

# Journal of Geophysical Research: Oceans

## RESEARCH ARTICLE

10.1002/2017JC013423

### Special Section:

Oceanography of the 2015/16 El Niño and Global Impacts on Tropical Marine Ecosystems

#### Key Points:

- 20°N large-scale extra-equatorial sea surface salinity anomalies associated with historical 2015 El Niño
- A combination of In situ, modeled and SMOS surface salinity products give an unprecedented insight on the anomalies and mechanisms
- 20°N SSS anomaly is a superposition of a persisting weak El Niño 2014 anomaly and 2015 El Niño anomaly both advected by mean Ekman currents

#### Correspondence to:

A. Hasson,  
audrey.hasson@locean.upmc.fr

#### Citation:

Hasson, A., Puy, M., Boutin, J., Guilyardi, E., & Morrow, R. (2018). Northward pathway across the tropical North Pacific Ocean revealed by surface salinity: How do El Niño anomalies reach Hawaii? *Journal of Geophysical Research: Oceans*, 123, 2697–2715. <https://doi.org/10.1002/2017JC013423>

Received 6 SEP 2017

Accepted 15 MAR 2018

Accepted article online 23 MAR 2018

Published online 20 APR 2018

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

Audrey Hasson<sup>1</sup> , Martin Puy<sup>2</sup>, Jacqueline Boutin<sup>1</sup> , Eric Guilyardi<sup>1</sup>, and Rosemary Morrow<sup>3</sup> 

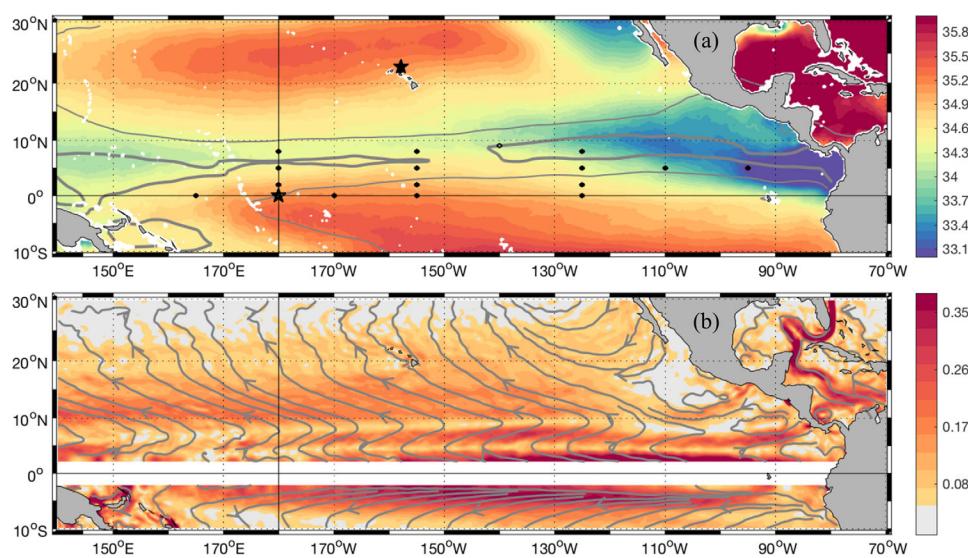
<sup>1</sup>LOCEAN, UMR 7159, CNRS, UPMC, IRD, MNHN, Paris, France, <sup>2</sup>UTIG, Austin, TX, USA, <sup>3</sup>LEGO, UMR 5566, CNES, CNRS, IRD, UPS Toulouse III, Toulouse, France

**Abstract** 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 (WPFP) (Delcroix & Picaut, 1998) and East-Pacific fresh-pool (EPFP) (Alory et al., 2012) respectively (Figure 1a). Higher salinities on the poleward sides of the low SSS band belong to the sub-tropical salinity maximum 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  $-1.5 \text{ m.yr}^{-1}$  isohyets (Figure 1a), the meridional shift between the two structures reveals the importance of ocean dynamics (Hasson et al., 2013b; Sena-Martins & Stammer, 2015; Tchilibou et al., 2015; Yu, 2011). The spatial distribution of the tropical Pacific SSS is characterized by longitudinal gradients along the Equator and 20°N with strong seasonal and interannual variations in their amplitude and zonal location (Figures 2a and 2c; Kao & Lagerloef, 2015; Maes et al., 2014). At the Equator, the mean seasonal cycle consists of an extension and intensification of the WPFP toward the east in the second half of the year and an extension of the EPFP to the west from November to June each year. At 20°N, the low SSS zonal variations are synchronous with the equatorial WPFP in the west. In the east, they are shifted with respect to the equatorial EPFP cycle by a few months: their extending phase occurs between June and January. This is consistent with the latitudinal displacement of the seasonal SSS anomaly (SSSA) associated with the Intertropical Pacific Convergence Zone (ITCZ) seasonality (Sena-Martins & Stammer, 2015; Yu, 2015).

Figure 2 also shows large year-to-year variations, following the El Niño Southern Oscillation (ENSO) phase, the leading mode of interannual variability in the Tropical Pacific. ENSO has both local and global impacts on the oceanic and atmospheric circulations and leads to many environmental impacts and societal havoc (McPhaden et al., 2006; Sarachik & Cane, 2010; Wang & Picaut, 2004). It includes a warm phase, El Niño, and a cold phase, La Niña (see Philander et al., 1989) which intensity are usually measured by the Niño 3.4 index



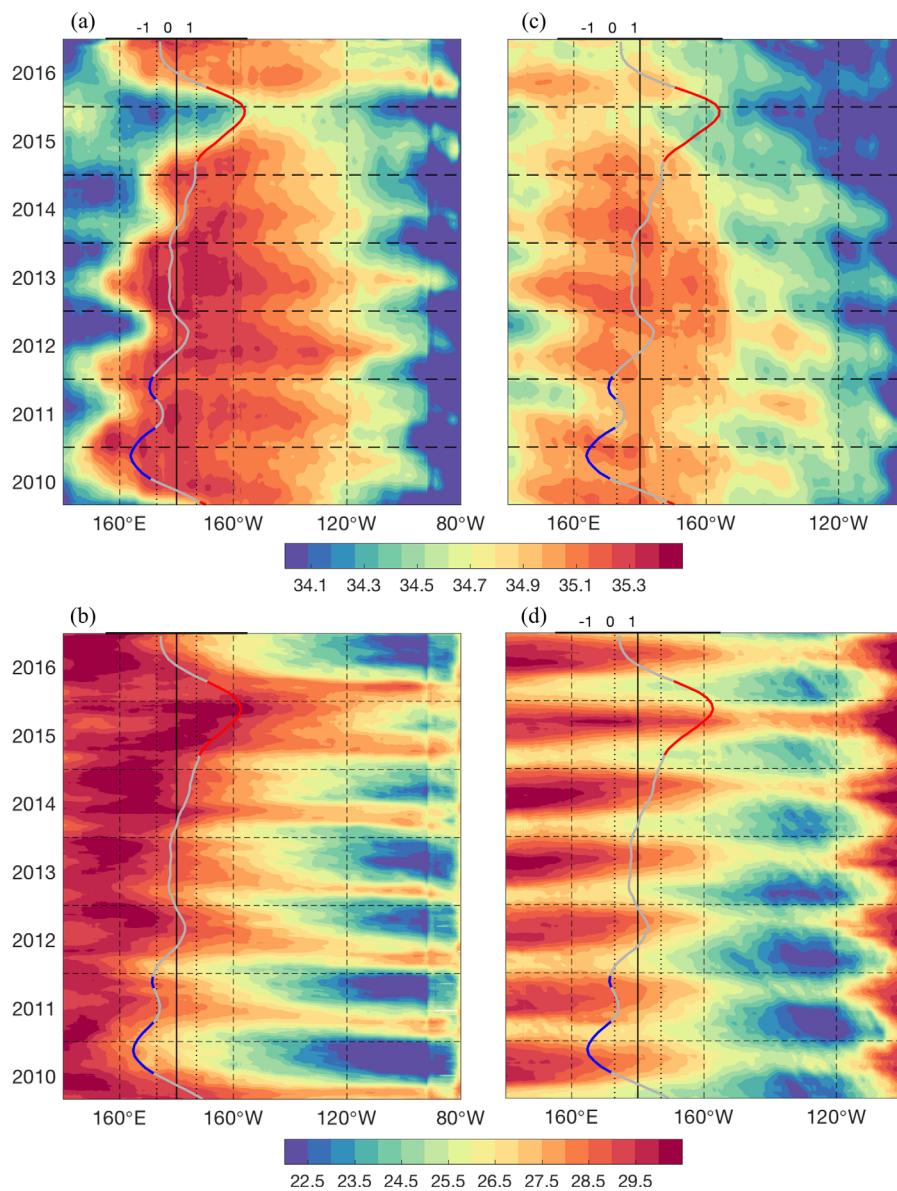
**Figure 1.** 2010–2016 mean fields of (a) SSS (SMOS) and freshwater flux ( $0$  and  $-1.5 \text{ m.yr}^{-1}$  contours, OAFlux and GPCP) and (b) current velocity and associated streamlines (GEKCO). Stars and dots denotes moorings used to produce Table 1. Time series from moorings denoted by stars at shown on Figure 3.

(surface temperature anomaly within the 3.4 region –  $5^{\circ}\text{S}$ - $5^{\circ}\text{N}$ ,  $170^{\circ}$ - $120^{\circ}\text{W}$ ) shown on Figure 2. The relationship between ENSO and the sea surface temperature (SST) is well described in the literature. At the equator, ENSO is associated with the zonal displacement of the western Pacific warm pool (WPWP, Figures 2b and 2d). The WPWP plays a key role in the zonal basin-scale atmospheric circulation called the Walker Circulation which is greatly perturbed during ENSO events.

A number of studies have explored the connection between salinity and ENSO (e.g., Bosc et al., 2009; Delcroix & Picaut, 1998; Gouriou & Delcroix, 2002; Picaut et al., 2001; Qu & Yu, 2014; Qu et al., 2014). Deep atmospheric convection, associated with the ascending branch of the Walker circulation over the WPWP, induces precipitation above  $10 \text{ mm/d}$  on average in the area (<https://pmm.nasa.gov/TRMM/TRMM-based-climatology>). At  $140^{\circ}\text{W}$ , the interannual SSS signal amplitude reaches 1, which is twice the seasonal signal. Interannual SSS changes are due to variations of the surface freshwater fluxes but also of the ocean dynamics. Both horizontal and vertical processes have been shown to play an important role (Gasparin & Roemmich, 2016; Hasson et al., 2013a, 2013b, 2014; Qu et al., 2014; Vialard et al., 2002). SSS was shown to be a robust tracer for ENSO (Delcroix & Picaut, 1998; Qu & Yu, 2014; Singh et al., 2011). Unlike SST, the ENSO signature in SSS is not only located within a few degrees of the equator but reaches higher latitudes (Delcroix et al., 1998; Hasson et al., 2014). This allows us to track the ENSO-related signal away from the Equator, something not possible with SST because of the strong thermal air-sea coupling.

