Impacts of El Niño on the South China Sea surface salinity as seen from satellites

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Abstract
The impacts of El Niño on sea surface salinity (SSS) in the South China Sea (SCS) are investigated using satellite observations, in-situ data, and reanalysis products. Here, we show that positive SSS anomalies cover most of the SCS during the mature phase of El Niño. The physical processes controlling these positive SSS anomalies are different from region to region, and the differences are especially obvious between the northern and southern SCS. In the northern SCS, the positive SSS anomalies are primarily caused by horizontal advection in response to an enhanced Kuroshio intrusion through the Luzon Strait, while changes in surface freshwater fluxes act to reduce SSS. In the southern SCS, the positive SSS anomalies are largely due to reduced surface freshwater fluxes, with ocean dynamics playing a secondary role. An anomalous anticyclone associated with El Niño is mainly responsible for the reduction of surface freshwater fluxes in the southern SCS.

1. Introduction
The South China Sea (SCS), as the largest marginal sea of the western Pacific, plays a significant role in the world’s climate system (Xie et al. 2003, Gordon et al. 2012, Sprintall et al. 2012). Recently, studies of the SCS have focused on ocean salinity, because its variability has notable impacts on regional ocean circulation and air-sea interactions (Yu et al. 2008, Zeng et al. 2018, Wang et al. 2021). For example, enhanced surface stratification induced by surface freshwater flux may limit wind stirring to a shallow mixed layer, resulting in the formation of a barrier layer that directly contributes to regional temperature anomalies (Pan et al. 2006, Zeng et al. 2009). Variability in ocean salinity may also play a role in regulating deep circulation (Wang et al. 2011), and heat and freshwater distribution in the SCS (Qu et al. 2006). Therefore, it is of climate importance to clarify how the SCS salinity varies over space and time and what mechanisms are responsible for this variability.

Variability in ocean salinity is governed by surface freshwater forcing (evaporation minus precipitation-EMP) and ocean processes (Feng et al. 2000, Ren and Riser 2009, Du et al. 2015, 2019, Qu et al. 2019). As an important part of the Indo-Pacific warm pool, the SCS is strongly influenced by major climate modes, such as El Niño/Southern Oscillation (ENSO) and
Indian Ocean Dipole (IOD) (Wang et al 2006, Xiao et al 2020). Corresponding to these climate modes, significant changes in EMP, wind, and ocean current have been observed, further influencing the sea surface salinity (SSS) in the SCS (Zeng et al 2016, Wang et al 2021).

Several earlier studies have been devoted to investigating the SSS variability in the SCS using observations and numerical models (Zeng et al 2016, Yi et al 2020). However, compared to other oceanic variables, such as sea surface temperature (SST) (Tan et al 2016) and sea surface height (Wang et al 2006), SSS variability and its relationship with ENSO in the SCS remain poorly understood due to data limitations. Recent advances in satellite observations, especially those by the Soil Moisture and Ocean Salinity, Aquarius, and Soil Moisture Active Passive (SMAP) missions (Lagerloef et al 2012, Mecklenburg et al 2012, Fore et al 2016), has provided an unprecedented opportunity to study SSS variability in the SCS. Using a satellite-based SSS dataset, Yi et al (2020) recently showed that the 2015/2016 El Niño event has an influence on the SSS in the SCS. However, the mechanisms responsible for this El Niño influence have not been carefully examined, and merit a more detailed investigation. The present study aims to address this issue by providing a quantitative assessment of the mixed layer salinity (MLS) budget in the SCS.

2. Data and methods

2.1. Data

This study uses a monthly SSS dataset produced by Melnichenko et al (2019), which merges observations from two NASA satellite missions (Aquarius and SMAP) with a horizontal resolution of 0.25° × 0.25° and a time interval of 4 d. Also used are the hydrographic data from World Ocean Atlas 2018 (WOA18; Zweng et al 2019), the evaporation data from Objectively Analyzed air-sea Fluxes project (OAFlux; Yu and Weller 2007), the precipitation data from the GPCP (Adler et al 2003), the near-surface current data from Ocean Surface Current Analysis Real-time project (OSCAR; Bonjean and Lagerloef 2002), and the ECMWF Ocean Reanalysis System version 5 (ORAS5) products (Zuo et al 2019). The monthly mixed layer depth (MLD) is estimated from a gridded Argo dataset produced by Roemmich and Gilson (2009). The Niño 3.4 and Dipole Mode Index (DMI) indexes obtained from the NOAA (National Oceanic and Atmospheric Administration) Physical Sciences Laboratory will also be used.

