Intramonth oscillations of Atlantic ITCZ observed in SMAP satellite salinity

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Abstract :

The time variability of wind and rainfall in the Atlantic Intertropical Convergence Zone (ITCZ) has a wide oscillation spectrum that includes strong intra-month periodicities. These latter short-period oscillations span from individual convection lifecycle events of a few hours to longer pentad and multi-week convective cluster periods. This study reports on measured ITCZ rain variability at periods of a few weeks and its imprint on sea surface salinity (SSS) observed using satellite remote sensing. Despite small amplitude of variations of only 0.1–0.2 psu, these changes are shown to be detectable in radiometer SSS estimates collected by the Soil Moisture Active Passive (SMAP) satellite. They are shown to develop in the mid-Atlantic ITCZ latitude band and to follow its seasonal meridional progression. These rain-correlated sea surface signatures appear quasi-synchronously across a wide range of longitude. Both the ITCZ-related seasonal migration and high zonal propagation speeds distinguish these intra-month SSS oscillations from that of tropical instability waves (TIW), with TIWs having periods greater than 1 month and slower westward propagation. While detection of tropical Atlantic TIW salinity signatures using satellite data has received significant attention, it appears that atmospheric freshwater forcing impacts on the upper ocean at these shorter periods represents an additional process resolvable from space using SMAP. Correlation analyses of precipitation and winds indicate that low latitude convection clusters are accompanied by an upward Ekman pumping anomaly, which uplifts saltier water to surface layers diluted by enhanced precipitation. These vertical processes modify the salt balance and change the phase relationship between the oceanic SSS response and the atmospheric freshwater forcing.

1. Introduction

One of the major sources of intraseasonal variations of near surface salinity in the tropical oceans is associated with oceanic tropical instability waves (TIW). Mixed layer current perturbations produced by TIWs induce cusp-shaped features in the sea surface temperature (SST) (e.g., Weisberg and Weingartner 1988), sea surface salinity (SSS), (e.g., Grodsky et al. 2005), sea surface height (SSH) (e.g., Polito et al. 2001), and Chlorophyll-*a* (Chl-*a*) (e.g., McClain et al. 2002). In the Pacific, wave-induced meridional excursions of salty and cold equatorial water periodically produce negatively correlated SST and SSS signatures that propagate westward at characteristic TIW speed of less than about 1 m s^{-1} , periods of 20–40 days, and wavelengths of

1000–2000 km e.g., (Chelton et al. 2001). In the Atlantic, TIW signatures are generally similar to Pacific TIWs but have somewhat shorter wavelengths (< 1000 km), e.g., (Lee et al. 2014).

TIW-induced sea surface salinity structures have been detected in satellite salinity data obtained from orbiting L-band radiometers (Lee et al. 2012); (Yin et al. 2014). Differing from SST and SSH, TIW SSS signatures in the Eastern Pacific were found strongest at the equator. The satellite SSS imagery revealed that the dominant westward propagation speed of TIW at the equator is twice as fast as the TIW phase speed widely reported in the literature, which is mostly based on observations of SST and SSH away from the equator. These intraseasonal salinity perturbations are not simply TIW manifestations. They can also have an important effect on the magnitude of baroclinic energy transfer cascades in the tropical oceans due to significant meridional gradient of salinity (that between the saline equator and relatively fresh ocean of the Intertropical Convergence Zone, ITCZ) and the corresponding large magnitude of TIW-salinity perturbations, which contribution to water density perturbations is significant (Grotsky et al. 2005; Lee et al. 2014).

Atmospheric boundary layer interactions with TIW-induced SST gradients can result in remarkably coupled spatio-temporal variations of winds, wind curl, and wind divergence (Chelton et al. 2001). The coupling between SST gradients and winds confirms earlier observations indicating that surface winds respond to SST-induced changes in marine atmospheric boundary layer thermal stability (e.g., Beal et al. 1997). Moreover, TIW-modulation of the wind divergence may also induce organization in atmospheric convection and rainfall, with additional impacts on the original TIW-related surface salinity perturbations. While such equatorial TIW salinity signatures and eddy salinity signatures (Melnichenko et al. 2017); (Hasson et al. 2019) have received significant attention, surprisingly, there has been less examination of tropical ocean salinity change due to atmospheric freshwater forcing at frequencies higher than seasonal and apart from TIW influences.

