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Salty anomalies forced by Tehuantepec and Papagayo gap winds: Aquarius observations

Semyon A. Grodsky[a, *], James A. Carton[a] and Abderrahim Bentamy[b]

[a] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD, USA
[b] Institut Francais pour la Recherche et l'Exploitation de la Mer, Centre Bretagne - ZI de la Pointe du Diable, Plouzané, France

*: Corresponding author : Semyon A. Grodsky, email address : mailto:senya@atmos.umd.edu

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Abstract:

In the presence of stable near-surface haline stratification, intermittent cold sea surface temperature (SST, upwelling) events produced by gap winds off the Central American Pacific coast should be accompanied by uplifts of saltier water. We illustrate that Aquarius satellite sea surface salinity (SSS) captures these high SSS events. In boreal winter when the intense gap winds are frequent, two tongues of anomalously salty water develop off the Gulfs of Tehuantepec and Papagayo. During that season the average SSS in the meridionally oriented Tehuantepec tongue is about 0.4 psu saltier than the background SSS. The zonally elongated Papagayo tongue stands out even more strongly, being 1–2 psu saltier than SSS in the neighbouring Panama Bight. The spatial locations and orientations of the salty tongues closely correspond to the locations and orientations of the cool SST tongues, suggesting they have similar governing mechanisms.

1. Introduction

The Central American Pacific (CAP) seasonal upwelling in the Gulfs of Tehuantepec, Papagayo and Panama Bight has been studied extensively (e.g. Stumpf and

Legeckis, 1977; Legeckis 1988, and others). This regional upwelling occurs from November to March in response to episodic gale-force offshore jet-like winds, which amplify in response to a combination of the cool synoptic-scale systems and undulations in the strength of trade winds in the Atlantic sector over the Gulf of Mexico and Caribbean (e.g. Chelton et al., 2000a,b; Brennan et al., 2010). The northerly and easterly winds associated with these synoptic systems are blocked by the Central American Cordillera, except for winds tunneling at the three gaps at the Isthmus of Tehuantepec (T), the Lake of Nicaragua (Papagayo jet, PP), and Panama Channel (PA, see Fig.1). Typically the resulting air flow jets are about 200 km wide, extend several hundred kilometers (up to 500km) downstream, and the period of intensified air flow lasts for 3 to 10 days (McCreary et al., 1989; Brennan et al, 2010).

These gap wind jets induce a remarkable oceanic response seen in low SST patterns that are spatially co-aligned with the jets (Legeckis, 1988). These winds also force pronounced intra-seasonal variability in the sea surface height (SSH) that is organized into trains of eddies propagating southwestward at speeds of 15-17 cm s^{-1} from Tehuantepec and Papagayo (McCreary et al., 1989; Giese et al., 1994; Chang et al., 2012). All of these features generate very complex dynamics, reflected in the thermohaline structure, which shows not only significant temporal variation but also strong salinity fronts resulting from interaction between cold and warm core eddies (Brenes et al., 1998).

The wind-induced upwelling physics producing the cool SSTs off the CAP coast should also produce high SSS because the ocean mixed layer has lower salinity than the submixed layer water due to dilution by local rainfall (Alory et al., 2012). The freshwater pool disruptions in the Panama Bight have been linked to the gap winds and associated upwelling that brings cold and salty water to the surface (Reul et al., 2014). The recent availability of remotely sensed SSS (e.g. Lagerloef et al., 2012) significantly improves our ability to monitor this variable and is used in this paper to detect the SSS signature of the ocean response to gap wind jets. Our analysis predominantly focuses on the seasonal mean patterns because the combination of spatial and temporal sampling of satellite SSS doesn’t fully resolve the ocean response to individual wind events.