2.2. Methods

To identify processes responsible for the SSS variability associated with ENSO, we analyze MLS budget using existing observations. Following several earlier studies (Qu et al 2011, Gao et al 2014), the equation is as follows:

\[
\frac{\partial S}{\partial t} = \frac{S(E-P)}{h} - \left( \frac{\partial S}{\partial x} u + \frac{\partial S}{\partial y} v \right) - w_e \frac{S-S_{-h}}{h} + \text{RES}. \tag{1}
\]

Here S is the satellite-based SSS, a proxy of MLS. \(u\) and \(v\) are OSCAR velocity in the zonal and meridional direction, respectively. \(h\) is the MLD based on the 0.125 kg m\(^{-3}\) density criterion (Huang and Qiu 1998). \(S_{-h}\) is the salinity at the base of the mixed layer. \(E\) and \(P\) are evaporation and precipitation, respectively, \(w_e\) is the vertical entrainment velocity at the base of mixed layer, and is computed as \(w_e = H(\partial h/\partial t + \nabla h V)\), where \(H(\chi) = \begin{cases} 1, & \chi \geq 0 \\ 0, & \chi < 0 \end{cases}\), and \(V\) is horizontal velocity. RES represents the residual term of budget.

Each variable of equation (1) is divided into two parts: the climatological seasonal cycle and an interannual perturbation. For example, \(S = S + S'\), where overbar represents the climatological mean and prime represents the anomaly. By neglecting higher-order nonlinear terms, equation (1) can be rewritten as:

\[
\frac{\partial S'}{\partial t} = \frac{S(E-P)'}{h} - \left( \frac{\partial S'}{\partial x} u' + \frac{\partial S'}{\partial y} v' \right) - w_e \frac{S-S_{-h}}{h}. \tag{2}
\]

In this study, anomalies of each variable are obtained by subtracting the climatological seasonal cycle from its monthly values, which are calculated based on the full data record period. Both a linear trend removal and 13 month moving average are applied to time series of each variable before analyses. Other methods such as correlation analysis, and empirical orthogonal function (EOF) analysis are also used.

3. Results

3.1. Climatological mean SSS and validation

First, we validate the satellite-derived SSS product using WOA18. The spatial pattern of long-term mean SSS from satellites agrees well with that from in-situ observations in many details, such as the relatively high salinity observed in the northern SCS and relatively low salinity in the southern SCS (figure 1). The SSS distribution is generally oriented in the meridional direction, with its value gradually decreasing southward. A high salinity tongue (>33.7 psu) is seen to extend westward from Luzon Strait to about 110°E, which is associated with the intrusion of the Kuroshio water through Luzon Strait (Hu et al 2000, Qu et al 2000, Xue et al 2004). Relatively low (<31.6 psu) SSS...
is found near the coasts, where freshwater discharge from rivers, such as the Mekong River and Rajang River, occurs.

On the basin scale, satellite SSS shows a good agreement with WOA18, despite some quantitative discrepancies in some areas (figure 1). In the southeastern part of the SCS at about 5°N–10°N and 112°E–117°E, for instance, satellite SSS is about 0.3 psu higher than that of WOA18, while in the northeastern part of the SCS at about 21°N–24°N and 115°E–119°E, the satellite SSS is somewhat fresher. These discrepancies may be due to differences in time period and depths of measurements. In general, the satellite SSS captures most of the important features identified by in-situ observations, and its spatially extensive and temporally continuous nature provides an unprecedented opportunity to study SSS variability in the SCS, where in-situ observations from Argo floats are especially sparse.

