through the salinity balance equation (Eq. 1).
467 Freshwater fluxes are important in the region of interest with the strongest values (below -1.5
468 m.yr⁻¹) occurring in the ITCZ, South Pacific Convergence Zone (SPCZ) and WPWP regions,
469 roughly between 5 and 10°N across the basin and between 10°S and 10°N west of 170°E (Fig.
470 1a). Freshwater fluxes have a strong variability at all timescales, which is evident from April
471 2014 to October 2015 (Fig. 5) and are consistent with SSSA to the first order, especially in

472 October 2014 and 2015. Discrepancies however underline the non-negligible role of ocean
473 dynamics. North of 10°N, the westward flowing North Equatorial Current (NEC) is the
474 southern branch of the sub-tropical gyre (Fig. 1b, grey contours). The North Equatorial
475 Counter-current (NECC) runs eastward between 3 and 10°N with an average speed of .25 m/s.
476 The SEC spans from 10°S to 3°N and is concentrated in two westward jets on each side of the
477 equator of about .3 m/s speed. Trade winds not only force the zonal currents but also induces
478 the equatorial upwelling and associated poleward meridional divergence called the Ekman
479 drift. Tropical oceans have a short response time to atmospheric variations and therefore the
480 currents system shows intense variability at seasonal and interannual time scales (Philander,
481 1990) as shown from April 2014 to October 2015 (Fig. 5, arrows). Patterns of SSSA and
482 currents show an interesting coherence. It is however not straight forward how freshwater
483 fluxes and surface currents interact to produce the observed SSS anomalies. Further
484 investigation is performed in the following section, by considering the salinity budget over
485 2014-2015 from observations and modelling to shed light on the mechanisms leading to the
486 20°N SSSA.

487

488 **3.1.1. Associated Processes**

489 Observations of SSS, freshwater fluxes and surface currents can provide an estimation of the
490 SSS budget (Eq. 2) that can only represent surface processes (Fig. 6). The model on the other
491 hand provides a full budget (Eq. 1) and provides details on the mechanisms that are
492 unresolved by observations such as vertical processes (Fig. 7dhl).

493 Between April and October 2014, negative SSS tendencies are found between approximately
494 5° and 10°N across the basin (Fig. 6a and 7a) leading to the narrow SSSA extension described
495 above (Fig. 5bf). The observation budget shows that the freshwater fluxes do not account for
496 all of this SSS decrease (Fig. 6, left column). East of 150°W, the freshwater fluxes act to
497 decrease the SSS north of the negative SSS tendency. The model confirms the role of
498 advection which can only be indirectly inferred from observations (Fig. 7, left column). The
499 SEC-induced advection increases SSS within 5° of the equator, whereas an intensified NECC
500 brings fresher waters from the western part of the basin between 5° and 10°N. The equatorial
501 anomalous fresh waters associated with the 2014 weak El Niño are therefore advected by the
502 NECC far into the center of the basin. Vertical processes have a damping effect on the SSS
503 changes because of their dependence on the vertical stratification as described by Vialard et
504 al. (2002) and Hasson et al. (2013a).

505 During the following 6-month period (October 2014 to April 2015) shows negative SSS
506 tendency north of 10°N, corresponding to the 20°N anomaly build-up. It is also accompanied
507 by the equatorial SSS decrease due to the developing 2015 El Niño event (Fig. 6 and 7,
508 central column). Observed and modelled freshwater fluxes are important during this period
509 but do not coincide with the northern SSS tendency as they are mostly damped by vertical
510 processes. In the model, horizontal advection appears to be the main driver of the SSS
511 decrease north of 10°N brought by zonal currents (Fig. 7). Currents indeed drive low SSS
512 advected in the 5-10°N area during the previous 6-month period to the north. Hasson et al.
513 (2014) found the Ekman drift to drive SSSA southward during the 2010-2011 La Niña in the
514 western tropical Pacific. It is hypothesized that the Ekman drift is also responsible for the
515 northward SSSA advection observed in 2014-2015. This hypothesis is further explored below.
516 This low SSS signal is not as affected as much by vertical processes as waters brought by the
517 zonal currents. As shown by Gasparin et al. (2016), horizontal advection and vertical
518 processes control the equatorial SSS decrease.

519 The 20°N anomaly continues its build-up through the next 6-month period (Fig. 6 and 7, right
520 column). Negative SSS tendency is found within 10° of latitude of Hawaii. Similarly to the
521 previous period, the freshwater flux does not drive this SSS change as seen both for
522 observations and the model. If the analysis of observed horizontal advection does not allow to
523 draw any conclusions, the modelled advection clearly has an impact on the SSS tendency (Fig
524 7k). In mid 2015, El Niño is developing in the Pacific and the seasonal eastward flowing
525 NECC is in place whereas the SEC has nearly disappeared. The NECC reverts north into the
526 NEC around 100°W, then flowing westward between 10° and 20°N. As for the previous 6-
527 month period, we make the hypothesis that the Ekman drift is driving this northward
528 advection. Vertical processes are opposing horizontal advection north of Hawaii and help to
529 eventually dissipate the negative SSSA. During this period, the 20°N anomaly appears in
530 conjunction with the canonical 10°S-10°N El Niño SSSA, with a strong negative tendency
531 between April and October 2015 and extending to the American continent. From April 2015,
532 El Niño develops and the entire atmospheric circulation is gradually modified, impacting
533 freshwater fluxes. Precipitation then increases across the tropical Pacific Ocean and especially
534 east of the WPWP climatological position and south of the ITCZ and SPCZ climatological
535 positions, leading to intense interannual surface freshwater fluxes across the tropical Pacific
536 ocean. Our budget confirms that a combination of all terms explains the associated equatorial
537 SSS decrease (Gasparin et al. 2016). North of Papua New-Guinea and in the Solomon Sea, the
538 effect of interannual freshwater forcing is positive, which is consistent with the modification

539 of the Walker circulation. A region of weakly increasing SSS is also present around 10°N
540 separating the two negative tendency regions. Modelled advection reveals the role of the
541 NECC advecting positive SSSA from the north of the Papua New-Guinea to the center of the
542 basin.

543

544 Analyzing the SSS budget over successive 6-month periods has enabled us to track the
545 sequence of processes leading to the unexpected 20°N SSS anomaly observed and modelled in
546 October 2015. To summarize these processes, negative SSSAs are formed at the Equator,
547 west of the dateline, under El Niño conditions during January-April of the 2014 and 2015.
548 They are subsequently advected eastward between 5° and 10°N by the NECC and amplified
549 by freshwater fluxes until October of each year. The 2014 and 2015 negative SSSAs continue
550 to be advected north but also zonally as the NECC retroflects to the north into the westward
551 flowing NEC. The SSSAs diminish as the seasonal NEC declines and are advected northward
552 reaching the Hawaiian Islands by April. They subsequently linger in the area. This cycle
553 happened twice, with the weak El Niño in 2014 and the strong event in 2015, and created the
554 unprecedented anomaly of October 2015.