Studies have also underlined the active role of salinity in the tropical ocean dynamics through its effect on the vertical density stratification. The presence of a haline stratification in the WPFP, shallower than the thermal one, controls the mixed layer (ML) depth and creates barrier layers (Lukas & Lindstrom, 1991; Qu et al., 2014; Sprintall & Tomczak, 1992). The ocean responds to this salinity-controlled density stratification by decreasing entrainment cooling and by intensifying the local response to wind stress. The westward South Equatorial Current (SEC) brings saline water under the WPFP from the equatorial upwelling and reinforces the barrier layer (Cronin & McPhaden, 2002). As the SEC is modulated by ENSO, it induces a strong interannual variability of the barrier layer strength (Vialard & Delecluse, 1998). SSS is found to play an active role in ENSO evolution (Ballabriga-Poy et al., 2002; Vialard et al., 2002; Zhu et al., 2014) and a recent study found that the assimilation of SSS in coupled forecasts yields longer ENSO predictability (Hackert et al., 2014).

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



**Figure 2.** 2010–2016 longitude-time plots of SSS (SMOS) averaged between (a) 2°S and 2°N and (c) 16 and 20°N and of SST (Reynolds) averaged between (b) 2°S and 2°N and (d) 18 and 22°N. Niño3.4 on top of all plots, blue during La Niña and red during El Niño.

Salinity has been extensively observed since the 2000s by the Argo program, with vertical profiles from 5 to 2000 m depth (Roemmich et al., 2009). Since 2010, SSS is monitored at an unprecedented resolution from space by the European satellite mission Soil Moisture Ocean Salinity (SMOS), by the Argentinian-American satellite mission Aquarius and by the American satellite mission Soil Moisture Active Passive (SMAP). These missions enable the observation of SSS globally at a resolution between  $50 \times 50 \text{ km}^2$  and  $150 \times 150 \text{ km}^2$  every 3–8 days. More details on these are given in the Data/Methods section of the present paper. This suite of observations provides a unique opportunity for studying the interannual variability of the upper ocean salinity with unprecedented details.

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

developed and lasted for about 2 years. SMOS observations of the 2010–2011 La Niña event show a strengthened WPFP eastern front and high salinity waters (above 35) reaching 150°E at the equator (Figure 2a). The strongest part of the signal is however found south of the equator in the SPCZ as was shown in a previous study by Hasson et al. (2013b).

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

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

Additionally, significant freshening was observed around 20°N (Figures 2b and 4) accompanied with a slight increase in SST (Figure 2d). While the equatorial SSS anomalies associated with past El Niño have been well documented, thanks, in particular, to the SSS observations of the TOGA/TAO network, the extra-equatorial anomalies less well known. This double anomalous negative SSS feature appears to be specific to 2015. The extra-equatorial SSS anomaly is indeed not represented by the canonical SSS patterns associated with either the Central or Eastern Pacific El Niño events, as described by Singh et al. (2011) with 30 years of in situ observations (their Figure 5). The negative SSS anomaly associated with El Niño events of the observed period is located between 10°N and 20°S.

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

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

## 2. Data/Methods

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

### 2.1. Observational Data Sets

SMOS satellite salinity and an optimal interpolation of Argo float salinity measurement data sets are at the center of our investigation.

The SMOS satellite mission was launched in November 2009 as the second European Space Agency (ESA) Earth Explorer (Kerr et al., 2010). It has been delivering space borne SSS since January 2010. The level-3 SMOS product used here is developed by the CATDS CEC-LOCEAN and known as debias\_v2. This product is corrected for coastal biases following an improved method described in Kolodziejczyk et al. (2016) and for latitudinal biases (Boutin et al., 2017, in revision). This data set is available on a  $0.25 \times 0.25^\circ$  EASE grid, smoothed over 18 days and available every 4 days from January 2010 to the end of 2016. The accuracy of this SMOS SSS data set in the open ocean is estimated to be better than 0.2 and is specifically assessed in our region in the present paper.

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

The TAO-TRITON array has been deployed in the tropical Pacific Ocean in order to study ENSO and its predictability following the 1982–1983 event. Moorings provides many high temporal resolution ocean and atmosphere measurements. Here, we use daily salinity and temperature measurements at various depth (McPhaden et al., 2006). As many moorings have gaps in their timeseries surface salinity and temperature data were also retrieved from the Woods Hole Oceanographic Institution Hawaii Ocean Timeseries Site (WHOTS) mooring at  $22^\circ 45'N$ ,  $158^\circ W$ . Mooring data are used in the present study for point-comparison of SSS and SST in order to assess other data quality. Whenever available, measurements from sensors at 1m depth were used and, when unavailable, the 10 m depth sensor was used to get the longest possible time series. Stratification in the first 10 m is assumed to be negligible at the interannual time scale. Difference between the surface and 10m salinity can however sometimes reach 1 locally but on average the vertical salinity differences are  $-0.03$  in the tropics (Drucker & Riser, 2014) No flag was used for the TAO data as they were found to be not fully reliable as shown by Tang et al. (2017). This is further explained in section 2.4. Only “Acceptable measurements” were used for WHOTS mooring.

The optimal interpolation “In Situ Analysis System” (ISAS) combines temperature and salinity measurements mainly from Argo floats profiles, TAO-TRITON moorings and vessels CTD casts. ISAS provides monthly fields of temperature and salinity from the surface ocean down to 2,000 m and on a near global  $0.5^\circ \times 0.5^\circ$  horizontal mesh (Gaillard et al., 2016). In this paper, we use the 5m depth level and version 6.2 of the ISAS algorithm applied in a delayed mode (with careful in situ data evaluation) until 2012 (Gaillard et al., 2016) and in near real-time data after 2012 (Brion et al., 2011). ISAS uses covariance scales of 300 km in longitude, proportional to the Rossby radius of deformation in latitude, and 30 day in time. The resolution of scales less than 300 km by the monthly gridded values is expected to be poor, even though it is weighted by the number of nearby data and their location.

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

The SST product is hereafter referred to as Reynolds SST (Reynolds et al., 2007). This gridded  $1/4$ -degree daily product (V2.0) is an optimal interpolation from combined data sets derived from satellites and in-situ data (from ships and buoys). Reynolds SST is available from 1981 till present. Based on satellite wind stress and altimeter sea level, GEKCO provides daily geostrophic and Ekman currents at a  $0.25^\circ$  spatial resolution from 1992 to present (Sudre et al., 2013). Currents within  $2^\circ$  of the equator are discarded. GPCP precipitation data are available in its version 2.1 from October 1996 to October 2015 in a daily  $2.5^\circ$  resolution mesh (Huffman et al., 2009). The OAFlux project supplies evaporation data on a monthly  $1^\circ$  spatial grid from 1958 to present (Yu et al., 2008). Niño 3.4 SST anomalies were retrieved from the NOAA Earth Sciences Research Laboratory (ESRL) and subsequently smoothed by a 5 month moving average.

Nearly all in situ salinities are based on seawater conductivity providing Practical Salinity measurements. Even though the difference is not noticeable at our scale of interest in the tropical Pacific Ocean, all salinities have been converted into absolute salinities using the Thermodynamic Equation of Seawater (TEOS-10) established by the Intergovernmental Oceanographic Comity (IOC) and are expressed in  $g\cdot kg^{-1}$

(Wright et al., 2011). Using absolute salinity allows a direct comparison of observations and model salinities (Wright et al., 2011).

## 2.2. Numerical Simulation

To further analyze the SSSA associated with ENSO in 2015, forced oceanic experiments were performed. The NEMO v3.2 model (Nucleus for European Modelling of the Ocean; Madec, 2008) was set up in a 1° resolution global configuration (ORCA1; Hewitt et al., 2011), with local transformations in the tropics leading to a 1/3° meridional resolution at the equator. The model vertical resolution is 10m at the surface, 25m at 100m depth and 300 m at 5,000 m depth, resulting in 42 vertical levels. More details on the model configuration and assessment can be found in Puy et al. (2016a). The numerical simulation provides daily outputs of all the needed parameters for this study such as salinity, temperature and currents but also all the terms of the mixed layer salinity budget equation (see section 2.5).

The model is forced by the DRAKKAR Forcing Set v5.2 (DF5.2; Dussin & Barnier, 2013), derived from ERA 40 (Uppala et al., 2005) until 2002 and ERA-Interim reanalysis (Dee et al., 2011) afterward. The model is used in the present study to compute the salinity budget of the mixed layer (ML) and therefore no direct SSS restoring can be used. In order to prevent the salinity drift associated with the absence of restoring, a correcting term is computed as an additional freshwater surface fluxes. This methodology was already used and described by Vialard et al. (2002) and more recently by Hasson et al. (2013a, 2013b, 2014). The computation of the correcting terms requires the run of a first simulation with a very strong surface damping (i.e., 1,000 mm/d). The 1985–2015 average correction on the freshwater fluxes is computed from this first simulation and then added to the DF5.2 forcing in the second simulation. This way the simulation does not drift over time but keeps its dynamical integrity for the time scales of interest. The correction corresponds to about 3.26% of the average forcing field on our region of interest (10°S–30°N, 140°E–70°W). The ML salinity budget is computed online at every model computation time step, the ML depth being defined as the depth at which the density differs by 0.01 from the surface.