TIW-induced wind perturbations represent one example of local air-sea interactions that contribute to the cluster organization of tropical convection. On much larger scales, the most notorious organization is associated with the Madden–Julian Oscillation (MJO), a 30- to 90-day variability in the tropical atmosphere that propagates eastward at approximately 4 to 8 m s^{-1} . MJO oscillations exhibit maximum amplitude over the Indian and western Pacific Oceans and

their impacts on the upper ocean have been detected in satellite remote sensing salinity (e.g., Shinoda et al. 2013; Guan et al. 2014). Although (Foltz and McPhaden 2004) reported wind oscillations in a similar frequency band (30-70day) over the Atlantic, the MJO impacts east of the dateline, including the Atlantic sector, are less prominent. In the tropical Atlantic, the intraseasonal 30–80 day eastward-propagating convection and rainfall clusters (similar to the MJO) have been observed by (Gu 2009). These rainfall anomalies appear first in the northwestern tropical Atlantic right off the coast of South America and gradually extend eastward to cover the entire basin. In the Atlantic ITCZ, a shorter scale, 15-20 day variability is also present, which (Tomaziello, Carvalho, and Gandu 2016) associate with mid-latitude Rossby wave trains in the cold Hemisphere. The above two significant spectral peaks reflect in rainfall and winds not only over the Atlantic but also in tropical West Africa as well e.g. (Maloney and Shaman 2008).

The global view provided by satellite imagery has helped to illustrate that tropical convection can be organized at a wide range of spatial and temporal scales, from mesoscale convective systems to planetary-scale Madden-Julian Oscillations (Kiladis et al. 2009), scales that are virtually impossible to observe without such imagery. In monsoon regions, precipitation can appear to be organized on monthly and shorter periods (Krishnamurti and Bhalme 1976). In the Atlantic ITCZ, spatially coherent bi-weekly oscillations in winds and rainfall associated with the west African monsoon have been observed by Grodsky and Carton, (2001). At shorter periods, the tropical convection is normally clustered by waves that move eastward, or westward, either along the equator or within the ITCZ (Kiladis et al. 2009). Such convectively-coupled equatorial waves introduce a band intra-month organization in the tropical convection and rainfall within bands that seasonally migrate with the ITCZ.

This paper uses multi-year satellite datasets over the tropical Atlantic to identify likely precipitation events associated with convective clusters that are organized in a few week-long oscillations and, in turn, their imprint on SSS as measured using data from the Soil Moisture Active Passive (SMAP) satellite mission. While L-band radiometer imaging has shown some capability to detect the impact of strong individual rain events on both horizontal and vertical gradients of near surface ocean salinity (Boutin, Chao, et al. 2016; Boutin, Martin, et al. 2016) and even infer rainfall from SSS data (Supply et al. 2018), continuous satellite monitoring of

such events is not feasible due to the polar-orbit satellite sampling issues (full coverage requires roughly 3 days with a repeat cycle of 8 days), which allows systematic detection only of integral impact of cumulated rainfall (Boutin et al. 2013). Here, we focus instead on the satellite detection of the possible time-integrated ocean impacts of organized convection on SSS considering the longer time scale of convective/rainfall clusters with periods of about 3 weeks.

Satellite salinity missions operate in the L-band (1.4 GHz) where water emissivity depends on salinity. The background Earth thermal radiation in this band is almost 7 orders of magnitude weaker than in the infrared band widely used for SST. Such weak L-band radiation makes SSS retrieval challenging. Nevertheless, satellite SSS is reasonably close (to within 0.2 psu) to quasi-synchronous in-situ data in the tropics (e.g., Lee, 2016). But such SSS accuracy is about 3% of its global ocean range (32 – 38 psu) in comparison to 0.1 °C accurate SST, which accuracy is about 0.3% of its range (0 – 30 °C). Although the time mean dilution by ITCZ rainfall reaches ~1 psu and is routinely detectable, the detection of smaller magnitude signals is not apriori achievable. This paper shows that besides well-known intraseasonal ocean SSS variations associated with TIW, there exist atmospheric-induced component of intraseasonal SSS associated with convection clustering. Regardless of its small amplitude of 0.1 – 0.2 psu, it is detectable by satellite SSS remote sensing.

Wind-induced intraseasonal ocean oscillations are known to exist in the equatorial wave guide (e.g., Grodsky, Carton, and McClain 2008), but are also present at higher latitudes. Part of the impetus for this study comes from (Krishnamurti and Bhalme 1976) and (Grodsky and Carton 2001) who identified the presence of approximately bi-weekly oscillations in both surface wind and rainfall in Indian and west African monsoon systems. Such oscillations are tied with the corresponding monsoon and are seasonally present along with the monsoon. But, as demonstrated further, similar intramonth transients are present in the tropical atmosphere (precipitation, winds) and ocean response (SSS) all year long and occupy vast areas of the tropical open-ocean beyond coastal regions affected by monsoons.