555 It is however still not clear which mechanisms are behind the northward advection of the
556 equatorial SSSAs, whether it is specific to El Niño conditions and why it has not been
557 observed in the past. In order to investigate this, the longer records of SSS from SMOS, ISAS
558 and the model are now considered.

559

560 **3.2. Northward pathway of equatorial SSSA**

561

562 At every occurrence of El Niño during the observed period (i.e. 2002-2003, 2009-2010 and
563 2014-2015) a negative SSS anomaly shows an apparent northward displacement between
564 150-170°W (Fig. 8a-c). In addition, northward displacements of SSSAs also occur during
565 neutral periods, i.e. 2005 or 2007. Negative SSSAs are present at the equator west of 170°W
566 during strong El Niño events especially in 1998 and 2015 when the equatorial anomaly
567 spreads eastward. During the 1997-1998 El Niño event and in the model, only a weak
568 anomaly reaches 20°N early 2000. SSSAs in 2002, 2010 and 2014 only reach 170°W at 5°N
569 (Fig. 8a-c). In 2014, the SSSA is advected by the NECC eastward to 170°W between 5° and
570 10°N (Fig. 5c). The evolution of SSSA patterns from October 2002 to April 2004 and from
571 October 2009 to April 2011 (Fig. 9) is coherent with what has been described above for 2015

572 (Fig. 5). An equatorial anomaly is present west of the dateline in October of the first year. Six
 573 months later, the anomaly spans across the basin between 5 and 15°N. The SSSAs become
 574 apparent between 150°-170°W (Fig. 8a-c). In October of the second year, the anomaly begins
 575 its northward course and reaches 20°N by April of the second year (Fig. 8a-c and Fig. 9).

576 To focus on this northward displacement the interannual SSS budget is computed from the
 577 model and presented as latitude-time plots averaged within 150-170°W (Fig. 10). The SSS
 578 tendency shows the displacement of anomalies from 5-10°N to 20-25°N in about 18 months
 579 over the entire period (Fig. 10a) mirroring Figure 8c. Significant freshwater fluxes only occur
 580 south of 10°N and do not show any northward displacement (Fig. 10b). The horizontal
 581 oceanic processes clearly appear as the main driver of the SSSA displacement (Fig. 10c).
 582 Vertical oceanic processes have a buffer effect on abrupt changes in SSS, resulting from
 583 surface fluxes and horizontal dynamics (Fig. 10f), as found in the 2014-2015 budget analysis.
 584 In order to investigate in more detail the role of the different terms acting in the horizontal
 585 processes and to better understand the northward movement of SSSAs, the Ekman advection
 586 is computed off-line from the model as follows:

587

$$\begin{aligned}
 589 \quad \underbrace{\vec{u} \cdot \vec{\nabla} \mathbf{S}}_{III} + \underbrace{\vec{\nabla}(\mathbf{K}_h \cdot \vec{\nabla} \mathbf{S})}_{IV} &= (\vec{u}_e + \vec{u}_{ne}) \cdot \vec{\nabla} \mathbf{S} + \underbrace{\vec{\nabla}(\mathbf{K}_h \cdot \vec{\nabla} \mathbf{S})}_{IV} \\
 590 \quad &= \underbrace{\vec{u}_e \cdot \vec{\nabla} \mathbf{S}}_{VII} + \underbrace{\vec{u}_{ne} \cdot \vec{\nabla} \mathbf{S}}_{VIII} + \underbrace{\vec{\nabla}(\mathbf{K}_h \cdot \vec{\nabla} \mathbf{S})}_{IV} \quad (3)
 \end{aligned}$$

588

591 Budget term numbers follow Equation 1, where III is the horizontal advection, IV is the
 592 horizontal mixing. VII represents the Ekman advection and VIII the non-Ekman advection
 593 (Fig. 10de). The Ekman current (u_e) is computed from the model wind and the non-Ekman
 594 current (u_{ne}) is the difference of u_e from the total current. Ekman currents are not computed
 595 within two degrees of the equator.

596 We hypothesized from the 2014-2015 budget analysis, that northward advection of SSSA is
 597 mostly driven by the Ekman currents. SSSAs are advected poleward throughout the 1996-
 598 2016 period, regardless of the ENSO phase of the ocean (Fig. 10cd). ENSO however
 599 modulates the 0-10°N SSSA intensity (Singh et al., 2011) that is subsequently advected north
 600 (Fig. 8a-c). The large SSSA created by ENSO acts as a tracer to highlight the northward
 601 pathway described in the present study. This northward movement is further modulated by
 602 freshwater fluxes (Fig. 10b) as seen for instance in 2014-2015 when they reinforce the
 603 negative SSSA. Conversely, the 1997-1999 SSS budget suggests that the equatorial negative

604 anomaly advected north by the Ekman currents (Fig. 10d) is opposed by positive freshwater
605 fluxes and vertical processes (Fig. 10bf). The 1997 El Niño event therefore triggered a strong
606 freshening of the equatorial region that hardly appears at 20°N.

607 Following their advection within the NECC (5-10°N), the equatorial SSSAs continue their
608 northward journey driven by the Ekman drift into the NEC (10-15°N) and then northward out
609 of NEC to around the latitude of the Hawaiian Islands (~20°N) where they are slowly eroded.

610

611 **4. Summary and conclusions**

612 In 2015, an unusually large negative SSS basin-wide anomaly was measured at 20°N in the
613 Pacific ocean from space by the SMOS mission and in situ by Argo floats. In the same year,
614 one of the strongest El Niño events on record developed and created disruptions in the
615 atmospheric and oceanic circulations. The analysis of this 20°N negative SSS anomaly reveals
616 its origin almost 20 months earlier at the Equator. A sigma-shaped negative SSS anomaly
617 centered on the Equator and the dateline is also observed in October 2015, as expected from
618 the development of the 2015-2016 El Niño. This double-anomaly pattern at the equator and
619 20°N was not found in the historical measurements of surface salinity during previous El Niño
620 events. The mechanisms leading to this double anomaly were investigated here, using both in
621 situ and satellite observations together with a validated ocean-only numerical simulation
622 performed with the NEMO ocean model.

623 El Niño creates equatorial SSSA both via anomalous freshwater fluxes and modified ocean
624 dynamics (advection, entrainment and mixing). The Walker circulation is strongly altered and
625 its ascending branch is displaced and scattered from the western equatorial Pacific to a more
626 central position. This leads to a modification of the precipitation patterns and of the trade
627 winds over the Pacific Ocean, leading to changes in evaporation and in the equatorial currents
628 system.