2. Data

This study mostly relies on measurements of satellite surface salinity, temperature, and winds. The main SSS data set used in this study is the daily level 3 version 2.8.1 Aquarius SSS beginning 25 August, 2011 and extending through 17 February 2014, obtained from the NASA Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center on a $1^{\circ} \times 1^{\circ}$ grid (Lagerloef et al., 2012). These data now span three boreal winter seasons (when the gap winds are strong). Although daily Aquarius SSS is available, complete spatial coverage is available only for weekly averages. To emphasize features present during all years, the seasonal climatology of SSS is evaluated using Fourier series truncated after the annual and semiannual harmonics. It is reasonable to estimate the SSS climatology because of the dominance of the annual cycle in the tropics (e.g. Xie and Carton, 2004). We also compare daily SST and SSS in a spatially averaged region, recognizing that such a daily SSS time series will be quite noisy. Surface winds are based on the Advanced SCATterometer (ASCAT), which are available at $0.25^{\circ} \times 0.25^{\circ}$ resolution (Bentamy and Croize-Fillon, 2012) since November 2008. SST is also available at a resolution of

$0.25^{\circ} \times 0.25^{\circ}$ based on the NOAA optimum interpolation analysis of Reynolds et al. (2007). To evaluate the surface salt flux we use the monthly OaFlux evaporation analysis of Yu (2007) available on a $1^{\circ} \times 1^{\circ}$ grid and the Tropical Rainfall Measuring Mission monthly mean precipitation (trmm.gsfc.nasa.gov).

3. Results

The freshest SSS in the tropical Pacific occurs in the Panama Bight due to abundant rainfall and a pattern of surface currents that trap the fresh water locally (Alory et al., 2012). Further along the north CAP coast, SSS is relatively fresh (about 33 psu south of 15° N) in summer and fall due to the seasonal northward shift of the Intertropical Convergence Zone (ITCZ) and cumulating impact of the surface freshwater forcing (Fig. 1e,g). During the dry boreal winter, as the ITCZ is displaced to the south, SSS increases with latitude along the CAP coast (Fig. 1a). In boreal spring, SSS increases even more, up to 35 psu, in a near-coastal tongue of salty water stretching down to 10° N (Fig. 1c). This salty tongue is probably produced by southeastward salt advection by the southeastern extension of the shallow geostrophic California Current (Kessler, 2006).

In boreal winter, two additional tongues of salty water develop off the Gulfs of Tehuantepec and Papagayo (Fig. 1a). SSS contrast in the meridionally oriented Tehuantepec tongue is about 0.4 psu. The zonally elongated Papagayo tongue is 1 to 2 psu saltier than the mean SSS in the Panama Bight. It is worth noting that the impact on water density of an increase in salinity by 1psu is the equivalent of a 3°C drop in SST. So the SSS and SST changes induced by the gap winds have similar sized effects on mixed layer density, at least for Papagayo.

The orientation of the gap winds that develop in boreal fall and winter is defined by the terrestrial elevation profiles of the gaps in the Cordillera. These winds intensify from November to March and produce remarkable seasonal cooling of SST in the Tehuantepec and Papagayo upwelling regions (Fig. 1b). In winter, this SST cooling is accompanied by increasing SSS. During other seasons (when the gap winds are not as intense as in boreal winter) the salty tongues are weaker and are not detectable by the Aquarius. Although the gap winds are also present in the Panama Bight (seen in SST maps in Fig. 1b), an expected increase in the seasonal SSS is not observed there (in contrast to transient disruptions of the fresh pool reported by Reul et al. (2014)). This absence, we believe, is due to the effects of land contamination on the Aquarius SSS retrievals, which result in a negative SSS bias.

The salty tongues off the CAP coast develop late each fall and persist to early spring (Fig. 2a). Their location corresponds with the location of cool SST tongues suggesting a similarity in mechanisms responsible for the two types of anomalies. Because both the salty and cold SST tongues are forced by strong gap winds, the former may originate due to stronger evaporation. But, closer inspection of the net surface salt flux (evaporation minus precipitation, E-P, in Fig. 2b) doesn’t reveal patterns of higher E-P spatially collocated with the gap winds. This unexpected feature is explained by changes in the sea surface saturated humidity, which decreases over cold water and leads to decreased air-sea humidity difference. This humidity effect counteracts the effect of the wind increase, thus attenuating spatial anomalies of E-P otherwise expected in response to the gap winds.