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

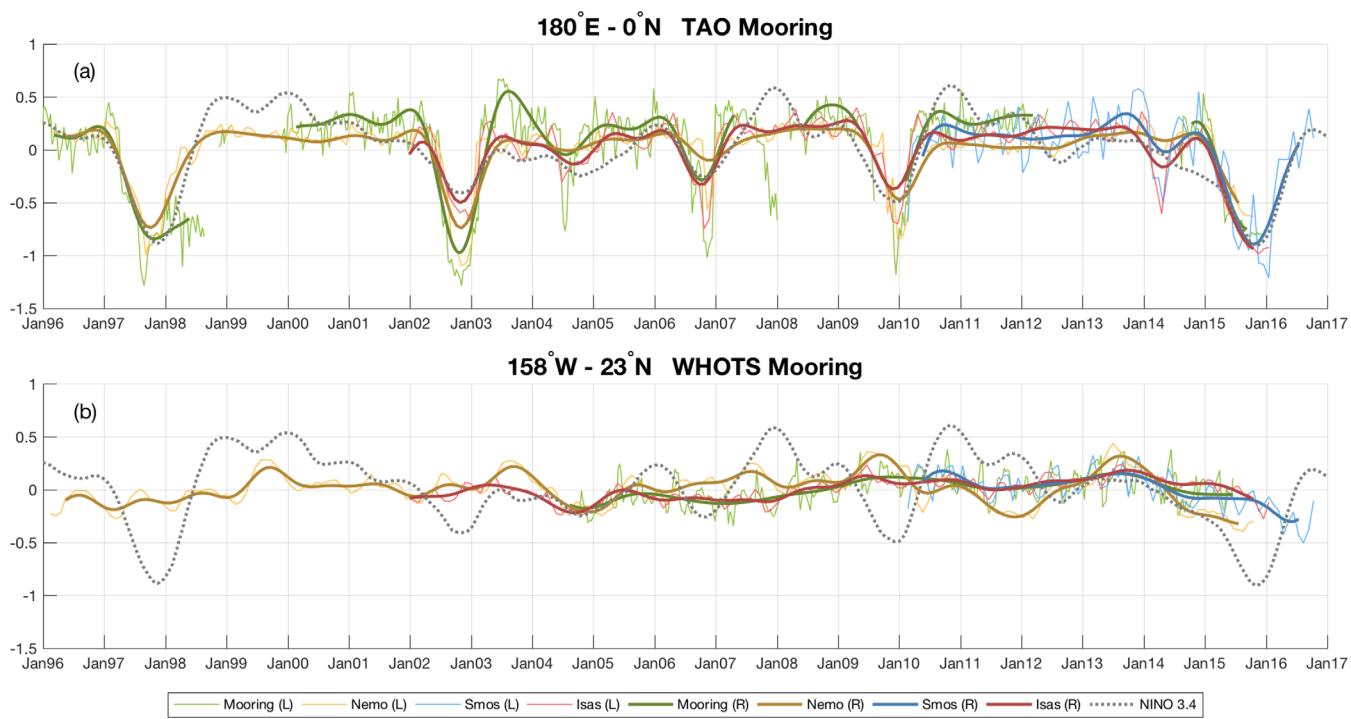
## 2.3. Filtering Time Series

All anomalies were computed as described below. The common period of all data sets 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 data set is small and does not impact the results of this paper. This high-passed monthly climatology is then subtracted from the original data set 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 Figure 1a). Both filters remove the seasonal cycle adequately. As expected the “limited” filter leaves out some intra-seasonal variability. This signal appears to be associated with waves such as tropical instability waves and barotropic Rossby waves (Farrar, 2011; Kessler, 2006).

## 2.4. SSS Data Sets Assessment

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

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



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

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

In order to further assess the data sets, statistics at 18 moorings (stars and dots on Figure 1a) were computed (Table 1). Statistical comparisons were made for the TAO moorings Quality Control (QC)’ed data and for the whole time-series regardless of the QC, and it was found 1) that there were not enough QCed data points to compute significant comparisons at most moorings and 2) the results presented below do not differ substantially whether non-QCed data are used or not. The TAO moorings measurement and the ISAS product are not strictly independent but it is expected that the objective analysis of ISAS will smooth out large TAO errors so it could be used to remove the largest errors in the TAO data. TAO minus ISAS SSS Root

**Table 1**

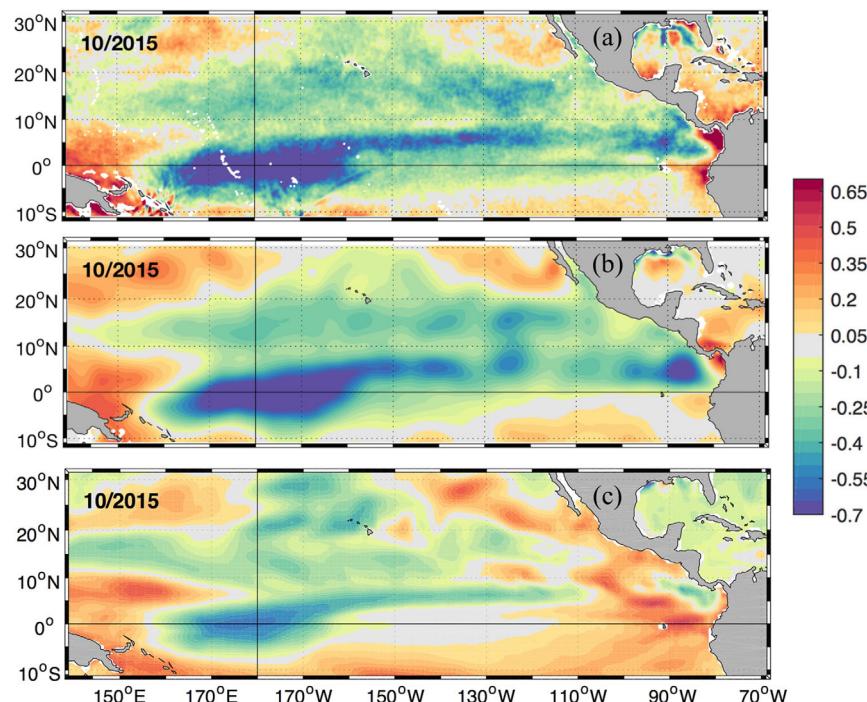
*Root Mean Square Differences (RD) Between Mooring Observations (Selected TAO and WHOTS Moorings (Same as Figure 3) and All TAO and WHOTS) and the Model (NEMO), Interpolated In Situ (ISAS), Interpolated In Situ and Satellite (Reynolds) and Satellite Only (SMOS) Data, in Terms of Sea Surface Temperature 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	6,805	0.60	161	0.27	1,614	0.45	5,904	0.33	135	0.19	354	0.33
WHOTS	3,980	0.35	131	0.16	1,073	0.24	3,980	0.25	131	0.22	200	0.18
All	62,756	0.48	1,445	0.24	14,638	0.37	4,1045	0.28	1,203	0.15	3,987	0.24

Mean Square Deviation (RMSD) is used to test the TAO data set. Wherever the TAO-ISAS RMSD is larger than  $0.3^{\circ}\text{C}$  for SST and larger than 0.2 for SSS the TAO mooring data set is discarded. Filters described above are not used for this comparison. The mooring data were averaged in time to reflect the other data sets time-resolution, leading to significant differences in the number of points of comparison between data sets. Table 1 provides a summary of the RMSD at the two moorings presented above (Figure 3) and at all sites together. NEMO- and Reynolds- TAO SST RMSD are below .5 and  $.4^{\circ}\text{C}$  respectively showing a good accuracy of both means of SST. NEMO and SMOS reproduce accurately TAO measurements (RMSD both around 0.25) even though some dubious measurements are still present in the TAO data set.

In order to further validate the large scale features which are of particular interest for the present study, the October 2015 SSA is shown for SMOS, ISAS and the model in Figure 4 using the “limited filter.” Patterns of the zonally-oriented basin-wide negative SSSA are consistent amongst the products. Firstly, the structure of the strongest anomaly, centered around the Equator and the dateline, is well simulated by the model when compared to both observation data sets, although its eastward extent is slightly reduced. Secondly, a fresh tongue extends eastward from the first anomaly, centered around  $8^{\circ}\text{N}$  and  $5^{\circ}$  wide in latitude, as seen in SMOS observations and as reproduced well by the model. It is however very smooth and non-continuous in the ISAS optimal interpolation as expected from the product’s effective resolution. Thirdly, the vast region of negative anomaly north of  $10/15^{\circ}\text{N}$  is consistently seen in the model and in the observations. Finally, the patches of positive SSSA bracketed by the negative ones west of the dateline are also very coherent from one product to another. These features will be further described in the Results section. The good agreement between in situ and SMOS SSS data sets is well known. Since satellites only measure the first cm of the water column and Argo top measurement is on average 5 m, stratification in the tropical areas can be substantial (see Boutin et al., 2016, for a review). It was however shown that at the large scale the impact of stratification is reduced (Drucker & Riser, 2014). Differences in measurement methods must hence be kept in mind.

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



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

## 2.5. Salinity Budget Processes

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

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

Term *I* ( $\text{g} \cdot \text{kg}^{-1} \cdot \text{yr}^{-1}$ ) denotes the rate of change of salinity within the ML. The salinity averaged within the ML is denoted by  $\mathbf{S}$ . The terms on the right-hand side of the equation describes the budget. Term *II* represents the freshwater forcing from the atmosphere onto the ML of depth  $H$ . The land freshwater contribution to the budget can be neglected in the tropical Pacific Ocean at the scales of interest. The horizontal processes are described by terms *III* and *IV*, which represent the advection by the ML horizontal currents and the horizontal mixing, respectively. Terms *V* and *VI* describe the vertical processes at the bottom of the ML. The vertical advection and entrainment are represented by term *V*. Term *VI* corresponds to the vertical mixing.  $K_h$  and  $K_z$  are the horizontal and vertical diffusion coefficients, and  $\delta \mathbf{S}$  the vertical salinity gradient across the ML base.

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

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

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

Where the SSS and the surface currents ( $u$ ) are assumed to be representative of the ML. All of the vertical and fine scale terms are included in the residuals (*IV*, *V*, *VI* of equation (1)) and only the SSS tendency (*I*), freshwater fluxes (*II*) and horizontal advection (*III*) are represented. Following the SMOS product resolution, the observation based budget is computed from 18 day low pass filtered data from which the median is computed within  $2.5^\circ$  of latitude and  $5^\circ$  of longitude to force all data sets to have the most consistent resolution and to smooth out the noise.

## 3. Results

### 3.1. The October 2015 $20^\circ\text{N}$ SSS Anomaly

#### 3.1.1. Description

By the end of 2015, significant freshening is observed around  $20^\circ\text{N}$  (Figures 2c and 4). SSS decreases across the basin at this latitude from mid-2014 to 2016 (Figure 2c). The EPFP edge, denoted by the “eastern” 35 isohaline, reaches the dateline. This basin-wide freshening is represented in all SSS observations and the model (Figures 3b and 4) and has an amplitude greater than 0.5 between  $10$  and  $25^\circ\text{N}$ . This feature is hereafter referred to as the  $20^\circ\text{N}$  anomaly. It is accompanied by a large equatorial freshening of about 1 in the western part of the basin, centered around the dateline (Figures 2a and 4). Fresh waters (below 35) are found east of the dateline from mid-2015 to mid-2016 and the two freshpools join one another (Figure 2a). As described in the introduction, the equatorial SSS decrease is associated with the eastward shift of the WPFP associated with El Niño and was described by Gasparin and Roemmich (2016) and Corbett et al. (2017). The large equatorial negative SSSA (below  $-0.5$ ) lies between  $160^\circ\text{E}$ – $160^\circ\text{W}$  and  $8^\circ\text{S}$ – $8^\circ\text{N}$  with an extension spreading all the way to  $90^\circ\text{W}$  and  $10^\circ\text{N}$ , forming a “sigma-shaped” pattern.

The two large-scale SSSAs are separated by a band of weaker anomalously fresh waters centered around  $10^\circ\text{N}$ . A positive  $+0.3$  anomaly extends east from north of Papua New Guinea to  $170^\circ\text{E}$  (Figure 4). This is consistent with Singh et al. (2011) analysis of El Niño composite patterns of SSS.