629 The SSS budget from observations provides the first key on the role of the surface processes
630 described by Eq. 1. Observed surface freshwater forcing echoes the modifications in the
631 Walker circulation in 2015. Even though the observed horizontal advection is noisy, some
632 patterns can be distinguished but the results are too noisy to be quantified. Further analysis is
633 conducted with the numerical simulation and confirms that horizontal advection is the main
634 driver of SSS changes at the Equator. The WFPF is indeed advected eastward during the first
635 4 months of 2014 and 2015, driven by the weakening Trade winds and successive westerly
636 wind events in 2015 (Puy et al., 2016b, Gasparin et al., 2016). During the following months,

637 these anomalies are further advected eastward by the NECC in a narrow band between 5 and
638 10°N. Satellite observations and the model simulation (Fig. 5) indicate that the NECC
639 intensity is particularly strong in 2015, as described by Guimbard et al., (2015; their Figure
640 12). The intensification of ITCZ precipitation between 5° and 10°N associated with El Niño
641 conditions from April to October 2015 also drives a strong decrease of SSS with a rate below
642 -3 year^{-1} . A combination of surface advection and surface forcing is thus responsible for the
643 narrow extension of the intense equatorial anomaly that extends zonally from the dateline to
644 almost the American continent in October 2014 and 2015. The 5-10°N SSSAs are
645 subsequently advected north by the Ekman drift into the westward flowing NEC and then
646 north out of it again. The westward advection of the EPFP does not appear to play a major
647 role in the 5-10°N SSS anomaly, as suggested by Guimbard et al. (2017).

648 The October 2014 SSSA is further advected North reaching 20°N during the following year.
649 Our analysis confirms that the Ekman drift acts as a basin-wide treadmill advecting these
650 interannual anomalies poleward through the tropical zonal current system. Some part of the
651 net northward transport of the SSSA is also carried by the NECC's retroflexion northward
652 into the NEC. Furthermore, smaller scale current features appear to interact with the Ekman
653 northward drift, as revealed by the striking coherence of interannual SSSA and unfiltered
654 surface currents for example around Hawaii (5-20°N and 140-180°W, Fig. 11) in both the
655 model and observations. Cusps in the NECC and NEC are observed at these latitudes and it is
656 hypothesized that they play a significant role in the northward displacement of the SSSA.
657 They were described by Perigaut (1990) and Farrar and Weller (2006) as being baroclinic
658 instability waves. Furthermore, they could transport anomalies in SST and SSS meridionally
659 in a similar way to tropical instability waves near the equator (Kessler et al., 2006 and Lee et
660 al., 2014). Note that the model SSSA structure is much smoother than the observations and
661 may not resolve small scale eddies due to its 1° horizontal resolution at 20°N. The cusps
662 indeed create northward pathways for the fresh waters brought by the NECC from the western
663 Pacific as seen in January 2015 (Fig. 11).

664 The present study demonstrates the importance of the Ekman drift, the NECC to NEC
665 transport and suggests the role of smaller scale features in generating the October 2015 20°N
666 basin-wide SSSA as they all provide northward pathways for equatorial anomalies to reach
667 the extra tropics. Analogous mechanisms occurred in the successive years in 2014 and 2015,
668 led to a superimposition of SSSAs and created the unusually strong double structure in
669 October 2015. Moreover, we find a strong anomaly by the end of 2016 (Fig. 2ac). The record
670 of the past 20 years of observed and simulated SSS shows a continuous northward advection

671 of SSSA from the Equator to the Subtropics that is balanced by freshwater fluxes and vertical
672 processes. This advection is particularly clear during El Niño events as anomalously strong
673 SSSA are generated in the equatorial region. The 1997-1998 El Niño equatorial negative SSS
674 anomaly was also advected north, but in this event it was counteracted by strong positive
675 freshwater fluxes and vertical processes, especially in the ITCZ. The sequence of the halted
676 2014 El Niño producing a first equatorial SSS anomaly which was then reinforced by the
677 ITCZ freshwater fluxes and lingered in the Pacific, then followed by El Niño conditions in
678 2015 led to the formation of the very large 20°N anomaly in 2015.

679 In the recent years, the improvement of satellite SSS retrieval has enabled the study of the
680 mean state and the variability of the SSS field at scales that are not resolved by the sparsely
681 distributed very high frequency moorings, nor by the Argo network whose nominal resolution
682 is about 300km and 10-day globally (Roemmich et al., 2009). The coherence of satellite-
683 borne SSS and independent datasets such as altimetry currents gives us confidence in the
684 quality of the data and their capacity to provide information at the large mesoscale. Both Argo
685 profiling floats and TAO/TRITON moorings provide complementary *in situ* datasets giving
686 valuable insight into subsurface processes that cannot be observed from space (Gasparin et al.
687 2015) and provide a benchmark of in situ observations for the calibration and validation of
688 space missions as well as models. Their first order importance should not be disregarded and
689 this complementary observing capacity needs to be maintained in the future (Durack et al.
690 2016).

691 This study shows the ability of SSS to retain El Niño-generated anomalies for up to 20
692 months from the equator to 20°N, in striking contrast to SST (Figure 8cd) which is rapidly
693 eroded by air-sea interactions. This close-to-passive behavior is another testimony of the
694 central role of salinity as an essential tracer to understand the ocean and its role in climate.

695

696

697 **Acknowledgements**

698 AH acknowledges the support of a CNES Postdoctoral fellowship. This work is a contribution
699 to the TOSCA/ SMOS-Ocean proposal supported by CNES. We benefited from numerous
700 datasets made freely available and are listed here: The SMOS debias_v2 SSS produced by
701 LOCEAN/IPSL (UMR CNRS/UPMC/IRD/ MNHN,) laboratory which participates in the
702 Ocean Salinity Expertise Center (CECOS) of Centre Aval de Traitement des Données SMOS
703 (CATDS) at IFREMER, Plouzane, France (<http://www.catds.fr/Products>, see documentation :
704 <http://www.catds.fr/Products/Available-products-from-CEC-OS/L3-Debiased-Locean-v2>);

705 the TAO-TRITON moorings data by GTMBA Project Office of NOAA/PMEL
706 (<https://www.pmel.noaa.gov/gtmba/>); the WHOTS mooring supported by NOAA through the
707 Cooperative Institute for Climate and Ocean Research (CICOR) and by National Science; the
708 in situ Analysis System (ISAS) by LPO (CNRS/ IFREMER/IRD/UBO) and products were
709 made available by F. Gaillard (wwz.ifremer.fr/lpo/La-recherche/Projets-encours/GLOSCAL),
710 the Precipitation Climatology Project data
711 (<http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html>), Nino 3.4 Index
712 (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/), Woods Hole Oceanographic
713 Institution OAFlux evaporation dataset (<http://oaflux.whoi.edu/evap.html>), GEKCO product
714 by Joël Sudre at LEGOS, France (<http://ctoh.legos.obs-mip.fr/products/global-surface-currents/global-surface-current-data-product>)
715 and Reynolds SST
716 (<ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/>). We acknowledge the support of the
717 Belmont project GOTHAM, under grant ANR-15-JCLI-0004-01. We thank Jérôme Vialard
718 for some very helpful discussions.