The studies cited above have shown that the cool SST tongues are produced by wind jets due to the entrainment of cooler water from below the mixed layer. This entrainment cooling, $w_e \Delta T_e$, occurs due to the upward cross-isopycnal velocity, w_e, that entrains colder water (ΔT_e<0) into the shallow 10-50m mixed layer. Here we suggest that the same entrainment mechanism, $w_e \Delta S_e$, leads to increasing mixed layer salinity in the CAP region where strong salinity stratification results from heavy local rainfall and more salty water ($\Delta S_e > 0$) locates below the mixed layer. This mechanism is similar to that producing salty signature of strong wind forcing over river plumes (e.g. Grodsky et al., 2012).

Entrainment velocity across the base of the mixed layer has two components, mixed layer deepening and vertical velocity, $w_e = dh/dt + w$. The mixed layer depth (h) may deepen in time (dh/dt) due to wind-induced stirring. Also, a positive (upward) vertical velocity (w) is induced by positive Ekman pumping, which is most prominent on the left side of the wind jet where the wind stress curl is positive. The central axes of the Tehuantepec SST and SSS anomalies are located along the axes of the maximum wind speed, which is where the Ekman pumping is a minimum (Figs. 2c, 2d) suggesting that at this location entrainment due to wind stirring dominates over entrainment due to Ekman pumping. In contrast the central axes of the Gulf of Papagayo SST and SSS anomalies are shifted left of the maximum wind speed suggesting that for this region wind stirring and Ekman pumping both contribute to entrainment.

As illustrated for the Gulf of Tahuantepec in Fig. 3a, the cool season November to March is the season with frequent 3 to 10 day cool SST anomalies. Because the Aquarius provides no-gap coverage only once in seven days, the corresponding time series of SSS are subject to considerable sampling errors. Nevertheless, a comparison of the time series shows that many of the 3 to 10 day cool SST anomalies correspond to high SSS (Fig. 3a) and that the correspondence is higher when the data counts are higher. As a result the two time series are negatively correlated (the correlation coefficient is about -0.3 at zero lag, Fig. 3b), but the correlation is reduced because of the satellite SSS sampling problems. The lagged correlation of anomalous wind speed and SST is stronger, and the fact that the maximum SST cooling lags behind wind speed amplification by only 1 to 2 days highlights the rapid response of the ocean to these wind events.

4. Summary

Rainfall off the Central American Pacific (CAP) coast dilutes the ocean mixed layer, which is thus fresher than the water beneath the mixed layer. The CAP region is characterized by intermittent 3-10 day gale-force wind events in boreal winter which cause surface cooling in several geographically narrow regions. Using new observations of SSS collected by the Aquarius satellite we show that these cool SST events coincide with high SSS events.

In this study we focus on two regions: the Gulfs of Tehuantepec and Papagayo. During boreal winter, the seasonally average SSS in the meridionally oriented Tehuantepec cool tongue is about 0.4 psu saltier than the climatological average SSS. The zonally elongated Papagayo tongue is 1 to 2 psu saltier than SSS in the Panama Bight. The spatial location and orientation of the salty tongues closely follows those of the cool SST tongues, in turn suggesting similarity of their governing mechanisms.

Salty signatures produced by individual gap wind events are not well sampled by Aquarius. Nevertheless, a comparison of a spatially averaged index time series for the

Tehuantepec index region shows some salinity events that correspond to SST events (sampling issues reduce the average correlation between anomalous SST and SSS to -0.3 at zero lag). A similar lagged correlation of anomalous wind speed and SST shows that the mixed layer is responding to the wind events with a lag of only 1 to 2 days.