To describe and analyze these intramonth oscillations, the presentation is organized in the following way. First, we demonstrate the presence of accorded intramonth variations in precipitation and satellite-observed SSS in the central north tropical Atlantic, which meridional location follows the ITCZ. Next, we perform correlation analyses between intramonth variations

of SSS, precipitation, and surface wind divergence that show an almost out-of-phase relationship between SSS and precipitation variations. This out-of-phase relationship suggests that other factors besides the pure surface forcing are involved, among which the ocean Ekman pumping and the fast relaxation of rain-induced salinity anomalies are found contributing to the phase characteristics of SSS response. Finally, we discuss precipitation and wind satellite data to illustrate how atmospheric convective clusters originate and propagate along the Atlantic ITCZ.

2. Data and methods

Satellite salinity: This study relies on satellite SSS from the Soil Moisture Active Passive (SMAP) mission. Global Level 3 SMAP SSS is available daily as an 8-day running mean on a 0.25° grid (Version 3) produced by the Remote Sensing Systems, www.remss.com/missions/smap, (Meissner, Wentz, and Vine 2018). The surface footprint of each measurement is 39×47 km so the effective resolution is close to 40 km. On monthly and ~ 100 km scales, satellite SSS values match with in-situ measurements in the warm tropics to within ~ 0.2 psu, (Lee 2016). Due to several limitations (e.g., remaining residual error due to extra-terrestrial radiation, ionospheric effects, land-sea transitions, and sea surface roughness impacts on the radiometer brightness temperatures), satellite SSS often exhibit systematic seasonally-dependent biases versus ground truth (Meissner et al. 2016). As shown by several studies (e.g., Boutin, Martin, et al. 2016), the SSS anomaly (SSSA) determined from the background longer-term satellite SSS data, (i.e., the difference computed relative to a slow varying SSS signal, such as a monthly satellite-based SSS climatology) is significantly less affected by these seasonal biases. The filtering procedure effectively removes such retrieval artifacts along with any actual slow varying SSS component. For the entire SMAP observation period (April 2015 – onward), the intra-month SSS variation at each grid point was estimated as the difference of observed SSS from its monthly moving mean.

Other satellite data: Satellite SST data come from the Canadian Meteorological Centre. Here we use the level 4 SST produced by combining infrared, microwave, and in-situ daily analyses resampled at 0.25° spatial resolution. These SST data are used for the SMAP SSS processing and included in SMAP data files. The using of microwave-derived SST is important in this cloudy ITCZ region. To characterize the surface wind, we use the gridded daily 10m neutral winds from the ASCAT scatterometer onboard the European Meteorological Satellite

Organization MetOp which are described in (Bentamy and Fillon 2012) and available at <ftp.ifremer.fr/ifremer/cersat/products/gridded/MWF/L3/ASCAT>).

The precipitation data set is the Tropical Rainfall Measuring Mission (TRMM) Level 3 3B42v7 (Huffman et al. 2007). This is constructed by merging active and passive TRMM microwave along with microwave-calibrated infrared measurements (<http://dx.doi.org/10.5067/TRMM/TMPA/3H/7>). The TRMM orbit is specifically designed to achieve rapid repeat sampling at low latitudes. The TRMM data set has $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution and is available from 1998 - 2018.

3. Results

3.1 General characteristics of intramonth salinity variations

In order to explore such transient rainfall-induced SSS features using SMAP SSSA data, we choose to focus on an area where local precipitation is the primary term in the surface salinity budget. The large scale SSS distribution in the tropical Atlantic reflects the meridional pattern of the net freshwater flux with higher SSS in the evaporative subtropics and fresher SSS in the rainy tropical belt (Fig. 1a). Within the fresh tropical belt, the meridional position of SSS minimum roughly coincides with the ITCZ and there is also some significant west-to-east asymmetry. While the time mean ITCZ rainfall and corresponding wind convergence are apparently lower in the west (Figs. 1b, c), the SSS is fresher there in response to Amazon-Orinoco freshwater river discharge. The band of fresh SSS associated with these river discharge and advection extends from the shelf out into the central tropical Atlantic, reflecting seasonal eastward transport in the North Equatorial Counter Current (NECC). However, in the central tropical Atlantic (around 30°W), there exists a local SSS maximum in otherwise fresh zonal SSS band that separates relatively fresher water to the east and to the west of it. This implies different freshwater forcing mechanisms for the eastern and western edges of the basin. While the western fresh pole is primarily influenced by river discharge (e.g., Foltz et al. 2004; Coles et al. 2013), the eastern pole is more strongly driven by the local net freshwater forcing. In the east, this latter assumption is corroborated by mostly eastward local zonal currents associated with the NECC, which deflect the entrance of Gulf of Guinea fresh waters. Moreover, twin model experiments with the same atmospheric forcing but differing river discharges show that the entire eastern pole of fresh SSS is present even in simulations completely lacking any river discharge, including the Congo River