719

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943 **Figure Captions**

944 Table 1. Root mean square differences (RD) between Mooring observations (selected TAO,
 945 WHOTS and all TAO and WHOTS) and the model (NEMO), interpolated in situ
 946 (ISAS), interpolated in situ and satellite (Reynolds) and satellite only (SMOS) data,
 947 in terms of sea surface temperature and salinity.

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949 Figure 1. 2010-2016 mean fields of (a) SSS (SMOS) and freshwater flux (0 and -1.5 m.yr⁻¹
 950 contours, OAFlux and GPCP) and (b) current velocity and associated streamlines

951 (GEKCO). Stars and dots denotes moorings used to produce Table 1. Timeseries
952 from moorings denoted by stars at shown on Fig. 3.

953 Figure 2. 2010-2016 longitude-time plots of SSS (SMOS) averaged between 2°S and 2°N (a)
954 and 16 and 20°N (c) and of SST (Reynolds) averaged between 2°S and 2°N (b) and
955 18 and 22°N (d). NINO3.4 on top of all panels, blue during La Niña and red during
956 El Nino.

957 Figure 3. Time series of monthly interannual SSS at (a) the equator and 180°E and (b) at
958 158°W, 23°N from Moorings (green), ISAS (red), SMOS SSS (yellow) and the
959 NEMO numerical simulation (blue). Lighter colors and thinner lines for the
960 seasonal climatology anomaly (limited filter) and darker thicker lines when using
961 the “robust” filter. The dashed grey line denotes the Niño 3.4 index (-.4 scaling).

962 Figure 4. October 2015 SSS Interannual Anomaly from (a) SMOS, (b) ISAS and (c) the
963 model from the “limited” filtering technique.

964 Figure 5. Monthly average, every 6 months, of the interannual SMOS (a-d, left panels) and
965 modelled (e-h, right panels) SSS anomaly (color), unfiltered currents (arrows) and
966 isohyets (-2.5 and -3.5 m.yr⁻¹, magenta contours) for the months of April and
967 October 2014 and 2015.

968 Figure 6. 7-month SSS tendency (a, d, g), fresh water fluxes (b, e, h) and horizontal (c, h, i)
969 advection centered around July 2014 (a-c, left panels), January 2015 (d-f, middle
970 panels) and July 2015 (g-I, right panels) from observations. Panels a, d and g
971 represent SSS changes (Term I of Eq. 2) from April 2014 (Fig. 5a) to October 2014
972 (Fig. 5b), from October 2014 (Fig. 5b) to April 2015 (Fig. 5c) and from April 2015
973 (Fig. 5c) to October 2015 (Fig. 5d) respectively. SSS changes associated with
974 freshwater fluxes and horizontal advection (Terms II and III of Eq. 2) over the same
975 periods are shown on panels b, e, h and c, h, i respectively. Contours on all panels
976 represent the -0.1 year⁻¹ SSS tendency for each period.

977 Figure 7. 7-month SSS tendency (a, e, i), fresh water fluxes (b, f, j), horizontal (c, g, k) and
978 vertical (d, h, l) ocean processes centered around July 2014 (a-d, left panels),
979 January 2015 (e-h, middle panels) and July 2015 (i-l, right panels) from the NEMO
980 numerical simulation. Contours on all panels represent the -0.1 year⁻¹ SSS
981 tendency for each period. Analogous to Figure 6.

982 Figure 8. 150°-170°W Latitude-time plot of the interannual SSS anomaly from SMOS (a),
983 ISAS (b), and NEMO (c) and SST from NEMO (d). NINO3.4 on top of all panels,
984 blue during La Niña and red during El Nino (scaled by -2, centered on the Equator).

985 Figure 9. Interannual NEMO SSS anomaly for the months of October 2002 (a), April and
 986 October 2003 (b, c), April 2004 (d), October 2009 (e), April and October 2010 (f,g)
 987 and April 2011(h).

988 Figure 10. 150°-170°W latitude-time plots of the interannual NEMO SSS budget as described
 989 by Equations 1 and 3: (a) SSS tendency, (b) freshwater fluxes, (c) horizontal
 990 processes, (d) Ekman horizontal advection, (e) remaining horizontal processes from
 991 the Ekman horizontal advection and (f) vertical processes

992 Figure 11. SSSA and currents from (a) SMOS and (b) NEMO for January 2015

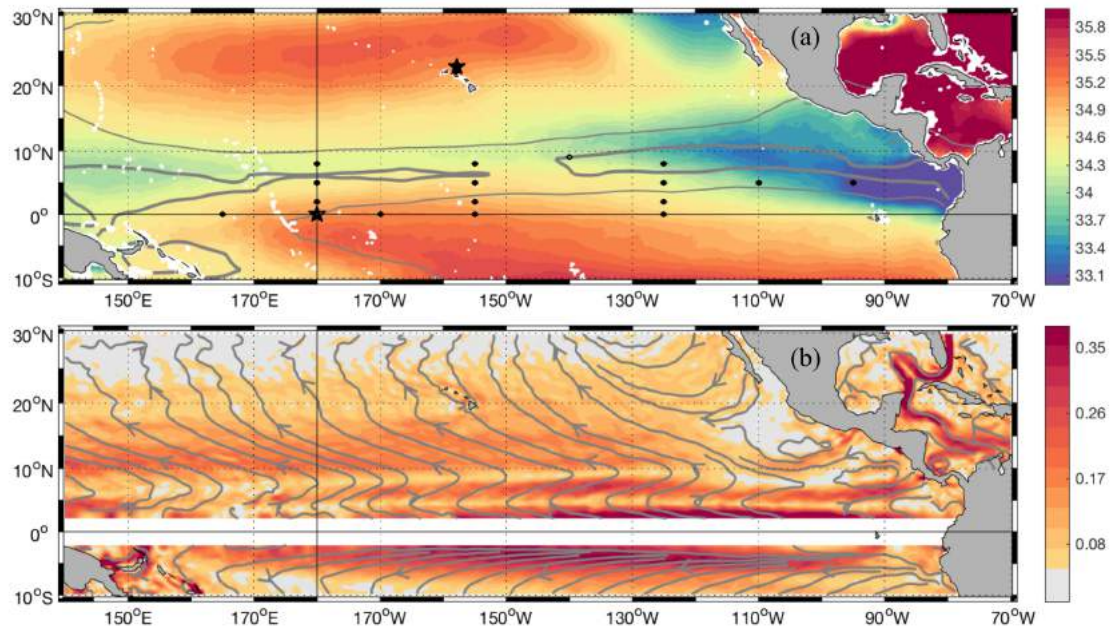
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995 **Tables**

996 Table 1. Root mean square differences (RD) between Mooring observations (selected TAO
 997 and WHOTS moorings (same as Fig. 3) and all TAO and WHOTS) and the model (NEMO),
 998 interpolated in situ (ISAS), interpolated in situ and satellite (Reynolds) and satellite only
 999 (SMOS) data, in terms of sea surface temperature and salinity.