This anomalous negative interannual SSS double-pattern (i.e., equatorial and extra-equatorial) is specific to the year 2015. Singh et al. (2011) found SSSA associated with El Niño events to be concentrated south of

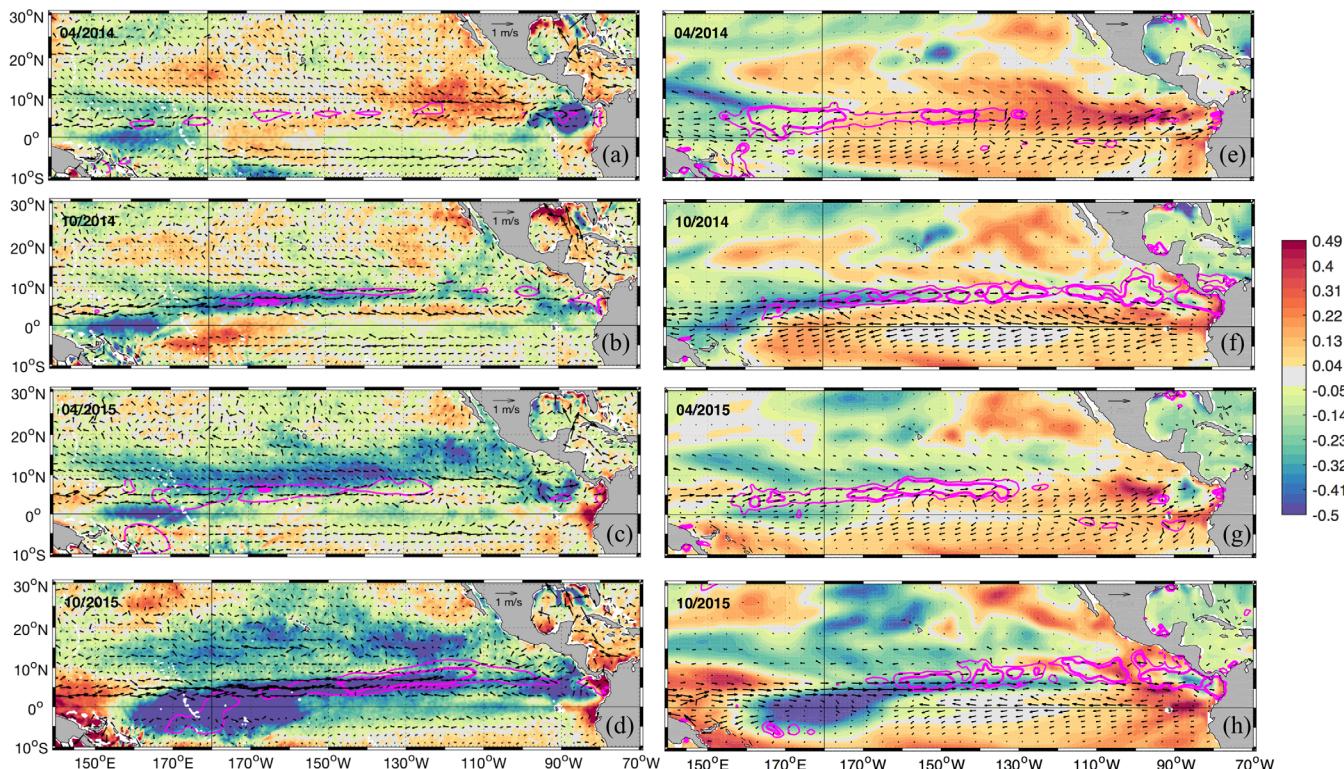
10°N. During the 2002–2003 and 2009–2010 El Niño events, no freshening is found around 20°N, both in ISAS, SMOS (2010 only) and modelling data sets (Figure 3b). In addition, the model does not show any significant freshening around 20°N for any of the simulated El Niño events during 1985–2013 (Figure 3b).

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

### 3.1.2. Build-Up of the 20°N SSS Anomaly

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

In April 2014, an equatorial negative interannual SSS anomaly of below  $-0.3$  is present west of the dateline (Figures 5a and 5e). From April to October 2014, SSS decreases across a large band, roughly from 5 to 10°N and from the dateline to the American coast. A zonal bipolar anomaly is in place around the equator in October 2014 with an anomaly of  $-0.3$  west of 170°E and  $+0.3$  to the east (Figures 5b and 5f). This “sigma shaped” anomaly resembles the canonical SSS signal associated with ENSO described by Singh et al. (2011), even if El Niño is not developing in 2014. By April 2015, the equatorial anomaly starts its eastward shift expected from the 2015 El Niño event development (Figures 5c and 5g). North of 5°N, the anomaly is intensified and spreads all the way to 20°N. From April to October 2015, the negative equatorial anomaly intensifies to be well over  $-0.5$  and reaches the dateline (Figures 5d and 5h). Similar to October 2014, the anomaly becomes “sigma shaped” as a narrow 5°–10°N less fresh anomaly band develops. By October 2014, the positive anomaly centered on 5°S and the dateline has nearly disappeared to the east. The 20°N anomaly ( $<-0.5$ ) is distinct and spans from 10 to 25°N (Figures 5d and 5h). The model shows a weaker anomaly than the observations but has consistent salinity patterns and timing. This discrepancy could be explained by very near surface stratification as the model averages salinity over the mixed layer (with a minimal depth



**Figure 5.** Monthly average, every 6 months, of the (a–d, left) interannual SMOS and (e–h, right) modeled SSS anomaly (color), unfiltered currents (arrows) and isohyets ( $-2.5$  and  $-3.5$   $\text{m.yr}^{-1}$ , magenta contours) for the months of April and October 2014 and 2015.

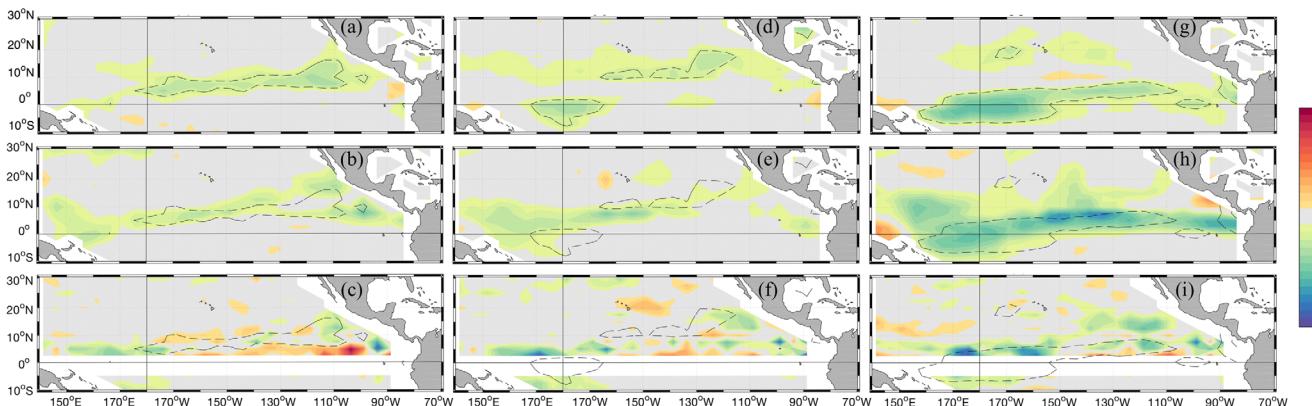
of 10m, corresponding to the 1<sup>st</sup> level of the model) whereas SMOS measures the first centimeter. Moreover, this discrepancy can also be due to imprecision in the model's mixing parametrization and its coarser resolution north of 10°N. Note that the equatorial Pacific Ocean is in a very similar state in April 2014 and April 2015 in terms of SSS (Figures 5a, 5e, 5c, and 5g). By October the difference between 2014 and 2015 is substantial. In 2015, the "sigma-shaped" anomaly fully develops and is seconded by the wide-spread 20°N anomaly (Figures 5d and 5h). In early-2016, both anomalies weaken, even though the northward extension is still apparent (not shown).

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

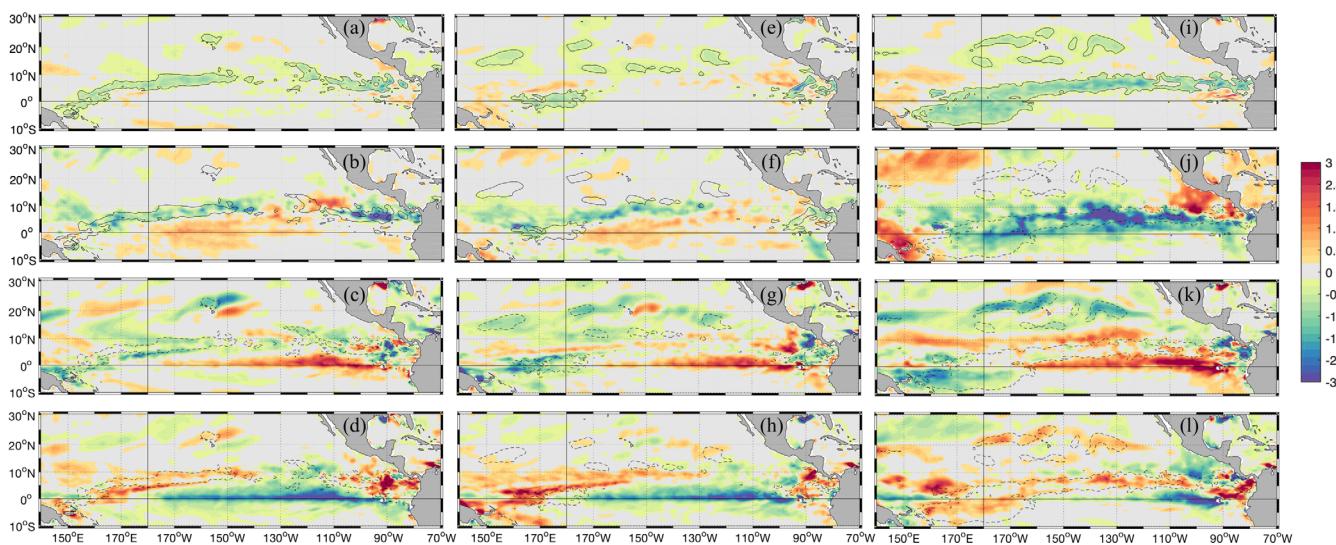
These strong interannual SSS variations are driven by freshwater fluxes (evaporation and precipitation) and the ocean currents and mixing through the salinity balance equation (equation (1)). Freshwater fluxes are important in the region of interest with the strongest values (below  $-1.5 \text{ m.yr}^{-1}$ ) occurring in the ITCZ, South Pacific Convergence Zone (SPCZ) and WPWP regions, roughly between 5 and 10°N across the basin and between 10°S and 10°N west of 170°E (Figure 1a). Freshwater fluxes have a strong variability at all timescales, which is evident from April 2014 to October 2015 (Figure 5) and are consistent with SSSA to the first order, especially in October 2014 and 2015. Discrepancies however underline the non-negligible role of ocean dynamics. North of 10°N, the westward flowing North Equatorial Current (NEC) is the southern branch of the sub-tropical gyre (Figure 1b, grey contours). The North Equatorial Counter-current (NECC) runs eastward between 3 and 10°N with an average speed of .25 m/s. The SEC spans from 10°S to 3°N and is concentrated in two westward jets on each side of the equator of about .3 m/s speed. Trade winds not only force the zonal currents but also induces the equatorial upwelling and associated poleward meridional divergence called the Ekman drift. Tropical oceans have a short response time to atmospheric variations and therefore the currents system shows intense variability at seasonal and interannual time scales (Philander, 1990) as shown from April 2014 to October 2015 (Figure 5, arrows). Patterns of SSSA and currents show an interesting coherence. It is however not straight forward how freshwater fluxes and surface currents interact to produce the observed SSS anomalies. Further investigation is performed in the following section, by considering the salinity budget over 2014–2015 from observations and modelling to shed light on the mechanisms leading to the 20°N SSSA.