(Dr. Ricardo Matano of OSU, personal communication, see also (Vizy and Cook 2010) for changes in atmospheric patterns). In the meridional plane, there exists also a northward displacement of the low salinity belt relative to the latitudinal position of ITCZ rainfall. This displacement is attributed to the time mean northwestward Ekman transport produced by the northeasterly trade winds (e.g., Grodsky, Carton, and Bryan 2014; Yu 2015).

Spatial structure of the time mean magnitude of intramonth SSS variability amplifies near the western and eastern boundaries due to river discharge impacts (Fig. 1d). More certainly, it is organized into two zonally elongated bands. The southern band extends along and just north of the equator and reflects the presence of intramonth, approximately 17-day TIWs (Grodsky et al. 2005; Lyman, Johnson, and Kessler 2007; Lee et al. 2012). The second band of increased SSS variability is located to the north of the equatorial band and is connected to the area of strong SSS variability in the western boundary (Fig. 1d), notably via the retroflexion of the North Brazil Current. But in the central Atlantic, the SSS variability in the northern band is dominantly driven by the corresponding atmospheric forcing (Figs. 1e, f). This was discussed in previous studies (e.g., Yu 2011; Sena Martins, Serra, and Stammer 2015; Tzortzi et al. 2016). Intramonth SSS variability in the central Atlantic box and its causes will be further explored here by correlation analyses of oceanic and atmospheric fields.

The atmospheric-driven nature of intramonth SSS oscillations can be inferred via their meridional behavior seen in Fig. 2a. Averaged over the zonal extent of the central Atlantic box (30°W - 15°W , see Fig. 1a for the box location), the area of enhanced intramonth SSS variability in Fig. 2a closely follows the meridional ITCZ and wind divergence anomaly ($divUA$) displacements (compare Figs. 2a, 2b, and 2d). These intramonth oscillations occur quasi-synchronously with latitude (to within the temporal resolution of Fig. 2a) and coherently with rainfall and surface wind divergence oscillations (Fig. 2b, 2d). Using spatial averaging over the central north tropical Atlantic box (Fig. 1a), which is 15° -wide in longitude, allows filtering out the majority of Atlantic TIW signatures.

In contrast with SSSA, Fig 2c suggests that the SST change does not follow intramonth ITCZ variations. The latter variations do display an equatorial band of SST variability associated with high frequency TIWs. Some of these TIW-induced variations are also detectable in intramonth SSS, especially in summer (Fig. 2a). SST oscillations are also amplified in the northeasterly

trade wind regime north of the ITCZ. The latter observation may suggest that organized ITCZ clustered rainfall leads to wind perturbations that extend well away from these rainfall clusters, which, in turn, modify SST through their impact on latent heat fluxes. These wide spread wind anomalies will be demonstrated in composite patterns analyzed below.

A longitude-time view of intramonth SSS (Fig. 3a) confirms that salinity variability is observed quasi-instantaneously over 30°W-15°W longitude band and is associated with fast-moving variations in atmospheric forcing. Along with the atmospherically-induced signal, a westward propagating TIW-induced signal is also present and distinguishable in all variables shown in Fig. 3, in particular, during the equatorial low rainfall period of the summer of 2015. This remaining TIW-related signal is still distinguishable after 15° zonal averaging even though the characteristic wavelength of Atlantic TIW (< 1000 km, e.g., Grodsky et al. 2005) is normally smaller than that for Pacific TIW that is evident by sample SST fields in Fig. 4. Spatial averaging over the central north tropical Atlantic box allows for significant (but not complete) filtering out of TIW-related signals and thus emphasizing of longer scale variability associated with atmospheric transients.

3.2 Correlation between intramonth SSS and precipitation

Temporal SSS variations in the central tropical Atlantic box show that they are organized in at least two frequency bands (Fig. 5). Low frequency (>30 days) box-averaged SSS (see Fig. 1a for the box location) essentially depicts the seasonal cycle with distinct semi-annual variations (Fig. 5a) on top of the significant interannual variability. Fig 5b suggests these semi-annual SSS variations can be largely explained by the semi-annual seasonal cycle of surface freshwater forcing that peaks twice a year with north-south ITCZ migration across the box (e.g., Foltz et al. 2004). Some remaining disconnect between magnitudes of the low frequency SSS and precipitation variations, especially noticeable during a fresh period in autumn 2017, reflects the presence of notorious interannual variability and suggests that other factors including the background vertical stratification (mixed layer depth) and the ocean currents may also impact SSS variations.