3.2. Relationship between SSS variability and ENSO

Figure 1 (d) shows the time series of SSS averaged over the SCS (5°N–24°N, 105°E–122°E) compared with Niño 3.4 index. On the interannual timescale, SSS variability is almost in phase with Niño 3.4 index. Both the time series show a negative phase during 2011–2014 and a positive phase during 2015–2016 followed by a small bounce during 2017–2019. The correlation coefficient between them reaches 0.87, satisfying 95% significant level, with Niño 3.4 index leading by 2 months. This result suggests that the SCS surface water tends to be saltier during El Niño years and fresher during La Niña years. The maximum positive SSS anomalies occurred during 2015–2016, when a strong El Niño event happened, while the maximum negative SSS anomalies occurred during 2017–2018, coinciding with a moderate La Niña event (figure 1(d)). No significant correlations are found between the SCS SSS anomalies and IOD ($r = 0.2$, not shown), implying that interannual variability of SSS in the SCS is dominated by ENSO. For comparison, the relationship between SST and ENSO was also examined (figure 1(d)). The correlation coefficient between the two time series reaches 0.85, with Niño 3.4 index leading by 5 months over the study period. SST in the SCS tends to be warmer during El Niño years and cooler during La Niña years, consistent with previous studies (Wang et al 2006, Tan et al 2016).
Next, we select the 2015/2016 El Niño event as a case study to investigate the dynamic linkages between the SCS SSS anomalies and El Niño. Basinscale positive SSS anomalies are observed in the SCS during the mature phase of the 2015/2016 El Niño event, except along the coast south of China and east of Vietnam, where negative SSS anomalies are visible (figure 2(a)). The amplitudes of positive SSS anomalies in the eastern half of the SCS are generally larger than those in the western half. The maximum (>0.5 psu) positive SSS anomalies occur southwest of the Luzon at 10°N–15°N and 113°E–120°E, while the maximum negative SSS anomalies (<−0.5 psu) appear along the coast south of China but north of 20°N.

During the mature phase of the 2015/2016 El Niño, the EMP pattern in the SCS is dominated by positive anomalies in the south and negative anomalies in the north, with a zero-line lying around 15°N (figure 2(b)). A prominent feature of surface wind during this period is an anomalous anticyclone, which is believed to play a role in modulating the EMP pattern over the SCS (figure 2(c)). Previous studies have indicated that this El Niño-induced anomalous anticyclone can cause anomalous sinking of air, leading to a weakening of precipitation but a strengthening of evaporation in the southern SCS. The situation is just reversed in the northern SCS (Wu et al 2003, Juneng and Tangang 2005). Here, we note that spatial pattern of EMP anomalies is inconsistent with that of SSS anomalies. For example, large discrepancies between the EMP and SSS anomalies are found in the northern SCS, where positive SSS anomalies correspond with negative EMP anomalies (figures 2(a) and (b)). These discrepancies reflect strong influence of ocean dynamics on the SSS distribution. During the mature phase of the 2015/2016 El Niño, stronger than normal Luzon Strait transport carries salty western
Pacific water into the SCS (Qu et al. 2004), resulting in positive SSS anomalies against reduced EMP in the northern SCS (figure 2(d)).

Negative SSS anomalies along the coast south of China may be related to anomalous surface freshwater flux and river runoff. Both precipitation and freshwater discharge from the Pearl River in the northern SCS get stronger during El Niño years (Wu et al. 2014), contributing to the negative SSS anomalies along the coast south of China. Negative SSS anomalies are also seen along the coast east of Vietnam, which are likely caused by abnormal runoff of the Mekong River.

3.3. Budget analyses
As discussed above, both the surface freshwater flux and ocean dynamics contribute to SSS variability, but their relative contribution varies with space, forming a sharp contrast between the northern and southern SCS. Here, we conduct a salinity budget analysis to assess the processes that control SSS variabilities, especially, those responsible for the differences between the northern and southern SCS. Given the characteristics of SSS and EMP associated with the 2015/2016 El Niño, two regions, marked as Box N and S, are chosen to represent the northern and southern SCS, respectively (figure 2).