### 3.1.3. Associated Processes

Observations of SSS, freshwater fluxes and surface currents can provide an estimation of the SSS budget (equation (2)) that can only represent surface processes (Figure 6). The model on the other hand provides a full budget (equation (1)) and provides details on the mechanisms that are unresolved by observations such as vertical processes (Figures 7d, 7h, and 7l).



**Figure 6.** (a, d, g) Seven month SSS tendency, (b, e, h) fresh water fluxes and (c, f, i) horizontal advection centered around (a-c, left) July 2014, (d-f, middle) January 2015 and (g-i, right) July 2015 from observations. Figures 6a, 6d, and 6g represent SSS changes (Term I of equation (2)) from April 2014 (Figure 5a) to October 2014 (Figure 5b), from October 2014 (Figure 5b) to April 2015 (Fig. 5c) and from April 2015 (Figure 5c) to October 2015 (Fig. 5d) respectively. SSS changes associated with freshwater fluxes and horizontal advection (Terms II and III of equation (2)) over the same periods are shown on Figures 6b, 6e, 6h and 6c, 6h, 6i, respectively. Contours on all plots represent the  $-0.1 \text{ year}^{-1}$  SSS tendency for each period.



**Figure 7.** (a, e, i) Seven month SSS tendency, (b, f, j) fresh water fluxes, (c, g, k) horizontal and (d, h, l) vertical ocean processes centered around (a-d, left) July 2014, (e-h, middle) January 2015 and (i-l, right) July 2015 from the NEMO numerical simulation. Contours on all plots represent the  $-0.1 \text{ year}^{-1}$  SSS tendency for each period. Analogous to Figure 6.

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

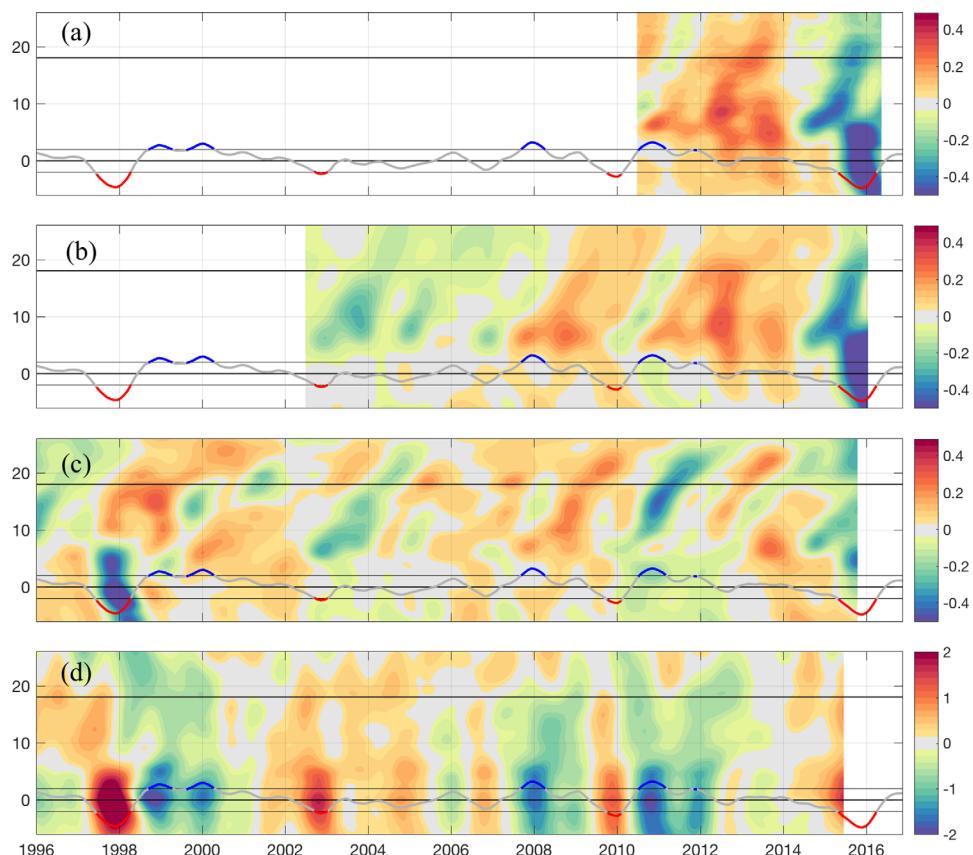
During the following 6 month period (October 2014 to April 2015) shows negative SSS tendency north of  $10^\circ\text{N}$ , corresponding to the  $20^\circ\text{N}$  anomaly build-up. It is also accompanied by the equatorial SSS decrease due to the developing 2015 El Niño event (Figures 6 and 7, central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

The  $20^\circ\text{N}$  anomaly continues its build-up through the next 6 month period (Figures 6 and 7, right column). Negative SSS tendency is found within  $10^\circ$  of latitude of Hawaii. Similarly to the previous period, the freshwater flux does not drive this SSS change as seen both for observations and the model. If the analysis of observed horizontal advection does not allow to draw any conclusions, the modeled advection clearly has an impact on the SSS tendency (Figure 7k). In mid-2015, El Niño is developing in the Pacific and the seasonal eastward flowing NECC is in place whereas the SEC has nearly disappeared. The NECC reverts north into the NEC around  $100^\circ\text{W}$ , then flowing westward between  $10^\circ$  and  $20^\circ\text{N}$ . As for the previous 6 month period, we make the hypothesis that the Ekman drift is driving this northward advection. Vertical processes are opposing horizontal advection north of Hawaii and help to eventually dissipate the negative SSSA. During this period, the  $20^\circ\text{N}$  anomaly appears in conjunction with the canonical  $10^\circ\text{S}\text{--}10^\circ\text{N}$  El Niño SSSA, with a strong negative tendency between April and October 2015 and extending to the American continent.

From April 2015, El Niño develops and the entire atmospheric circulation is gradually modified, impacting freshwater fluxes. Precipitation then increases across the tropical Pacific Ocean and especially east of the WPWP climatological position and south of the ITCZ and SPCZ climatological positions, leading to intense interannual surface freshwater fluxes across the tropical Pacific ocean. Our budget confirms that a combination of all terms explains the associated equatorial SSS decrease (Gasparin & Roemmich, 2016). North of Papua New-Guinea and in the Solomon Sea, the effect of interannual freshwater forcing is positive, which is consistent with the modification of the Walker circulation. A region of weakly increasing SSS is also present around 10°N separating the two negative tendency regions. Modeled advection reveals the role of the NECC advecting positive SSSA from the north of the Papua New-Guinea to the center of the basin.

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

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



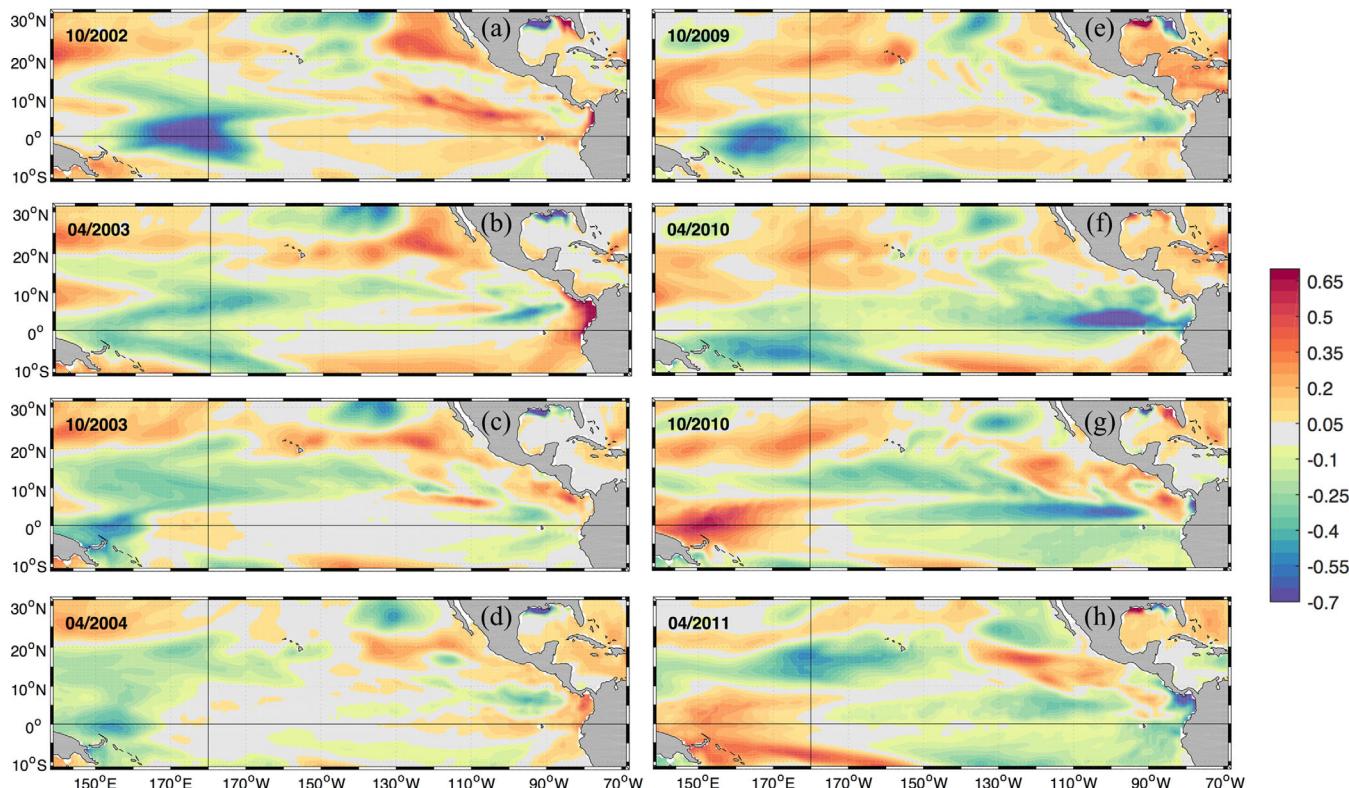
**Figure 8.** 150°–170°W Latitude-time plot of the interannual SSS anomaly from (a) SMOS, (b) ISAS, and (c) NEMO and (d) SST from NEMO. NINO3.4 on top of all plots, blue during La Niña and red during El Niño (scaled by –2, centered on the Equator).