Visual inspection of intramonth variations indicates an apparent negative correlation between precipitation enhancements and SSS decreases that are clearly seen in 8-day averaged raw data in Figs. 5a, 5b. Note that precipitation in Fig. 5b is also 8-day averaged to match the 8-day SSS averaging of satellite SMAP gridded salinity. The period of these precipitation and SSS oscillations is approximately 3 weeks (spectra are discussed later). The negative correlation between SSS and precipitation variations suggests the dominant role that surface freshwater flux plays in driving central tropical Atlantic SSS at a wide range of seasonal and intraseasonal periods. For intramonth periods, this negative correlation is further detailed in Fig. 5c, showing that the majority of positive/negative SSS deviations coincide with negative/positive precipitation change. Such a phase relationship is not fully expected because the maximum dilution is expected by the end of the rainfall event, which implies a $\pi/4$ phase delay between SSS freshening and rainfall.

As expected from Fig. 2a, the area of negatively correlated intramonth SSS and precipitation migrates meridionally following seasonal displacements of the ITCZ (Fig. 6). It shifts northward in the boreal summer and autumn and then back towards the equator in the winter and spring. The magnitude of the correlation is statistically significant (Fig. 6) but normally doesn't exceed 0.5. This weak level may be attributed to the SSS noise because the relatively weak magnitude of intramonth SSS (< 0.2 psu) is near the edge of satellite retrieval accuracy (e.g., Lee 2016). Another possible explanation may be the satellite's temporal SSS data coverage, which employs 8-day averaging for gridded fields. Such averaging of independent in-swath satellite observations may alias on longer periods and thus limit the magnitude of intramonth correlations.

Lagged correlation between timeseries of parameters area-averaged over the central tropical Atlantic box indicates that zero-lag correlation shown in Fig. 6 yields nearly the highest magnitude (Fig. 7b). Only a slight delay (a few days) between peaks of near-surface wind divergence and precipitation (Fig. 7a) is observed, and this is similar for precipitation and SSS (Fig. 7b).

3.3 Ekman pumping impact on intramonth SSS

The characteristic amplitude of intramonth SSS is about $\delta S = 0.1$ psu (Fig. 5c). In terms of the mixed layer salt budget, the magnitude of δS is roughly consistent with the magnitude of

organized rainfall oscillations in the ITCZ, $\delta P = 5 \text{ mm day}^{-1}$ (Figs. 2b, 5c). This level would give an SSS variation of, $\delta S = \frac{S\delta P}{D} \delta t = 0.05 \text{ psu}$, if acted on for $\delta t = 14$ days and with a typical local ocean mixed layer depth of $D = 50 \text{ m}$. Although it is only a half of the observed $\delta S = 0.1 \text{ psu}$, it is known that intense ITCZ rainfall produces shallow barrier layers, see e.g., Fig.2 in (Liu, Grodsky, and Carton 2009). Hence, surface freshwater flux anomalies may act on a layer shallower than $D = 50 \text{ m}$ and thus induce stronger SSS oscillations. Although the magnitude of δS is roughly consistent with the surface forcing scenario, the observed anti-correlation between SSS and precipitation variations (rather than rainfall leading SSSA integrated effects) suggests that other factors besides the pure surface forcing are involved (Fig. 5c).

While the approximately out-of-phase relationship (negative correlation) between $\text{div}U$ and precipitation is fully expected for tropical convection events, the almost out-of-phase relationship between precipitation and ocean SSS response is surprising. If the salinity rate of change was solely balanced by the precipitation ($\partial S / \partial t \sim \delta P$), this would imply a so-called quadrature phase relationship between precipitation and salinity, (rainfall variation, δP , leads SSSA integrated effect, δS , by a quarter of period). The observed deviation from this phase relationship suggests that other factors must contribute to intramonth salinity change. In fact, it is assumed that organized precipitation (convection) clusters are accompanied by anomalous wind curl, which alters the Ekman pumping, $W_{\text{EK}} = -1/\rho_w \text{ curl}(\tau_x/f, \tau_y/f)$. Here, (τ_x, τ_y) are the zonal and meridional surface wind stress components, ρ_w is the water density, and f is the Coriolis parameter. Lagged correlation in Fig. 7c illustrates the presence of in-phase variations between intramonth precipitation and W_{EK} (upward W_{EK} is positive). Hence, for low latitude convective clusters, the upward Ekman pumping brings saltier water to the surface that mixes with waters diluted by enhanced precipitation.