The MLS tendency is generally in phase with the sum of contributing terms (figure 3). This result suggests that most of the SSS variability can be explained by observed surface freshwater forcing and ocean dynamics in the two regions. In the northern SCS (Box N), there is a significant correlation between the MLS tendency and horizontal advection ($r = 0.78$, with no time lag), indicating the critical importance of horizontal advection in driving the region's SSS variability during the period from January 2015 to December 2016. Further analysis indicates that, during the mature phase of the 2015/2016 El Niño, horizontal advection in the northern SCS is dominated by zonal advection, whereas meridional advection plays a secondary role. The large contribution of zonal advection is likely caused by enhanced Kuroshio intrusion of salty water through Luzon Strait (Xue et al. 2004). Compared with horizontal advection, the contribution from vertical entrainment is minor. Note that the contribution from surface freshwater forcing is in opposite phase to that of horizontal advection during the mature phase of the 2015/2016 El Niño, and their combined effect determines the SSS variability in the northern SCS. In the southern SCS (Box S), the sum of MLS budget terms also captures most of the SSS variability, especially during the period from September 2015 to May 2016. The MLS tendency is significantly correlated with surface freshwater forcing, with their correlation coefficient reaching 0.88. This suggests that the positive MLS tendency during the mature phase of 2015/2016 El Niño is primarily caused by anomalous surface freshwater forcing. Both horizontal advection and vertical entrainment play a role, but their contributions to MLS tendency are relatively small, which is different from what was discussed for the northern SCS.

Although the sum of surface freshwater forcing and ocean dynamics explains most of the MLS tendency associated with the 2015–2016 El Niño, equation (2) is not completely closed. This is because, besides surface freshwater forcing, horizontal advection, and vertical entrainment discussed above, other small-scale processes including meso-scale eddies that were not resolved owing to data limitation, can also play a role.

3.4. Causes of SSS anomalies associated with El Niño
As mentioned above, basin-scale positive SSS anomalies were observed in the SCS during the mature
phase of the 2015/2016 El Niño. The question is whether these observed SSS anomalies are common features of El Niño. To address this question, we conducted a composite analysis of SSS, surface current, surface wind, EMP, and vertical velocity anomalies of all El Niño events during 1992–2019 using ORAS5 and OSCAR products (figure 4). There were seven significant El Niño events during this period, occurring at 1994/1995, 1997/1998, 2002/2003, 2004/2005, 2006/2007, 2009/2010, and 2015/2016, respectively (Qi et al 2019).

The composite SSS anomalies resemble the 2015/2016 SSS anomalies in many details, with positive anomalies covering most of the SCS and negative anomalies near the coast south of China and east of Vietnam (figure 4). This suggests that the spatial patterns of the SCS SSS anomalies associated with the 2015/2016 El Niño are common features of El Niño events. The composite EMP anomalies also show similar patterns to those associated with the 2015/2016 El Niño, with positive anomalies in the southern SCS and negative anomalies in the northern SCS. The EMP anomalies are generally negative in the northern SCS, which is out of phase with SSS anomalies there. The EMP anomalies are dominated by precipitation anomalies. Although the composite SSS increases over the entire basin, the causes of this increase in the southern and northern SCS are different. The details are discussed below.

In the northern SCS, horizontal (mostly zonal) advection is a dominant factor controlling interannual SSS variability (figure 3(c)), as a result of Kuroshio intrusion through Luzon (Xue et al 2004). During the mature phase of El Niño, enhanced Kuroshio intrusion, brings more salty water from the western Pacific into SCS through Luzon Strait (Kim et al 2004), leading to an increase of SSS against enhanced precipitation in the northern SCS (figures 4(a)–(c)).