### 3.2. Northward Pathway of Equatorial SSSA

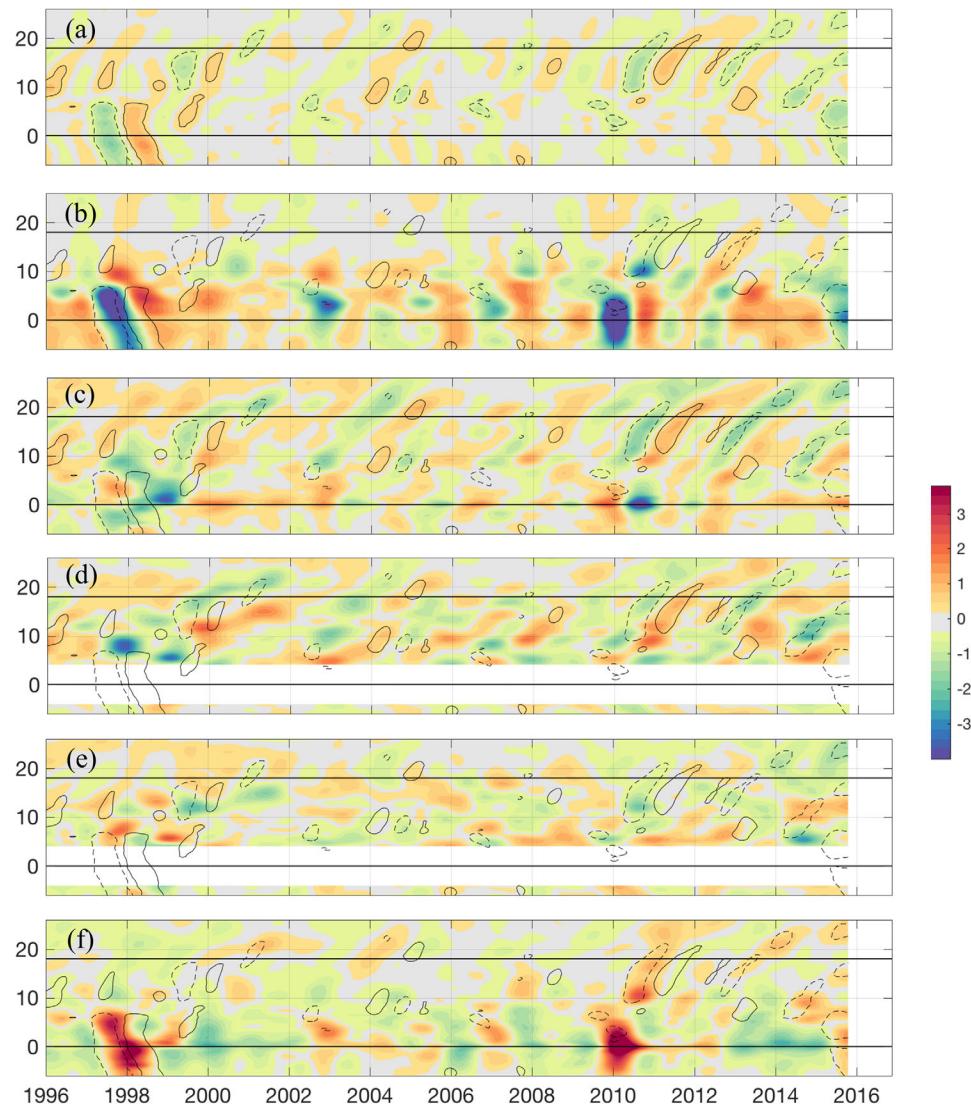
At every occurrence of El Niño during the observed period (i.e., 2002–2003, 2009–2010 and 2014–2015) a negative SSS anomaly shows an apparent northward displacement between 150–170°W (Figures 8a–8c). In addition, northward displacements of SSSAs also occur during neutral periods, i.e., 2005 or 2007. Negative SSSAs are present at the equator west of 170°W during strong El Niño events especially in 1998 and 2015 when the equatorial anomaly spreads eastward. During the 1997–1998 El Niño event and in the model, only a weak anomaly reaches 20°N early 2000. SSSAs in 2002, 2010, and 2014 only reach 170°W at 5°N (Figures 8a–8c). In 2014, the SSSA is advected by the NECC eastward to 170°W between 5° and 10°N (Figure 5c). The evolution of SSSA patterns from October 2002 to April 2004 and from October 2009 to April 2011 (Figure 9) is coherent with what has been described above for 2015 (Figure 5). An equatorial anomaly is present west of the dateline in October of the first year. Six months later, the anomaly spans across the basin between 5 and 15°N. The SSSAs become apparent between 150–170°W (Figures 8a–8c). In October of the second year, the anomaly begins its northward course and reaches 20°N by April of the second year (Figures 8a–8c and 9).

To focus on this northward displacement the interannual SSS budget is computed from the model and presented as latitude-time plots averaged within 150–170°W (Figure 10). The SSS tendency shows the displacement of anomalies from 5 to 10°N to 20–25°N in about 18 months over the entire period (Figure 10a) mirroring Figure 8c. Significant freshwater fluxes only occur south of 10°N and do not show any northward displacement (Figure 10b). The horizontal oceanic processes clearly appear as the main driver of the SSSA displacement (Figure 10c). Vertical oceanic processes have a buffer effect on abrupt changes in SSS, resulting from surface fluxes and horizontal dynamics (Figure 10f), as found in the 2014–2015 budget analysis.

In order to investigate in more detail the role of the different terms acting in the horizontal processes and to better understand the northward movement of SSSAs, the Ekman advection is computed off-line from the model as follows:



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



**Figure 10.**  $150^{\circ}$ – $170^{\circ}$ W latitude-time plots of the interannual NEMO SSS budget as described by Equations 1 and 3: (a) SSS tendency, (b) freshwater fluxes, (c) horizontal processes, (d) Ekman horizontal advection, (e) remaining horizontal processes from the Ekman horizontal advection and (f) vertical processes

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

Budget term numbers follow equation (1), where III is the horizontal advection, IV is the horizontal mixing. VII represents the Ekman advection and VIII the non-Ekman advection (Figures 10d and 10e). The Ekman current ( $u_e$ ) is computed from the model wind and the non-Ekman current ( $u_{ne}$ ) is the difference of  $u_e$  from the total current. Ekman currents are not computed within  $2^{\circ}$  of the equator.

We hypothesized from the 2014–2015 budget analysis, that northward advection of SSSA is mostly driven by the Ekman currents. SSSAs are advected poleward throughout the 1996–2016 period, regardless of the ENSO phase of the ocean (Figures 10c and 10d). ENSO however modulates the  $0$ – $10^{\circ}$ N SSSA intensity (Singh

et al., 2011) that is subsequently advected north (Figures 8a–8c). The large SSSA created by ENSO acts as a tracer to highlight the northward pathway described in the present study. This northward movement is further modulated by freshwater fluxes (Figure 10b) as seen for instance in 2014–2015 when they reinforce the negative SSSA. Conversely, the 1997–1999 SSS budget suggests that the equatorial negative anomaly advected north by the Ekman currents (Figure 10d) is opposed by positive freshwater fluxes and vertical processes (Figures 10b and 10f). The 1997 El Niño event therefore triggered a strong freshening of the equatorial region that hardly appears at 20°N.

Following their advection within the NECC (5–10°N), the equatorial SSSAs continue their northward journey driven by the Ekman drift into the NEC (10–15°N) and then northward out of NEC to around the latitude of the Hawaiian Islands ( $\sim 20^{\circ}\text{N}$ ) where they are slowly eroded.

#### 4. Summary and Conclusions

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

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

The SSS budget from observations provides the first key on the role of the surface processes described by equation (1). Observed surface freshwater forcing echoes the modifications in the Walker circulation in 2015. Even though the observed horizontal advection is noisy, some patterns can be distinguished but the results are too noisy to be quantified. Further analysis is conducted with the numerical simulation and confirms that horizontal advection is the main driver of SSS changes at the Equator. The WPFP is indeed advected eastward during the first 4 months of 2014 and 2015, driven by the weakening Trade winds and successive westerly wind events in 2015 (Gasparin & Roemmich, 2016; Puy et al., 2016b). During the following months, these anomalies are further advected eastward by the NECC in a narrow band between 5 and 10°N. Satellite observations and the model simulation (Figure 5) indicate that the NECC intensity is particularly strong in 2015, as described by Guimbard et al. (2017; their Figure 12). The intensification of ITCZ precipitation between 5° and 10°N associated with El Niño conditions from April to October 2015 also drives a strong decrease of SSS with a rate below  $-3 \text{ year}^{-1}$ . A combination of surface advection and surface forcing is thus responsible for the narrow extension of the intense equatorial anomaly that extends zonally from the dateline to almost the American continent in October 2014 and 2015. The 5–10°N SSSAs are subsequently advected north by the Ekman drift into the westward flowing NEC and then north out of it again. The westward advection of the EPFP does not appear to play a major role in the 5–10°N SSS anomaly, as suggested by Guimbard et al. (2017).

The October 2014 SSSA is further advected North reaching 20°N during the following year. Our analysis confirms that the Ekman drift acts as a basin-wide treadmill advecting these interannual anomalies poleward through the tropical zonal current system. Some part of the net northward transport of the SSSA is also carried by the NECC's retroflection northward into the NEC. Furthermore, smaller scale current features appear to interact with the Ekman northward drift, as revealed by the striking coherence of interannual SSSA and unfiltered surface currents for example around Hawaii (5–20°N and 140–180°W, Figure 11) in both the model and observations. Cusps in the NECC and NEC are observed at these latitudes and it is hypothesized that they play a significant role in the northward displacement of the SSSA. They were described by

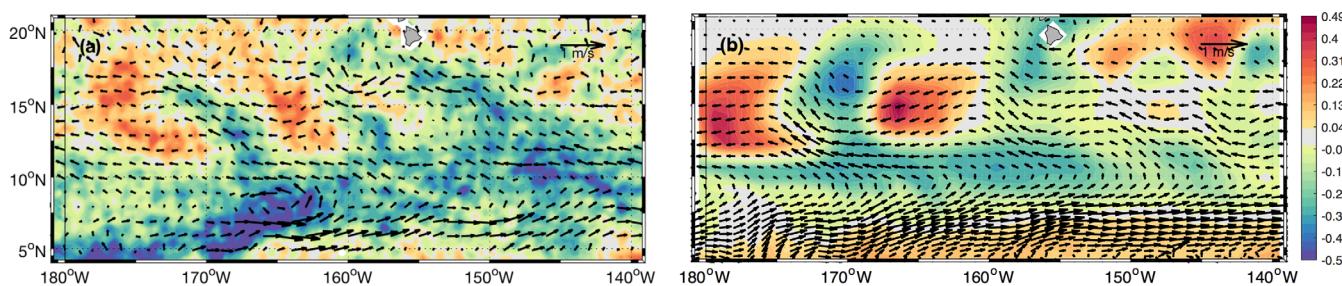


Figure 11. SSSA and currents from (a) SMOS and (b) NEMO for January 2015

Périgaud (1990) and Farrar and Weller (2006) as being baroclinic instability waves. Furthermore, they could transport anomalies in SST and SSS meridionally in a similar way to tropical instability waves near the equator (Kessler, 2006; Lee et al., 2014). Note that the model SSSA structure is much smoother than the observations and may not resolve small scale eddies due to its 1° horizontal resolution at 20°N. The cusps indeed create northward pathways for the fresh waters brought by the NECC from the western Pacific as seen in January 2015 (Figure 11).