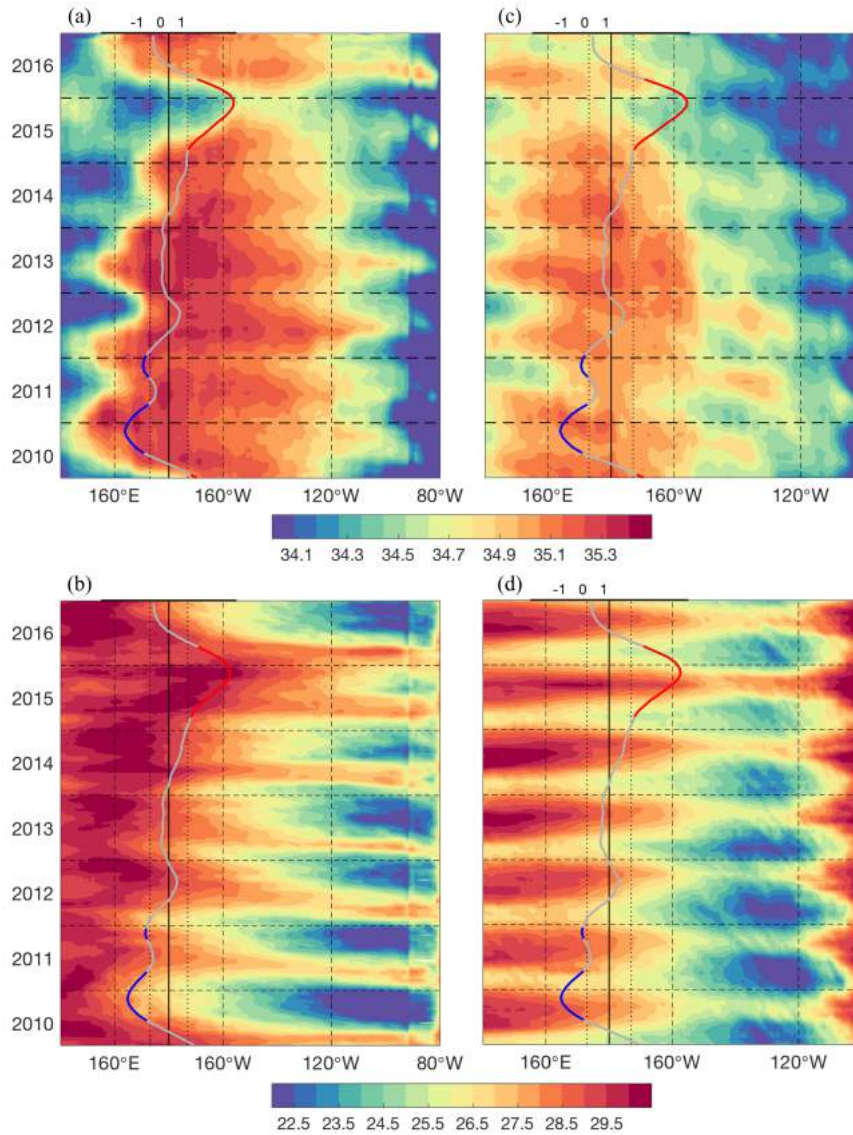
	Sea Surface Temperature (°C)						Sea Surface Salinity					
	NEMO		ISAS		Reynolds		NEMO		ISAS		SMOS	
	N	RD	N	RD	N	RD	N	RD	N	RD	N	RD
TAO	6805	0.60	161	0.27	1614	0.45	5904	0.33	135	0.19	354	0.33
WHOTS	3980	0.35	131	0.16	1073	0.24	3980	0.25	131	0.22	200	0.18
All	62756	0.48	1445	0.24	14638	0.37	41045	0.28	1203	0.15	3987	0.24

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 1001
 1002 **Figures**
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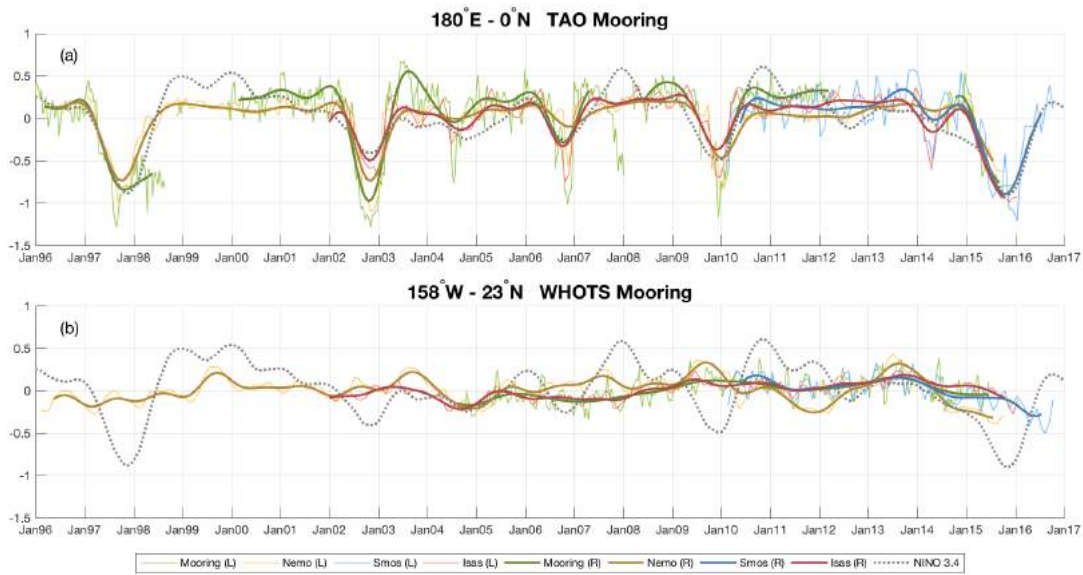
Figure 1. 2010-2016 mean fields of (a) SSS (SMOS) and freshwater flux (0 and -1.5 m.yr-1 contours, OAFflux and GPCP) and (b) current velocity and associated streamlines (GEKCO). Stars and dots denotes moorings used to produce Table 1. Timeseries from moorings denoted by stars at shown on Fig. 3.



