Interdecadal differences in the interannual variability of the winter monsoon over the South China Sea

Baochao Liu1,2 | Yue Fang1,2 | Shuangwen Sun1,2 | Celia Tana1,2 | Yongliang Duan1,2 | Guang Yang1,2

1Center for Ocean and Climate Research, First Institute of Oceanography, Ministry of Natural Resources, Qingdao, China
2Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

Correspondence
Baochao Liu, Center for Ocean and Climate Research, First Institute of Oceanography (FIO), Ministry of Natural Resources (MNR), No.6 Xianxialing Road, Qingdao 266061, China.
Email: liubc@fio.org.cn

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Abstract
We investigate interdecadal differences in the interannual variability of the South China Sea (SCS) Winter Monsoon (SCSWM) since 1950. The SCSWM is influenced by both the East Asian Winter Monsoon (EAWM) over the mid–high latitudes and the anomalous anticyclone over the western North Pacific (WNPAC). The EAWM tends to cause a positive linear correlation of wind speeds between the northern SCS (NSCS) and the southern SCS (SSCS). Because the cold surge of the EAWM can make wind speeds over the NSCS and SSCS increase simultaneously. While, the WNPAC tends to weaken this positive correlation (corNS) because anomalies associated with the WNPAC will decrease wind speeds over the NSCS but exert a small or even an opposite influence on wind speeds over the SSCS. The interannual variation of the EAWM before the late 1970s is greater than that after the early 1990s. And the WNPAC was weak and confined to the east of the SCS before the late 1970s but became strong and expanded towards the SCS after the early 1990s. As a result, the positive corNS was significant at the 95% confidence level before the late 1970s but became insignificant after the early 1990s.

KEYWORDS
East Asian Winter Monsoon (EAWM), ENSO, interannual variability, interdecadal differences, South China Sea Winter Monsoon (SCSWM)

1 INTRODUCTION

The South China Sea Winter Monsoon (SCSWM) is a key variable for the local climate and ocean (Fang et al., 2012; Quan et al., 2016; Sun et al., 2016; Wu, 2016). Because of the location of the South China Sea (SCS), the SCSWM is affected by climate systems over both the tropical ocean and the mid–high latitude region.

Several studies, using the empirical orthogonal function (EOF) method, report that the leading mode of wind vectors over the SCS presents an anticyclonic spatial pattern (Fang et al., 2006; Wang et al., 2009; Zhao et al., 2010; Lian et al., 2015). Because this anticyclonic pattern is similar to the anomalous anticyclone over the western North Pacific (WNP) during the El Niño event (hereafter referred to as the WNPAC, Wang et al., 2000), these studies usually propose that the WNPAC plays a dominant role in the interannual variability of SCSWM.

However, one shortcoming of these studies is that EOF modes are extracted from wind datasets that cover

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only the latest three or four decades. It is therefore arguable whether the WNPAC associated with El Niño–Southern Oscillation (ENSO) is also the main mechanism to understand the interannual variability of SCSWM at an earlier period. Because many decadal variations have been detected in the global climate system since 1950, some of these are likely to modulate SCSWM interannual variability.

First, previous studies have reported that the WNPAC experienced an interdecadal increase in intensity in the late 1970s (Wang et al., 2008) and that its location shifted westward in the late 1990s (Kim et al., 2017). So, in an earlier period (that is, before the late 1970s), did a WNPAC that was weaker and further east from the SCS still dominate SCSWM interannual variability? And did the leading mode of SCSWM variability also present the anticyclonic spatial pattern? Second, the SCSWM is a part of the East Asian Winter Monsoon (EAWM) and has varied consistently with monsoon over the mid–high latitudes for many years (Liu et al., 2013; Chen et al., 2014)—the cold surge from the mid–high latitudes is an important cause of strong wind events over the SCS. It has been reported that the intensity and interannual variation of the winter monsoon in the mid–high latitudes experienced an interdecadal weakening during the past several decades (He, 2013; He and Wang, 2013). Therefore, it is possible that the EAWM over the mid–high latitudes had a stronger influence on SCSWM variability at an earlier period than it does more latterly, and this may also have weakened the influence of the WNPAC on the SCSWM.

In brief, there are possible interdecadal differences in the interannual variability of the SCSWM and the WNPAC may not have been the only mechanism of interannual variability during an earlier period. In this present study, we discuss this issue using EOF analysis on long-term wind datasets. The remainder of the article is organized as follows: Section 2 introduces the datasets and methods; Section 3 describes the results; and Section 4 gives the summary and discussion.