The present study demonstrates the importance of the Ekman drift, the NECC to NEC transport and suggests the role of smaller scale features in generating the October 2015 20°N basin-wide SSSA as they all provide northward pathways for equatorial anomalies to reach the extra tropics. Analogous mechanisms occurred in the successive years in 2014 and 2015, led to a superimposition of SSSAs and created the unusually strong double structure in October 2015. Moreover, we find a strong anomaly by the end of 2016 (Figures 2a and 2c). The record of the past 20 years of observed and simulated SSS shows a continuous northward advection of SSSA from the Equator to the Subtropics that is balanced by freshwater fluxes and vertical processes. This advection is particularly clear during El Niño events as anomalously strong SSSA are generated in the equatorial region. The 1997–1998 El Niño equatorial negative SSS anomaly was also advected north, but in this event it was counteracted by strong positive freshwater fluxes and vertical processes, especially in the ITCZ. The sequence of the halted 2014 El Niño producing a first equatorial SSS anomaly which was then reinforced by the ITCZ freshwater fluxes and lingered in the Pacific, then followed by El Niño conditions in 2015 led to the formation of the very large 20°N anomaly in 2015.

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

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

## References

- Alory, G., Maes, C., Delcroix, T., Reul, N., & Illig, S. (2012). Seasonal dynamics of sea surface salinity off Panama: The far Eastern Pacific Fresh Pool. *Journal of Geophysical Research*, 117, C04028. <https://doi.org/10.1029/2011JC007802>
- Ballabrera-Poy, J., Murtugudde, R., & Busalacchi, A. J. (2002). On the potential impact of sea surface salinity observations on ENSO predictions. *Journal of Geophysical Research*, 107(C12), 8007. <https://doi.org/10.1029/2001JC000834>
- Blunden, J., & Arndt, D. S. (2016). State of the Climate in 2015. *Bulletin of the American Meteorological Society*, 97(8), S1–S275. <https://doi.org/10.1175/2016BAMSStateoftheClimate1>

## Acknowledgments

AH acknowledges the support of a CNES Postdoctoral fellowship. This work is a contribution to the TOSCA/SMOS-Ocean proposal supported by CNES. We benefited from numerous data sets made freely available and are listed here: The SMOS debias\_v2 SSS produced by LOCEAN/IPSL (UMR CNRS/UPMC/IRD/MNHN), laboratory which participates in the Ocean Salinity Expertise Center (CECOS) of Centre Aval de Traitement des Données SMOS (CATDS) at IFREMER, Plouzane, France (<http://www.catds.fr/>); Products, see documentation: <http://www.catds.fr/Products/Available-products-from-CEC-OS/L3-Debiased-Locean-v2>); the TAO-TRITON moorings data by GTMBA Project Office of NOAA/PMEL (<https://www.pmel.noaa.gov/gtmiba/>); the WHOTS mooring supported by NOAA through the Cooperative Institute for Climate and Ocean Research (CICOR) and by National Science; the *in situ* Analysis System (ISAS) by LPO (CNRS/IFREMER/IRD/UBO) and products were made available by F. Gaillard ([www.ifremer.fr/Ip0/La-recherche/Projets-en-cours/GOSCAL](http://www.ifremer.fr/Ip0/La-recherche/Projets-en-cours/GOSCAL)), the Precipitation Climatology Project data (<http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html>), Nino 3.4 Index ([https://www.esrl.noaa.gov/psd/gcos\\_wgsp/Timeseries/Nino34/](https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/)), Woods Hole Oceanographic Institution OAFlux evaporation dataset (<http://oaflux.whoi.edu/evap.html>), GEKCO product by Joël Sudre at LEGOS, France (<http://ctoh.legos.obs-mip.fr/products/global-surface-currents/global-surface-current-data-product>) and Reynolds SST (<ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/>). We acknowledge the support of the Belmont project GOTHAM, under grant ANR-15-JCLI-0004-01. We thank Jérôme Vialard for some very helpful discussions.

- Bosc, C., Delcroix, T., & Maes, C. (2009). Barrier layer variability in the western Pacific warm pool from 2000 to 2007. *Journal of Geophysical Research*, 114, C06023. <https://doi.org/10.1029/2008JC005187>
- Boutin, J., Chao, Y., Asher, W. E., Delcroix, T., Drucker, R., Drushka, K., et al. (2016). Satellite and In Situ Salinity: Understanding Near-Surface Stratification and Subfootprint Variability. *Bulletin of the American Meteorological Society*, 97(8), 1391–1407. <https://doi.org/10.1175/BAMS-D-15-00032.1>
- Boutin, J., Martin, N., Kolodziejczyk, N., & Reverdin, G. (2016). Interannual anomalies of SMOS sea surface salinity. *Remote Sensing of Environment*, 180, 128–136. <https://doi.org/10.1016/j.rse.2016.02.053>
- Boutin, J., Vergely, J.-L., & Marchand, S. (2017). SMOS SSS L3 debias v2 maps generated by CATDS CEC LOCEAN. SEANOE. <https://doi.org/10.17882/52804>
- Brion, E., Gaillard, F., Petit de la Villéon, L., Delcroix, T., Alory, G., & Reverdin, G. (2011). Collecting and gridding complementary in-situ SST–SSS data for the calibration and validation of smos, *Mercator Ocean – CORIOLIS Quarterly Newsletter*, 41, 33.
- Corbett, C. M., Subrahmanyam, B., & Giese, B. S. (2017). A comparison of sea surface salinity in the equatorial Pacific Ocean during the 1997–1998, 2012–2013, and 2014–2015 ENSO events. *Climate Dynamics*, 35(13–3526. <https://doi.org/10.1007/s00382-017-3527-y>
- Cronin, M. F., & McPhaden, M. J. (2002). Barrier layer formation during westerly wind bursts. *Journal of Geophysical Research-Oceans*, 107(C12), 8020. <https://doi.org/10.1029/2001JC001171>
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597. <https://doi.org/10.1002/qj.828>
- Delcroix, T., Gourdeau, L., & Henin, C. (1998). Sea surface salinity changes along the Fiji-Japan shipping track during the 1996 La Niña and 1997 El Niño period. *Geophysical Research Letters*, 25(16), 3169–3172. <https://doi.org/10.1029/98GL02320>
- Delcroix, T., & Picaut, J. (1998). Zonal displacement of the western equatorial Pacific “fresh pool. *Journal of Geophysical Research*, 103(C1), 1087–1098. <https://doi.org/10.1029/97JC01912>
- Di Lorenzo, E., & Mantua, N. (2016). Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, 6(11), 1042–1047. <https://doi.org/10.1038/nclimate3082>
- Drucker, R., & Riser, S. C. (2014). Validation of Aquarius sea surface salinity with Argo: Analysis of error due to depth of measurement and vertical salinity stratification. *Journal of Geophysical Research: Oceans*, 119, 4626–4637. <https://doi.org/10.1002/2014JC010045>
- Durack, P. J., Lee, T., Vinogradova, N. T., & Stammer, D. (2016). Keeping the lights on for global ocean salinity observation. *Nature Climate Change*, 6(3), 228–231. <https://doi.org/10.1038/nclimate2946>
- Dussin, R., & Barnier, B. (2013). *The making of DF55.1* (Drakkar project report, 40 pp.). Grenoble, France: LGGE.
- Farrar, J. T. (2011). Barotropic Rossby Waves Radiating from Tropical Instability Waves in the Pacific Ocean. *Journal of Physical Oceanography*, 41(6), 1160–1181. <https://doi.org/10.1175/2011JPO4547.1>
- Farrar, J. T., & Weller, R. A. (2006). Intraseasonal variability near 10 N in the eastern tropical Pacific Ocean. *Journal of Geophysical Research*, 111, C05015. <https://doi.org/10.1029/2005JC002989>
- Gaillard, F., Reynaud, T., Thierry, V., Kolodziejczyk, N., & von Schuckmann, K. (2016). In situ-based reanalysis of the global ocean temperature and salinity with ISAS: Variability of the heat content and steric height. *Journal of Climate*, 29(4), 1305–1323. <https://doi.org/10.1175/JCLI-D-15-0028.1>
- Gasparin, F., & Roemmich, D. (2016). The strong freshwater anomaly during the onset of the 2015/2016 El Niño. *Geophysical Research Letters*, 43, 6452–6460. <https://doi.org/10.1002/2016GL069542>
- Gentemann, C. L., Fewings, M. R., & García-Reyes, M. (2017). Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, 44, 312–319. <https://doi.org/10.1002/2016GL071039>
- Gordon, A. L., Giulivi, C. F., Busecke, J., & Bingham, F. M. (2015). Differences among subtropical surface salinity patterns. *Oceanography*, 28(1), 32–39.
- Gouriou, Y., & Delcroix, T. (2002). Seasonal and ENSO variations of sea surface salinity and temperature in the South Pacific Convergence Zone during 1976–2000. *Journal of Geophysical Research*, 107(C12), 8011. <https://doi.org/10.1029/2001JC000830>
- Guimbard, S., Reul, N., Chapron, B., Umber, M., & Maes, C. (2017). Seasonal and interannual variability of the Eastern Tropical Pacific Fresh Pool. *Journal of Geophysical Research: Oceans*, 122, 1749–1771. <https://doi.org/10.1002/2016JC012130>
- Hackert, E., Busalacchi, A. J., & Ballabrera-Poy, J. (2014). Impact of Aquarius sea surface salinity observations on coupled forecasts for the tropical Indo-Pacific Ocean. *Journal of Geophysical Research: Oceans*, 119, 4045–4067. <https://doi.org/10.1002/2013JC009697>
- Hasson, A., Delcroix, T., & Boutin, J. (2013a). Formation and variability of the South Pacific Sea Surface Salinity maximum in recent decades. *Journal of Geophysical Research: Oceans*, 118, 5109–5116. <https://doi.org/10.1002/jgrc.20367>
- Hasson, A., Delcroix, T., Boutin, J., Dussin, R., & Ballabrera-Poy, J. (2014). Analyzing the 2010–2011 La Niña signature in the tropical Pacific sea surface salinity using in situ data, SMOS observations, and a numerical simulation. *Journal of Geophysical Research: Oceans*, 119, 3855–3867. <https://doi.org/10.1002/2013JC009388>
- Hasson, A., Delcroix, T., & Dussin, R. (2013b). An assessment of the mixed layer salinity budget in the tropical Pacific Ocean. Observations and modelling (1990–2009). *Ocean Dynamics*, 63(2–3), 179–194. <https://doi.org/10.1007/s10236-013-0596-2>
- Hewitt, H. T., Copsey, D., Culverwell, I. D., Harris, C. M., Hill, R. S. R., Keen, A. B., et al. (2011). Design and implementation of the infrastructure of HadGEM3: The next-generation Met Office climate modelling system. *Geoscientific Model Development*, 4(2), 223–253. <https://doi.org/10.5194/gmd-4-223-2011>
- Hu, Z.-Z., Kumar, A., Jha, B., Zhu, J., & Huang, B. (2017). Persistence and predictions of the remarkable warm anomaly in the northeastern Pacific Ocean during 2014–16. *Journal of Climate*, 30(2), 689–702. <https://doi.org/10.1175/JCLI-D-16-0348.1>
- Huffman, G. J., Adler, R. F., Bolvin, D. T., & Gu, G. (2009). Improving the global precipitation record: GPCP Version 2.1. *Geophysical Research Letters*, 36(17), n/a–n/a. <https://doi.org/10.1029/2009GL040000>
- Kao, H.-Y., & Lagerloef, G. S. E. (2015). Salinity fronts in the tropical Pacific Ocean. *Journal of Geophysical Research: Oceans*, 120, 1096–1106. <https://doi.org/10.1002/2014JC010114>
- Kerr, Y. H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., et al. (2010). The SMOS Mission: New tool for monitoring key elements of the global water cycle. *Proceedings of the IEEE*, 98(5), 666–687. <https://doi.org/10.1109/jproc.2010.2043032>
- Kessler, W. S. (2006). The circulation of the eastern tropical Pacific: A review. *Progress in Oceanography*, 69(2–4), 181–217. <https://doi.org/10.1016/j.pocean.2006.03.009>
- Kolodziejczyk, N., Boutin, J., Vergely, J.-L., Marchand, S., Martin, N., & Reverdin, G. (2016). Mitigation of systematic errors in SMOS sea surface salinity. *Remote Sensing of Environment*, 180, 164–177. <https://doi.org/10.1016/j.rse.2016.02.061>
- Lee, T., Lagerloef, G., Kao, H.-Y., McPhaden, M. J., Willis, J., & Gierach, M. M. (2014). The influence of salinity on tropical Atlantic instability waves. *Journal of Geophysical Research: Oceans*, 119, 8375–8394. <https://doi.org/10.1002/2014JC010100>