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Figure 2. 2010-2016 longitude-time plots of SSS (SMOS) averaged between 2°S and 2°N (a) and 16 and 20°N (c) and of SST (Reynolds) averaged between 2°S and 2°N (b) and 18 and 22°N (d). NINO3.4 on top of all panels, blue during La Niña and red during El Niño.

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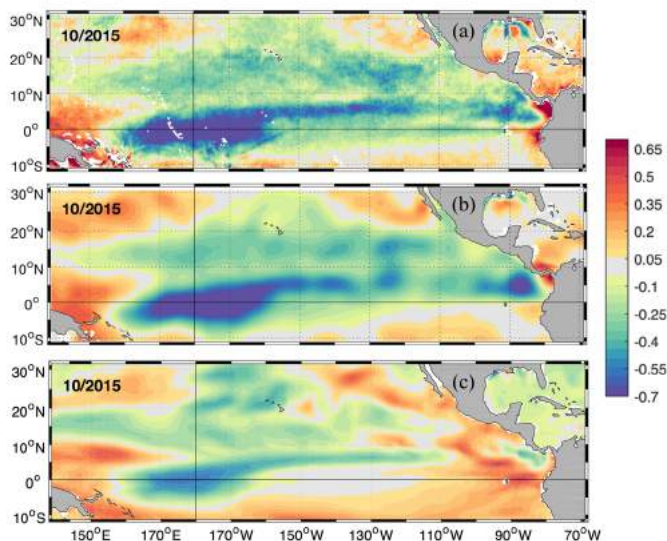


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1019 Figure 3. Time series of monthly interannual SSS at (a) the equator and 180°E and (b) at
1020 158°W, 23°N from Moorings (green), ISAS (red), SMOS SSS (yellow) and the
1021 NEMO numerical simulation (blue). Lighter colors and thinner lines for the
1022 seasonal climatology anomaly (limited filter) and darker thicker lines when using
1023 the “robust” filter. The dashed grey line denotes the Niño 3.4 index (-.4 scaling).

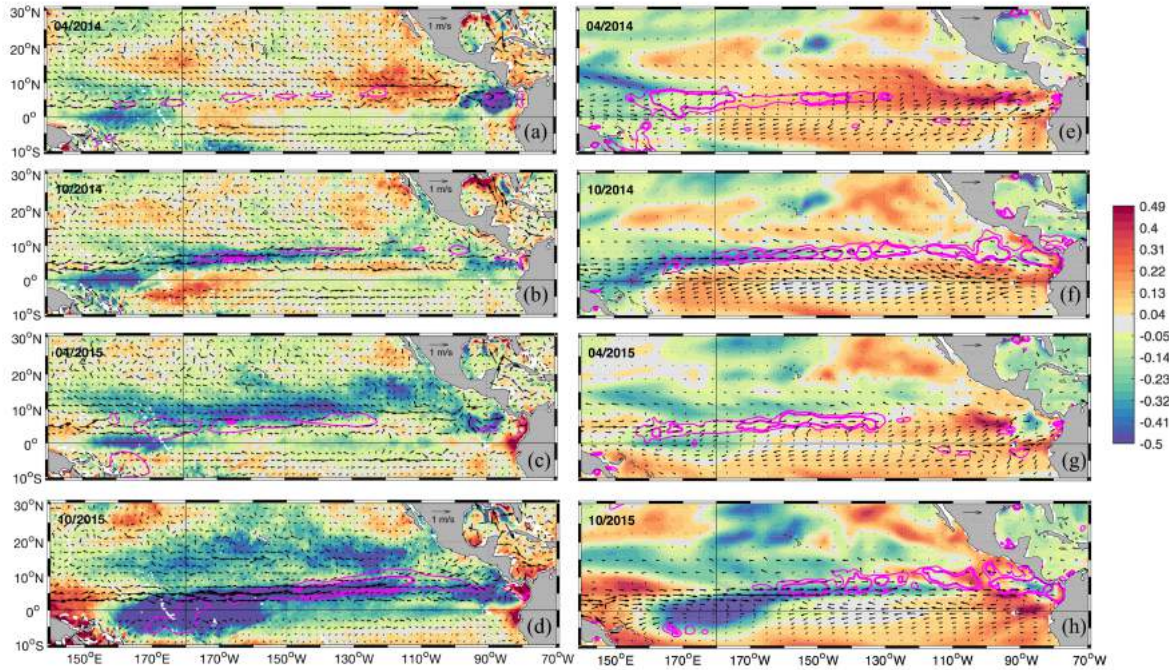
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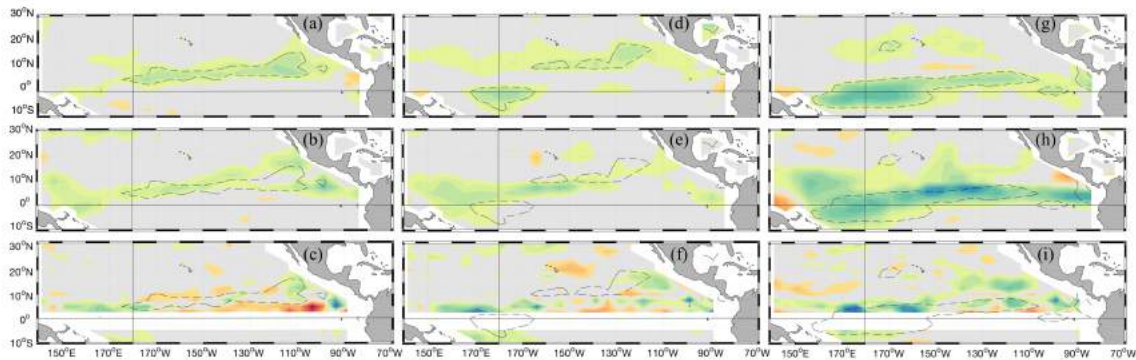
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1027 Figure 4. October 2015 SSS Interannual Anomaly from (a) SMOS, (b) ISAS and (c) the
1028 model from the “limited” filtering technique.