Correlation between Ekman pumping and convective clusters may be caused by organized cyclonic winds associated with the clusters, or by alternative factors. Fig. 8 explores likely alternatives showing several ocean and atmosphere parameters averaged over typical wet and dry events in the central Atlantic. These events are defined as periods when the magnitude of box-averaged intramonth precipitation anomaly exceeds its standard deviation (2.5 mm day^{-1}). Note, that this threshold is lower than rainfall standard deviation in Fig. 1e, where grid point rather

than box averaged values are shown. Due to the rainfall dilution, it is expected that wet and dry composites correspond to fresh and salty anomalies, respectively (Figs. 8a, b). The characteristic magnitude of intramonth SSS anomalies is about 0.1 psu in line with Fig. 5c. Wet and dry events are accompanied by convergent and divergent wind patterns, respectively, with the sign agreeing with corresponding changes in atmospheric convection and related precipitation (Figs. 8c, d). Wind velocity and curl anomalies associated with changes in intramonth precipitation are roughly symmetrical versus the center latitude of the box, but the pattern of W_{EK} is not (Figs. 8e, f). This asymmetry is related to the latitudinal dependence of the Coriolis parameter, which amplifies the magnitude of W_{EK} approaching the equator. This latitudinal asymmetry is characteristic of Ekman pumping at low latitudes. As a result, during wet/dry events, the box averaged W_{EK} is upward/downward, respectively. This vertical exchange then partially balances anomalous net freshwater forcing, impacting the salt budget and altering the phase relationship between the oceanic SSS response and rainfall.

4. Discussions

To provide further insight into the correlations discussed above, an expanded example of short-term wind and precipitation shifts at intramonth event scale is next examined for the November–December 2017 timeframe singled out in Fig. 5c. Fig. 9 provides a 2-day average spatio-temporal view for one positive/dry (Fig. 9 b-h) and a following negative/wet (Fig. 9 j-p) SSSA period. The results indicate a high correspondence between event-mean precipitation (Figs. 9a, 9i) and SSS (see Fig. 5c). There exists an apparent difference in mean precipitation values temporally averaged over a salty event (27 November – 10 December of 2017) and a fresh event (10 – 23 December of 2017). But, it should be noted that zonally continuous band of ITCZ rainfall is represented only in time averages while 2-day snapshots are dominated by mesoscale convective systems (Fig. 9). These systems are thus seen in both precipitation and wind patterns but are unresolved in 8-day SSS averages. During the salty event (Fig. 9, b-h), the mid-Atlantic ITCZ was relatively quiet, especially during the first week (27 November – 2 December). In the next week (3-10 December), the ITCZ intensified starting with a cluster of enhanced rainfall over the western tropical Atlantic area adjacent to South America (3-4 December). Interestingly, this area of enhanced rainfall is associated with atmospheric convection over the ocean and doesn't extend over the land. Next, this enhanced rainfall cluster propagated eastward along the

time mean ITCZ, at a speed of 6 to 7 m s⁻¹, finally reaching the Gulf of Guinea in about one week.

The above episode of eastward propagation of convection during 3-10 December is the only dry-period clear episode in Fig. 9. During the fresh event (10-23 December, Fig. 9, j-p), there is no apparent eastward propagation of convection clusters. The main differences between precipitation fields for wet and dry events is in the generally higher magnitude of rainfall for wet events and the larger number of days of depressed rainfall for dry events (more quiet rainfall days during dry periods).

Fig. 10 recalls this small sub-segment of the region of interest box-averaged intramonth SSS, wind and rainfall data. Comparison of Fig. 10 and with Fig. 9 variations in daily precipitation suggests that much of 8-day averaged precipitation/SSSA variation (Fig. 5c) is, in fact, an integration of high frequency (1-4 day) mesoscale convective events. As mentioned before, immediate surface ocean impacts of such precipitation spikes are unresolved in 8-day SSS averages, but the integrated oceanic effects in this mid-Atlantic region are apparent.