It is still an open question whether satellite SSS is useful in coastal areas and marginal seas where spatial and temporal variability occur at smaller scales and SSS retrievals are more likely contaminated by the radio frequency interference and land. This study along with the Gierach et al. (2013) examination of salinity in the Gulf of Mexico demonstrates the usefulness of Aquarius data in this challenging near-coastal environment

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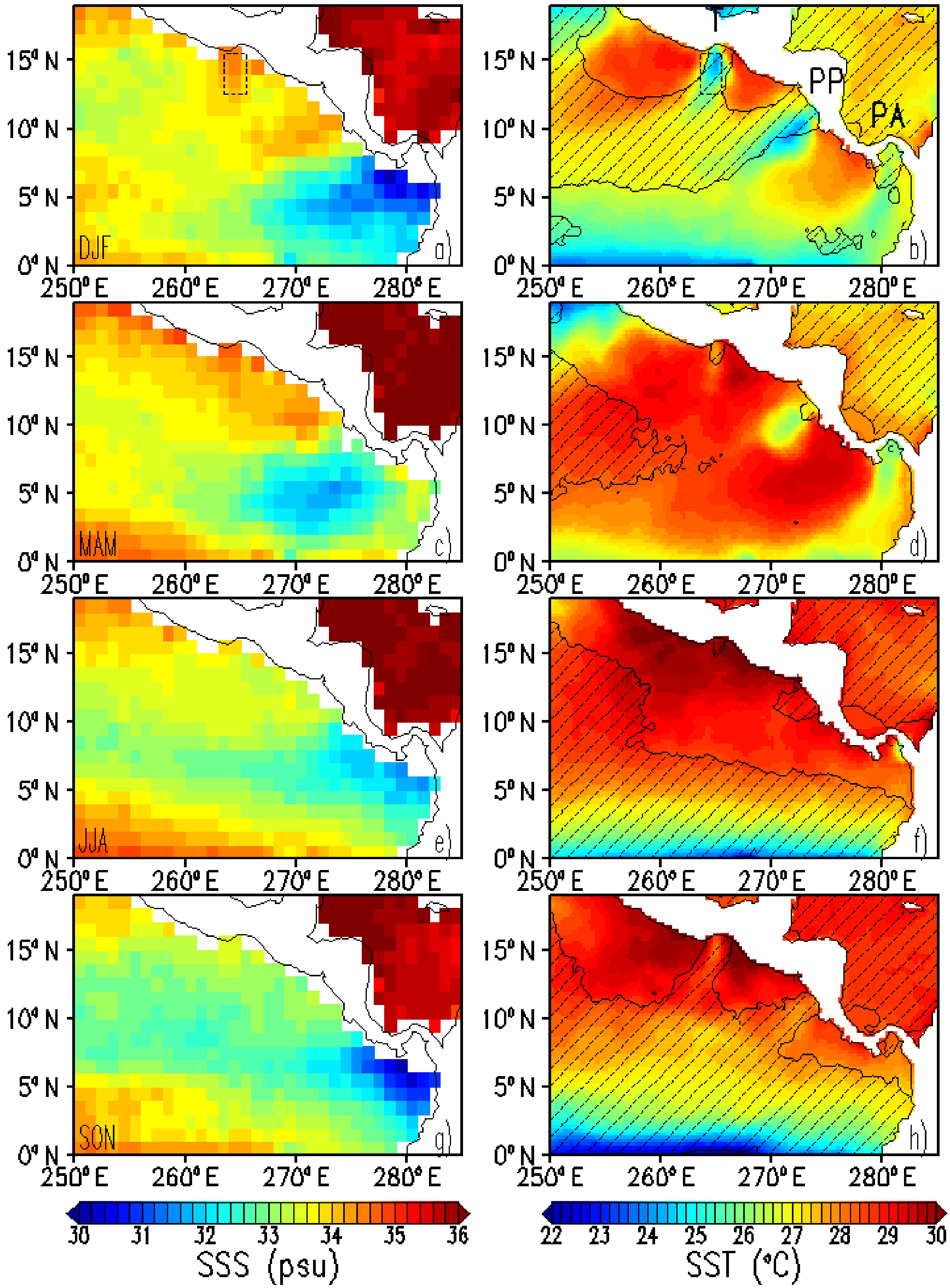

15° N
10° N
5° N
0° N
250° E
260° E
270° E
280° E
DJF
a)
b)
T
PP
PA
MAM
c)
d)
JJA
e)
f)
SON
g)
h)
30
31
32
33
34
35
36
SSS (psu)
22
23
24
25
26
27
28
29
30
SST (°C)

Figure 1. 3-month mean Aquarius SSS (left) and NOAA OI SST (right) based on the Decemeber 2011 –November 2012 data. The hatched areas in the SST maps show where the ASCAT wind speed was greater than 5 m s^{-1}. Gulf of Tahuantepec index region is shown in panels (a) and (b). Tehuantepec (T), Papagayo (PP), and Panama Bay (PA) regions are marked in panel (b). Common 3-month abbreviations, like ‘DJF’ for December−January−February etc., are used in (a).