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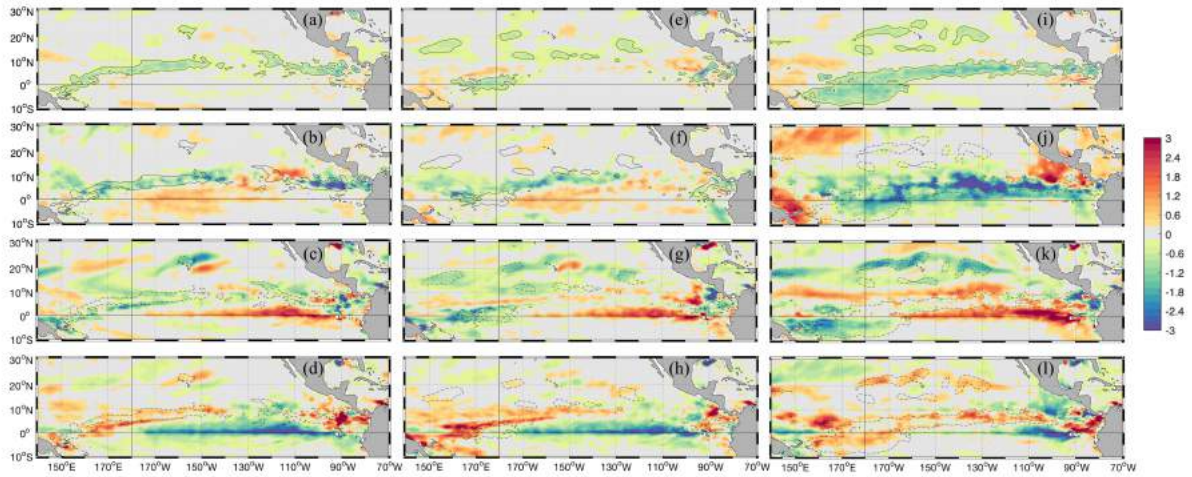
Figure 5. Monthly average, every 6 months, of the interannual SMOS (a-d, left panels) and modelled (e-h, right panels) SSS anomaly (color), unfiltered currents (arrows) and isohyets (-2.5 and -3.5 m.yr⁻¹, magenta contours) for the months of April and October 2014 and 2015.



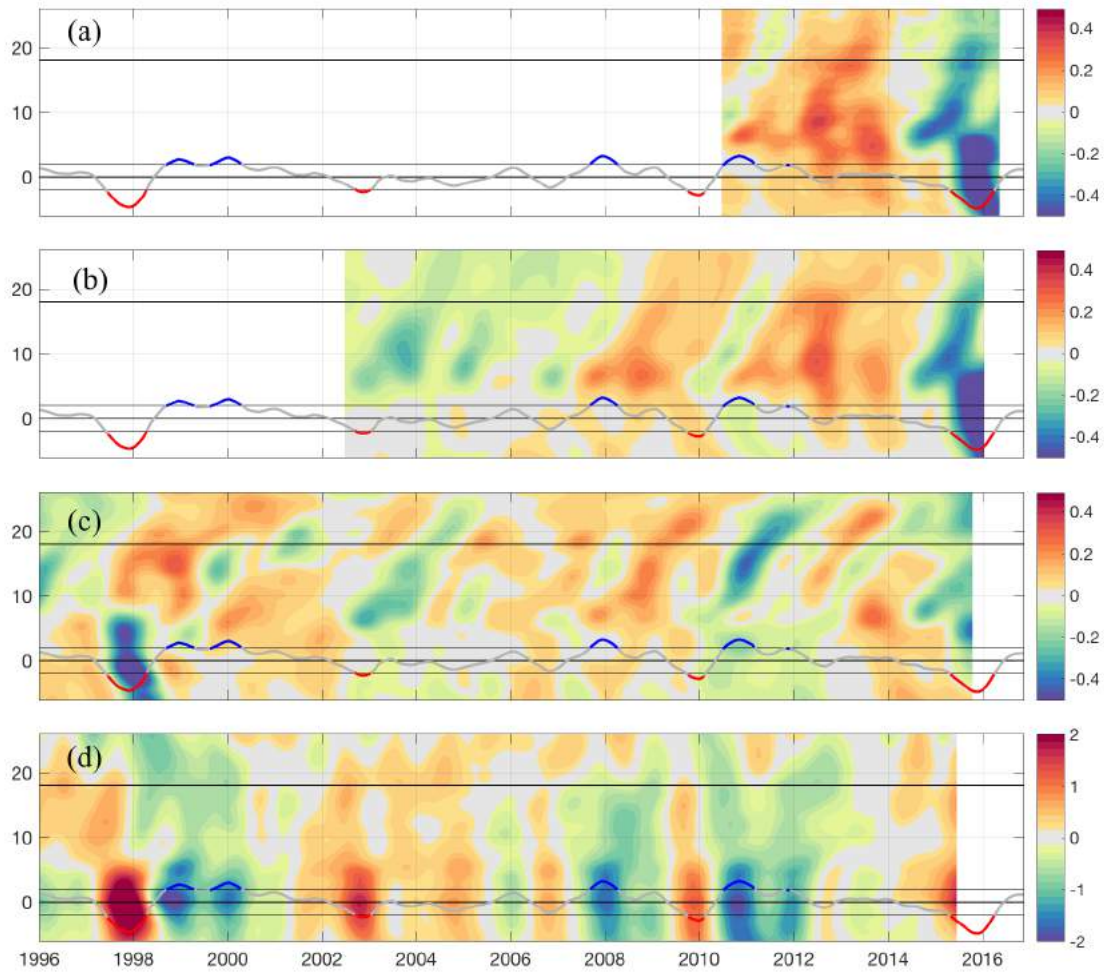
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Figure 6. 7-month SSS tendency (a, d, g), fresh water fluxes (b, e, h) and horizontal (c, f, i) advection centered around July 2014 (a-c, left panels), January 2015 (d-f, middle panels) and July 2015 (g-i, right panels) from observations. Panels a, d and g represent SSS changes (Term I of Eq. 2) from April 2014 (Fig. 5a) to October 2014 (Fig. 5b), from October 2014 (Fig. 5b) to April 2015 (Fig. 5c) and from April 2015 (Fig. 5c) to October 2015 (Fig. 5d) respectively. SSS changes associated with freshwater fluxes and horizontal advection (Terms II and III of Eq. 2) over the same