As noted before, many factors, including wind stirring, Ekman pumping, and others, contribute to fresh rain lenses decay. For each individual rainfall event, the SSS keeps freshening until the cessation of rainfall, which introduces the phase delay with a characteristic time-scale corresponding to individual rain event duration. Because SMAP SSS resolves only longer time scales (> 8 days), it can detect the dilution effect of convective clusters only. Each such cluster includes multiple individual rain events. In terms of cumulative freshwater deposit, these clusters are equivalent to the combined effect of individual rainfall events. But for fast decaying anomalies, the physical lag between SSS response and cumulative rainfall is not defined by the time scale of convective clusters. It remains the same as that for individual rainfall events and is defined by the short time-scale of individual rain events. This suggests that the integrated effect of intermittent rainfall leads to different phase delays between rainfall and salinity response depending on the characteristic decay time of fresh salinity anomalies. As schematically illustrated in Fig. 11, a phase delay comparable with rainfall cluster time scales would happen only if the signature of the precipitation (associated low SSS anomaly) remains for a significant time at the ocean surface (slow decay case), and thus slowly accumulates precipitation from the entire rainfall cluster. In contrast, if fresh anomalies decay considerably

between individual rainfall events, the corresponding phase delay is smaller and defined by the characteristic duration of individual rainfall events (fast decay case). The observed negative correlation between precipitation and SSS anomalies (Fig. 7b) suggests the second, fast decay case. This is corroborated by the observed near surface salinity anomaly decay time of less than 1 day (Drushka et al. 2016).

In late fall through spring, the ITCZ shifts southward towards the equator, and a wide spectrum of atmospheric oscillations is observed over the central Atlantic box (Fig. 12a). Like in Fig. 10, the spectral analysis in Fig. 12 depicts few-day oscillations, approximately 3-week oscillations, and also longer (about 50- to 60-day) oscillations. The latter band of oscillations was described by e.g., (Gu 2009), but it was removed from our main analysis in order to focus on intramonth frequencies. Both 3-week and ~50-day oscillations are reflected in SSS and manifest in the corresponding peaks of the SSS spectrum. When the ITCZ shifts northward, the spectrum of precipitation becomes smoother while 3-week and ~50-day peaks hold (Fig. 12b). Despite even stronger precipitation oscillations in summer months, they are not apparently reflected in the box-averaged SSS (Fig. 12b). During these months, the band of SSS oscillations shifts northward following rainfall and weak winds in the ITCZ (Fig. 2a). During this period, the southeasterly trade winds amplify over the fixed central north tropical Atlantic box area. Hence, the decreased level of SSS oscillations during the period shown in Fig. 12b simply reflects that these amplified winds stir rainfall fresh water vertically and thus decrease the magnitude of SSS response.

5. Summary

In summary, it is known that wind and rainfall in the Atlantic ITCZ experience a wide spectrum of oscillations, including intra-month periodicities. However, the impact of such episodic rainfall on the surface ocean freshwater in the tropics at similarly small time and space scales is largely unknown. Some of these periodicities are related to the presence of approximately bi-weekly oscillations of wind and rainfall in the West African monsoon (Grodsky and Carton 2001). But, such monsoonal oscillations are tied with the corresponding monsoon and are seasonally present along with the monsoon. Here it is demonstrated that accorded intramonth transients are present in the tropical atmosphere and near-surface ocean salinity all year long, occupy vast areas of internal ocean affected by ITCZ rainfall, and extend beyond coastal regions affected by monsoons. Although such rain-induced SSS oscillations are expected to occur across the entire

tropical Atlantic, their examination is limited to the central north tropical Atlantic box where the surface net freshwater forcing is the leading driver of SSS and where river discharge effects are less important.

This study reports on the presence of approximately 3 week ocean-atmosphere oscillations which result from organized groups of mesoscale tropical convection clusters and their apparent imprints on satellite-derived sea surface salinity (SSS). These SSS oscillations have a relatively small amplitude of up to 0.2 psu but are clearly detectable in Soil Moisture Active Passive (SMAP) SSS retrievals at resolutions as short as 8-days and spatial scales of 50-100 km. These SSS oscillations are produced by the corresponding precipitation oscillations, which are most intense in the ITCZ. As a result, the SSS oscillations develop in the ITCZ latitude band and follow its seasonal meridional displacements. They also develop quasi-synchronously in a wide range of longitudes. These seasonal displacements and high zonal speeds distinguish rainfall-forced intramonth salinity oscillations from signatures of tropical instability waves (TIW) which normally have periods exceeding 1 month and distinct slow westward propagation.

Lagged correlation of intramonth SSS and precipitation timeseries box-averaged over the central Atlantic box (30°W-15°W, 2°N-6°N) indicates only a slight delay ($< 2 - 3$ days) between peaks of high precipitation and SSS decrease. The almost out-of-phase relationship between ~ 3 -week precipitation events and ocean SSS response is unexpected. If the salinity rate of change was balanced by the precipitation only, it would imply a quadrature ($\pi/4$) phase delay between precipitation and salinity variations, with negative salinity anomaly peaking at the end of a rainy period. The deviation from this phase relationship implies that other factors, including salt anomaly dissipation, also contribute at intramonth periods. Besides commonly considered vertical turbulent dissipation, we also show that low latitude organized precipitation (convection) clusters are accompanied by an upward Ekman pumping anomaly that entrains saltier water to surface layers diluted by enhanced precipitation. All these vertical processes contribute to fast (~ 1 day) rainfall lenses decay and modify the salt balance and change the phase relationship between the oceanic SSS response and the atmospheric freshwater forcing. This leads to almost out-of-phase relationship suggesting that maximum dilution coincides with rainfall peaks even on time scales of few-week rainfall clusters.