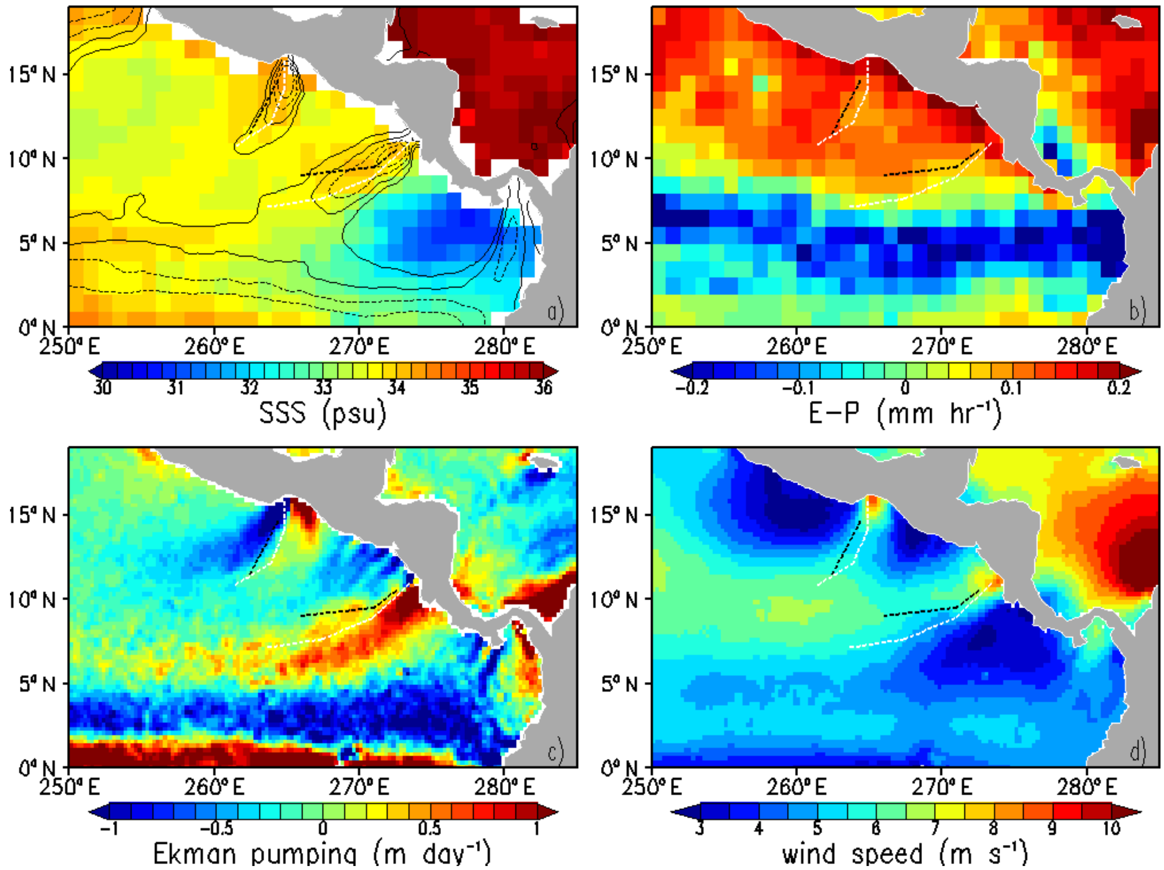

Figure 2. December-January-February (DJF) seasonal climatology based on the interval September 2011 to February 2014. (a) SSS (shaded), SST (contours, interval = 0.5°C, SST ≥ 26°C: solid; SST < 26°C: dashed). (b) Evaporation minus precipitation. (c) Ekman pumping computed using ASCAT winds (upward is positive). (d) ASCAT wind speed. Centroid lines of SSS and SST signatures are shown as black and white dashed lines, respectively.