- Levine, A. F. Z., McPhaden, M. J., & Frierson, D. M. W. (2017). The impact of the AMO on multidecadal ENSO variability: AMO IMPACTS ON ENSO. *Geophysical Research Letters*, 44, 3877–3886. <https://doi.org/10.1002/2017GL072524>
- Lukas, R., & Lindstrom, E. (1991). The mixed layer of the western equatorial Pacific Ocean. *Journal of Geophysical Research*, 96(S01), 3343–3357.
- Madec, G. (2008). NEMO ocean engine. *Note Du Pole De Modélisation*, 27, 300.
- Maes, C., Reul, N., Behringer, D., & O'kane, T. (2014). The salinity signature of the equatorial Pacific cold tongue as revealed by the satellite SMOS mission. *Geoscience Letters*, 1(1). <https://doi.org/10.1186/s40562-014-0017-5>
- McPhaden, M. J., Timmermann, A., Widiansky, M. J., Balmaseda, M. A., & Stockdale, T. N. (2015). The curious case of the El Niño that never happened: A perspective from 40 years of progress in climate research and forecasting. *Bulletin of the American Meteorological Society*, 96(10), 1647–1665.
- McPhaden, M. J., Zebiak, S. E., & Glantz, M. H. (2006). ENSO as an integrating concept in earth science. *Science*, 314(5806), 1740–1745.
- Paek, H., Yu, J.-Y., & Qian, C. (2017). Why were the 2015/2016 and 1997/1998 extreme El Niños different? *Geophysical Research Letters*, 44, 1848–1856. <https://doi.org/10.1002/2016GL071515>
- Palmeiro, F. M., Iza, M., Barriopedro, D., Calvo, N., & García-Herrera, R. (2017). The complex behavior of El Niño winter 2015–2016. *Geophysical Research Letters*, 44, 2902–2910. <https://doi.org/10.1002/2017GL072920>
- Périgaud, C. (1990). Sea level oscillations observed with Geosat along the two shear fronts of the Pacific North Equatorial Countercurrent. *Journal of Geophysical Research*, 95(C5), 7239–7248. <https://doi.org/10.1029/JC095iC05p07239>
- Philander, S. G., Holton, J. R., & Dmowska, R. (1989). *El Niño, La Niña, and the Southern Oscillation*. Amsterdam, the Netherlands: Elsevier Science. Retrieved from [http://books.google.fr/books?id=9fwrkW\\_B1YYC](http://books.google.fr/books?id=9fwrkW_B1YYC)
- Picaut, J., Ioulalou, M., Delcroix, T., Masia, F., Murtugudde, R., & Vialard, J. (2001). The oceanic zone of convergence on the eastern edge of the Pacific warm pool: A synthesis of results and implications for El Niño–Southern Oscillation and biogeochemical phenomena. *Journal of Geophysical Research*, 106(C2), 2363–2386. <https://doi.org/10.1029/2000JC900141>
- Puy, M., Vialard, J., Lengaigne, M., & Guilyardi, E. (2016a). Modulation of equatorial Pacific westerly/easterly wind events by the Madden–Julian oscillation and convectively-coupled Rossby waves. *Climate Dynamics*, 46(7), 2155–2178. <https://doi.org/10.1007/s00382-015-2695-x>
- Puy, M., Vialard, J., Lengaigne, M., Guilyardi, E., Voldoire, A., & Madec, G. (2016b). Modulation of equatorial Pacific sea surface temperature response to westerly wind events by the oceanic background state. *Climate Dynamics*, 1–25. <https://doi.org/10.1007/s00382-016-3480-1>
- Qu, T., Song, Y. T., & Maes, C. (2014). Sea surface salinity and barrier layer variability in the equatorial Pacific as seen from Aquarius and Argo: SEA SURFACE SALINITY AND BARRIER LAYER. *Journal of Geophysical Research: Oceans*, 119, 15–29. <https://doi.org/10.1002/2013JC009375>
- Qu, T., & Yu, J.-Y. (2014). ENSO indices from sea surface salinity observed by Aquarius and Argo. *Journal of Oceanography*, 70(4), 367–375. <https://doi.org/10.1007/s10872-014-0238-4>
- Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlaik, M. G. (2007). Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, 20(22), 5473–5496. <https://doi.org/10.1175/2007jcli1824.1>
- Roemmich, D., Johnson, G. C., Riser, S., Davis, R., Gilson, J., Owens, W. B., et al. (2009). The Argo Program: Observing the global ocean with profiling floats. *Oceanography*, 22(2), 34–43.
- Sarachik, E. S., & Cane, M. A. (2010). *The El Niño–southern oscillation phenomenon*. Cambridge, UK: Cambridge University Press.
- Sena-Martins, M., & Stammer, D. (2015). Pacific Ocean surface freshwater variability underneath the double ITCZ as seen by satellite sea surface salinity retrievals. *Journal of Geophysical Research: Oceans*, 120, 5870–5885. <https://doi.org/10.1002/2015JC010895>
- Singh, A., Delcroix, T., & Cravatte, S. (2011). Contrasting the flavors of El Niño–Southern Oscillation using sea surface salinity observations. *Journal of Geophysical Research*, 116, C06016. <https://doi.org/10.1029/2010JC06862>
- Sommer, A., Reverdin, G., Kolodziejczyk, N., & Boutin, J. (2015). Sea Surface Salinity and Temperature Budgets in the North Atlantic Subtropical Gyre during SPURS Experiment: August 2012–August 2013. *Frontiers in Marine Science*, 2, 107. <https://doi.org/10.3389/fmars.2015.00107>
- Sprintall, J., & Tomczak, M. (1992). Evidence of the barrier layer in the surface layer of the tropics. *Journal of Geophysical Research*, 97(C5), 7305–7316. <https://doi.org/10.1029/92JC00407>
- Sudre, J., Maes, C., & Garçon, V. (2013). On the global estimates of geostrophic and Ekman surface currents. *Limnology and Oceanography: Fluids and Environments*, 3(1), 1–20.
- Tang, W., Fore, A., Yueh, S., Lee, T., Hayashi, A., Sanchez-Franks, A., et al. (2017). Validating SMAP SSS with in situ measurements. *Remote Sensing of Environment*, 200, 326–340. <https://doi.org/10.1016/j.rse.2017.08.021>
- Tchilibou, M., Delcroix, T., Alory, G., Arnault, S., & Reverdin, G. (2015). Variations of the tropical Atlantic and Pacific SSS minimum zones and their relations to the ITCZ and SPCZ rain bands (1979–2009). *Journal of Geophysical Research: Oceans*, 120, 5090–5100. <https://doi.org/10.1002/2015JC010836>
- Uppala, S. M., Källberg, P., Simmons, A., Andrae, U., Bechtold, V. D., Fiorino, M., et al. (2005). The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, 131(612), 2961–3012.
- Vialard, J., & Delecluse, P. (1998). An OGCM study for the TOGA decade. Part II: Barrier-layer formation and variability. *Journal of Physical Oceanography*, 28(6), 1089–1106. [https://doi.org/10.1175/1520-0485\(1998\)028<1089:aosftt>2.0.co;2](https://doi.org/10.1175/1520-0485(1998)028<1089:aosftt>2.0.co;2)
- Vialard, J., Delecluse, P., & Menkes, C. (2002). A modeling study of salinity variability and its effects in the tropical Pacific Ocean during the 1993–1999 period. *Journal of Geophysical Research*, 107(C12), 8005, <https://doi.org/10.1029/2000JC000758>
- Wang, C., & Picaut, J. (2004). Understanding ENSO physics—A review. *Earth's Climate*, 147, 21–48.
- Wright, D., Pawlowicz, R., McDougall, T., Feistel, R., & Marion, G. (2011). Absolute Salinity, "Density Salinity" and the Reference-Composition Salinity Scale: Present and future use in the seawater standard TEOS-10. *Ocean Science*, 7(1), 1–26.
- Yu, L. (2011). A global relationship between the ocean water cycle and near-surface salinity. *Journal of Geophysical Research*, 116, C10025. <https://doi.org/10.1029/2010JC006937>
- Yu, L. (2015). Sea-surface salinity fronts and associated salinity-minimum zones in the tropical ocean. *Journal of Geophysical Research: Oceans*, 120, 4205–4225. <https://doi.org/10.1002/2015JC010790>
- Yu, L., Jin, X., & Weller, R. A. (2008). *Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: Latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables*. (OAFlux Project Technical Report, p. 64). Woods Hole, MA: Woods Hole Oceanographic Institution.
- Zhu, J., Huang, B., Zhang, R.-H., Hu, Z.-Z., Kumar, A., Balmaseda, M. A., et al. (2014). Salinity anomaly as a trigger for ENSO events. *Scientific Reports*, 4. <https://doi.org/10.1038/srep06821>
- Zhu, J., Kumar, A., Huang, B., Balmaseda, M. A., Hu, Z.-Z., Marx, L., & Kinter III, J. L. (2016). The role of off-equatorial surface temperature anomalies in the 2014 El Niño prediction. *Scientific Reports*, 6(1). <https://doi.org/10.1038/srep19677>