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588 **Figures**

Figure 1. Time mean (a) sea surface salinity (SSS), (b) precipitation (PREC), and (c) near-surface wind divergence (divU). Standard deviation of intramonth (d) SSS anomaly, (e) PREC anomaly, and (f) divU anomaly. Intramonth variation is defined as a deviation from the monthly running mean. Central tropical Atlantic box is shown in (a, d).

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Figure 2. Time-latitude diagram of zonally averaged (a) intramonth sea surface salinity anomaly (SSSA), (b) total precipitation (PREC), intramonth sea surface temperature anomaly (SSTA), and intramonth surface wind divergence anomaly (divUA). Zonal averaging is done over longitude extent of the box in Fig. 1a (30°W-15°W).

Figure 3. Time-longitude diagram of meridionally averaged (a) intramonth sea surface salinity anomaly (SSSA), (b) total precipitation (PREC), intramonth sea surface temperature anomaly (SSTA), and (d) intramonth surface wind divergence anomaly (divUA). Meridional averaging is done over latitude extent of the box in Fig. 1a (2°N-6°N).

Figure 4. Sample daily SST maps illustrating TIW length scale with respect to the averaging box size in (a) summer (b) fall-winter.

Figure 5. Box averaged time series of (shaded) monthly running mean and (black line) 8-day mean (a) sea surface salinity (SSS), (b) precipitation (PREC), (c) intramonth anomalies of sea surface salinity (SSSA), precipitation (PRECA), and wind divergence (divUA) zoomed over the time period marked by gray rectangles in (a, b). See Fig. 1a for the box location. Vertical dashed lines in (c) delineate a sequence of SSS anomalies detailed in Figs. 9, 10.

Figure 6. Temporal correlation of intramonth variations of sea surface salinity and precipitation for each season. Black contours show 3 mm day⁻¹ precipitation to illustrate the ITCZ position. Correlation magnitude > 0.14 is statistically significant at the 99% level.

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Figure 7. Lagged correlation of box-averaged intramonth anomalies of (a) near surface wind divergence and precipitation ($divU$, $PREC$), (b) precipitation and sea surface salinity ($PREC$, SSS), and (c) precipitation and vertical Ekman velocity ($PREC$, W_{EK}). $W_{EK} > 0$ is upward. See Fig. 1a for the box location. All correlations are based on 8-day running means. The 99% confidence intervals of zero correlation are shown by solid gray.

Figure 8. Composite maps of anomalies corresponding to (a, c, e) wet and (b, d, f) dry events in the central Atlantic box (black rectangle) for (a, b) SSS, (c, d) divU , and (e, f) Ekman pumping velocity (W_{EK}). Events are defined as periods when the magnitude of box averaged intramonth rainfall exceeds its standard deviation. Arrows show corresponding intramonth wind anomaly composites. Central latitude of the box is shown by magenta in (e, f).

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Figure 9. Time evolution of 2-day mean (shaded) precipitation and (arrows) winds during (b-h) 27 November-10 December dry event and (j-p) 10 December-23 December wet event (see Fig. 5c), (a) and (i) show event-mean fields. Central tropical Atlantic box (the same as in Fig. 1a) is also shown.

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Figure 10. Time series of box averaged (shaded) sea surface salinity (SSS) and precipitation (PREC) during the 3 events delineated in Fig. 5c. Baseline for SSS is its running monthly mean. Daily mean PREC is shown in distinction from Fig. 5c, where 8-day mean PREC is shown. See Fig. 1a for the box location.

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Figure 11. Schematic diagram of salinity response to intermittent rain events (blue) for slow (shaded) and fast (red line) fresh salinity anomaly decay time.

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Figure 12. Frequency spectra of anomalous SSS (S_{SSS}) and precipitation (S_{PREC}) spatially averaged over the fixed central tropical Atlantic box (see Fig.1a for the box location) when the ITCZ seasonally shifts south (a) and north (b). Shading represents the 67% spectral confidence intervals. Anomalies are calculated versus the seasonal cycle. Intramonth filtering is not applied. Spectra are shown in linear scale and normalized by the corresponding signal variance.

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