Interannual variability of the Kuroshio intrusion through Luzon Strait has been investigated by earlier studies (Qu et al 2009). It is believed to be closely related to the shift of North Equatorial Current (NEC) bifurcation latitude (NBL) associated with ENSO. During El Niño period, the NBL shifts northward, corresponding to a stronger Mindanao Dome and a weaker Kuroshio transport. This provides a favorable condition for the Pacific water to intrude into the SCS through Luzon Strait (Qu et al 2004). Previous studies suggested that, northward shift of the NBL during the mature phase of El Niño is mainly accounted for by the westward propagation of upwelling Rossby waves generated by an anomalous anticyclone located in the western North Pacific and anomalous winds in the central equatorial Pacific, both of which are closely related to changes in the trade winds over the Pacific Ocean (Wang et al 2000, Kim et al 2004).
In the southern SCS, positive SSS anomalies occur during the mature phase of El Niño, which are primarily induced by positive EMP anomalies (figure 4). The positive EMP anomalies in the southern SCS are due to a reduction in precipitation combined with an increase in evaporation, which in turn can be explained by changes in atmospheric circulation associated with El Niño. During and after the mature phase of El Niño, the regional Hadley circulation in the Indo-western Pacific sector is weakened, leading to anomalous descent (Klein et al 1999, Wang et al 2002). Corresponding to this anomalous descent is an anomalous anticyclone that extends to the SCS (figure 4(e)) (Weisberg and Wang 1997). The anomalous anticyclone over the SCS causes an anomalous sinking of air, resulting in weaker monsoonal winds in winter (Wu et al 2003) and consequently weaker precipitation and stronger evaporation in the southern SCS and stronger precipitation and weaker evaporation in the northern SCS. Previous studies indicated that this anomalous anticyclone over the SCS is closely related to variability in the trade winds over the tropical Pacific (Gill 1980, Wang et al 2000). The anomalous southwestward current induced by the anomalous anticyclone is also found west of Luzon Island, carrying relatively salty water to the southern SCS and directly contributing to the basin-wide salinification during the mature phase of El Niño.

4. Summary

Climatological distribution of SSS shows that surface isohalines are oriented chiefly in the meridional direction, with its value gradually decreasing southward. This SSS distribution is thought to occur primarily due to annual surface freshwater flux. The most significant feature is a high salinity tongue extending westward from Luzon Strait in the northern SCS, reflecting the Kuroshio intrusion through Luzon Strait. Analyses of satellite and in-situ observations have shown that the SCS SSS exhibits strong interannual variability, which is closely related to ENSO. During the mature phase of El Niño, a basin-wide salinification is observed over most of the SCS. Negative SSS anomalies are visible only in a small region along the coast south of China and east of Vietnam. Both the atmospheric bridge through an anomalous cyclonic circulation (Wang et al 2000) and the oceanic connection through an enhanced Kuroshio intrusion (Qu et al 2004) associated with El Niño are attributable to this basin-wide salinification. A question that arises is whether the response of SCS SSS during La Niña is symmetric in the opposite sense. To answer this question, we performed an EOF analysis. The first EOF mode of SSS exhibits a significant interannual variability tightly linked to ENSO, with negative SSS anomalies covering most of the SCS during the 2017/2018 La Niña event, and weak positive SSS anomalies in the coastal region of northern SCS (as shown in supplementary figure S1 available online at stacks.iop.org/ERL/17/054040/mmedia). This result implies that the response of SSS during La Niña event is mostly symmetric in an opposite sense to that during El Niño event.

Our results show that processes responsible for SSS variability are different between the northern and southern SCS. In the northern SCS, SSS increases against negative EMP anomalies during the mature phase of El Niño, primarily due to enhanced horizontal advection by the Kuroshio intrusion through Luzon Strait. Variability of the Kuroshio intrusion has been related to meridional migration of the NEC bifurcation latitude and consequently the large-scale wind anomalies over the Pacific. In the southern SCS, positive SSS anomalies are largely caused by anomalous surface freshwater flux during the mature phase of El Niño, with ocean dynamics playing a secondary role. An anomalous anticyclone associated with El Niño, triggered by the weakening of Hadley circulation in the Indo-western Pacific sector, is primarily responsible for the negative EMP anomalies and consequently positive SSS anomalies in the southern SCS. Negative SSS anomalies along the coast south of China may be caused by anomalous EMP and river runoff.

This study focuses on the impacts of El Niño on the SSS in the SCS. It should be noted, however, that some biochemical properties, such as alkalinity, are also influenced by ENSO. Earlier studies have shown that variability in these biochemical properties is closely related variability in SSS (Lee et al 2006, Jiang et al 2014). Therefore, the observed variability in SSS associated with ENSO may lead to variability in alkalinity and other biochemical properties in the SCS. The details require further investigation.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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