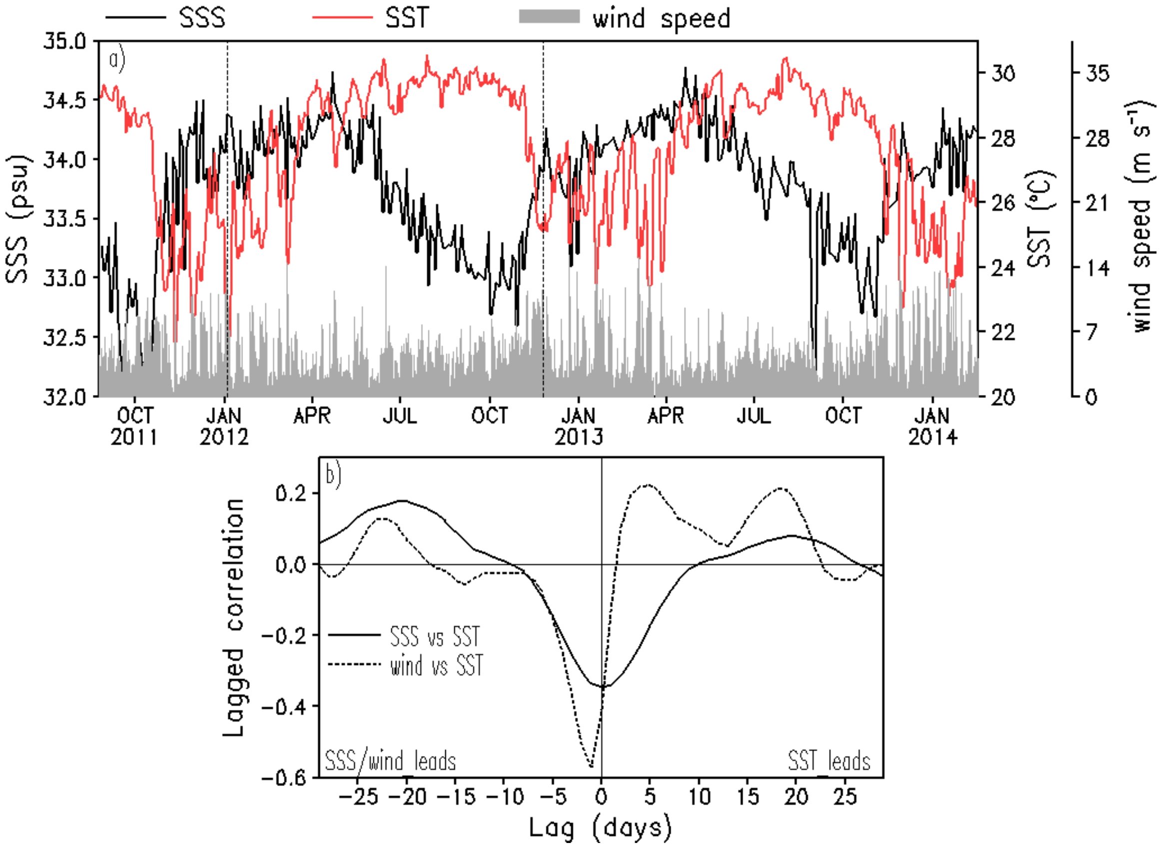

Figure 3. Variables averaged over the Gulf of Tahuantepec index region (see Fig. 1): (a) time series of SSS, SST, and wind speed; (b) lagged correlation coefficient for daily anomalies. Anomalies are calculated with respect to the seasonal cycle evaluated over the period for which Aquarius version 2.8.1 data are available (25 August 2011 through 17 February 2014). Two sample ‘high SSS’-‘cold SST” events (peaking on 01/04/2012 and 11/25/2012) are marked by vertical dashed lines in (a).