1044 periods are shown on panels b, e, h and c, h, i respectively. Contours on all panels
1045 represent the -0.1 year-1 SSS tendency for each period.
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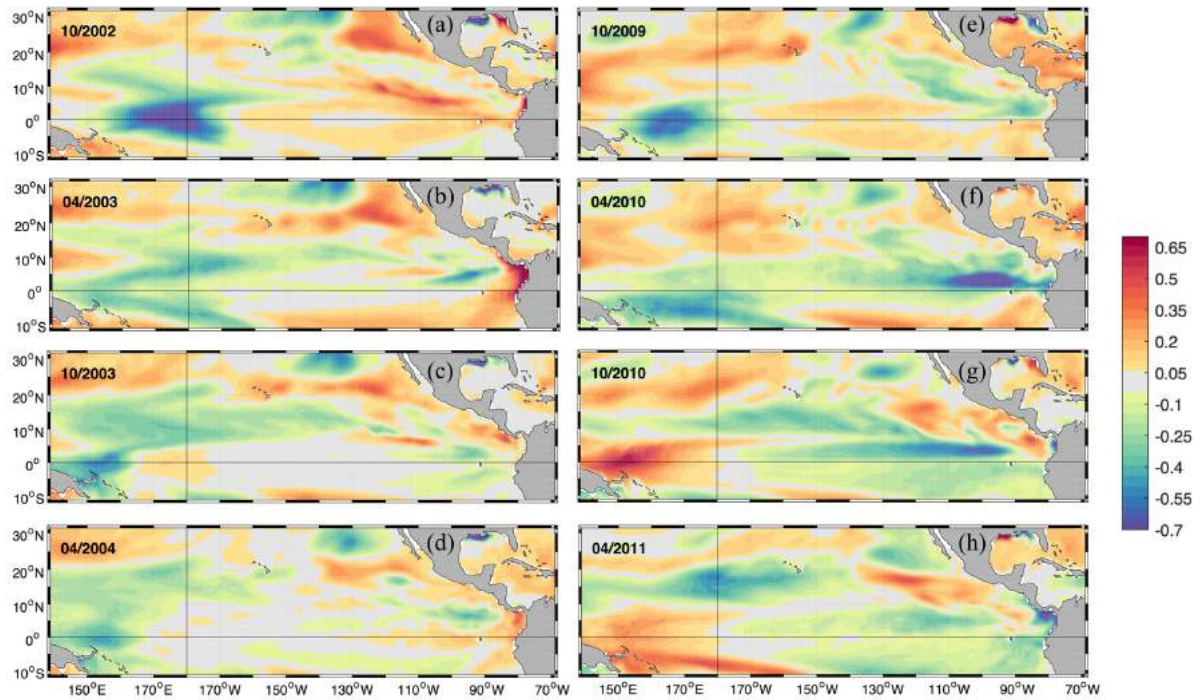
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1049 Figure 7. 7-month SSS tendency (a, e, i), fresh water fluxes (b, f, j), horizontal (c, g, k) and
1050 vertical (d, h, l) ocean processes centered around July 2014 (a-d, left panels),
1051 January 2015 (e-h, middle panels) and July 2015 (i-l, right panels) from the NEMO
1052 numerical simulation. Contours on all panels represent the -0.1 year-1 SSS
1053 tendency for each period. Analogous to Figure 6.



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1055 Figure 8. 150°-170°W Latitude-time plot of the interannual SSS anomaly from (a) SMOS, (b)
 1056 ISAS, and (c) NEMO and (d) SST from NEMO. NINO3.4 index is superimposed
 1057 on each panel (blue during La Niña, grey during normal conditions, and red during
 1058 El Niño events) (scaled by -2, centered on the Equator).

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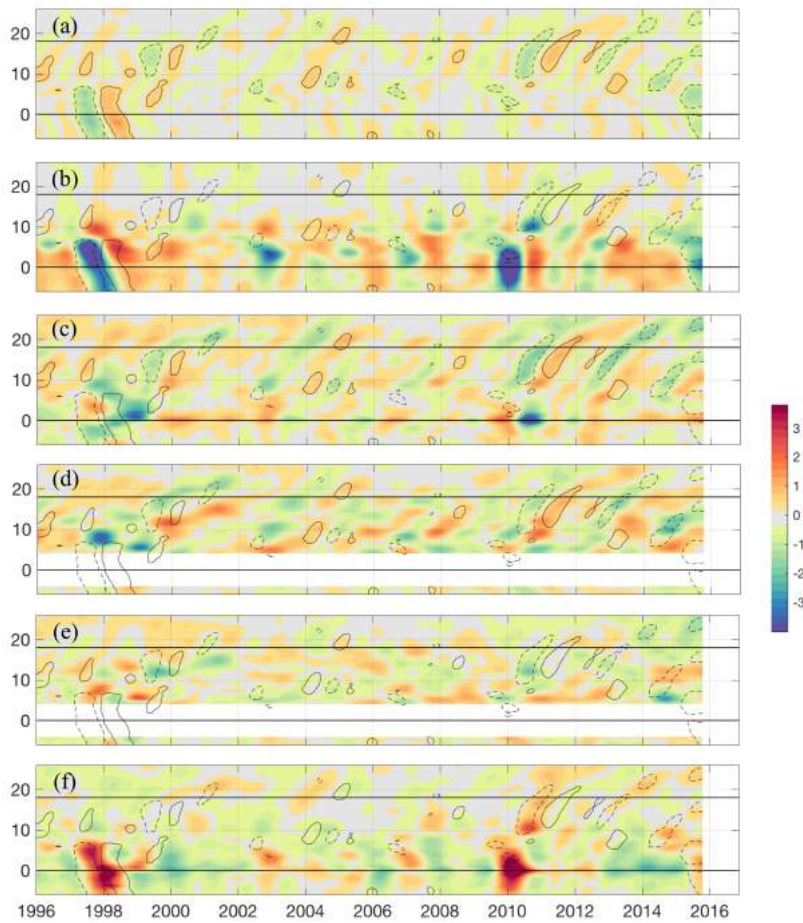
1061 Figure 9. Interannual NEMO SSS anomaly for the months of October 2002 (a), April and

1062 October 2003 (b, c), April 2004 (d), October 2009 (e), April and October 2010 (f,g)

1063 and April 2011(h).

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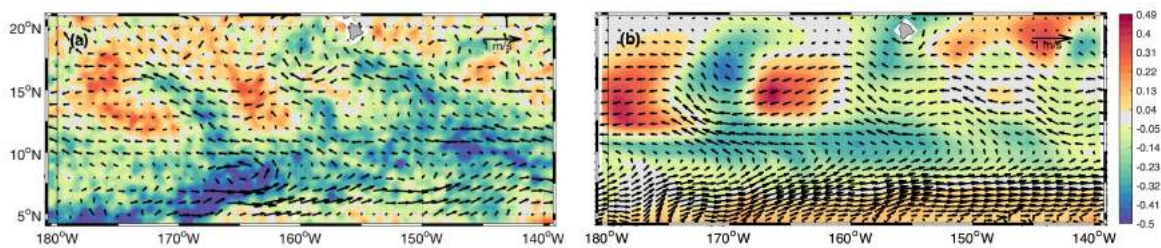
1067 Figure 10. 150°-170°W latitude-time plots of the interannual NEMO SSS budget as described

1068 by Equations 1 and 3: (a) SSS tendency, (b) freshwater fluxes, (c) horizontal

1069 processes, (d) Ekman horizontal advection, (e) remaining horizontal processes from

1070 the Ekman horizontal advection and (f) vertical processes

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1073 Figure 11. SSSA and currents from (a) SMOS and (b) NEMO for January 2015

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