2 | DATA AND METHODS

The ocean surface wind for EOF analysis is from the Wave- and Anemometer-based Sea Surface Wind (WASWind) dataset (Tokinaga and Xie, 2011), which is constructed from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) and represents well the seasonal-to-decadal variability over global oceans (Tokinaga and Xie, 2011). Because the WASWind covers only before 2011, wind measurements from other datasets are also analyzed as an auxiliary to reveal variations during the latest 10 years, including ICOADS, Cross-Calibrated Multi-Platform (CCMP) wind vector analysis (Atlas et al., 2011) and the surface wind from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis 1 (NCEP-R1) (Kalnay et al., 1996). Other variables for diagnosis include sea level pressure (SLP) and wind at 850 hPa from the NCEP-R1 and sea surface temperature (SST) from the Extended Reconstructed Surface Temperature (ERSST) dataset (Huang et al., 2017).

The winter means are constructed by averaging the monthly data from December, January and February (DJF). Here, the winter of 1950 refers to the 1950/51 winter. In order to focus on the interannual signal, a seven-year high-pass filter is performed on all variables. After removing the start and end years post-filtering, we have a total of 54 winters from 1953 to 2007 in WASWind datasets. The research region focuses only on the open SCS (Figure 1) and does not include the Gulf of Thailand because of the rough resolution of the WASWind data.

In this article, EOF analyses are not only performed on wind vectors, as in previous studies, but also on scalar wind speeds. Subsequent analyses will show that scalar wind speeds can help us to describe more clearly the interdecadal change in SCSWM interannual variability. It should be pointed out that monsoon variations represented by EOF modes of wind vectors and scalar wind speeds are of some differences, because of wind direction in the vectors. However, since these differences will not substantially change conclusions on the interdecadal change of SCSWM interannual variability, we will not discuss these further. Additionally, the EOF method is a mathematical analysis. Many factors within the dataset, such as region and resolution, may affect the extracted modes. Plus, a great deal of rigorous argument is needed to determine whether the extracted modes have exact physical meaning. In this article, we will not discuss these questions about the EOF method either. We focus only on differences between EOF modes that are extracted from wind datasets with the same region and resolution but different periods. Then, differences in EOF modes during different periods are used to reveal possible interdecadal differences in SCSWM interannual variability.

3 | RESULTS

3.1 | Interdecadal differences in SCSWM interannual variability

Primarily, we investigate leading EOF modes extracted from the surface wind during two periods: 1953–1979 and 1990–2007 (Figure 1). The reasons for selecting these two periods are that the 1980s is a transitional decade, as will be shown in subsequent analyses, and interdecadal differences will thus be more pronounced if the
comparative analysis is conducted between periods before 1979 and after 1990. Hereafter, the first (second) modes of scalar wind speeds and wind vectors are referred to as the SEOF1 (SEOF2) and VEOF1 (VEOF2), respectively. Because EOF modes of scalar wind speeds during two periods are of similar spatial patterns, only spatial coefficients of SEOF1 and SEOF2 during 1953–1979 are shown (shading in Figure 1a,b). Because percent variances of the first modes are much greater than those of the second modes, we focus on the first modes. Interdecadal differences are detectable in both the SEOF1 and the VEOF1.

First, the percent variance of SEOF1 is as high as 63% during 1953–1979, which is greater than that during 1990–2007 (51%). Spatial coefficients of the SEOF1 are of the same negative sign across the whole Basin, while spatial coefficients of the SEOF2 are of opposite signs between the northern SCS (NSCS) and the southern SCS (SSCS). The same sign means that if the wind speed increases over the NSCS, so will the wind speed over the SSCS. And, opposite signs indicate opposite variation of wind speeds between the NSCS and the SSCS. Therefore, the greater percent variance of the SEOF1 implies a higher positive linear correlation between the regional mean wind speeds over the NSCS (averaged within the red box in Figure 1b) and the regional mean wind speeds over the SSCS (averaged within the blue box in Figure 1b). Hereafter, this linear correlation coefficient is referred to as the corNS. The corNS is as high as 0.68 and significant at the 99% confidence level during 1953–1979. During 1990–2007, however, it is only 0.38 and not up to the 90% confidence level.

Second, in comparison to the vectors of the VEOF1 during 1990–2007 (yellow vectors), vectors of the VEOF1 during 1953–1979 (purple vectors) rotate clockwise over the SSCS. As a result, the anticyclonic structure of the VEOF1 is not obvious during 1953–1979. This

FIGURE 1  (a–b) Spatial patterns of the first two EOF modes of SCSWM interannual variability during different periods. Shading represents the first (a) and second (b) EOF mode of scalar wind speeds during 1953–1979. Purple (yellow) vectors represent EOF modes of wind vectors during 1953–1979 (1990–2007). Black vectors are climatological winter monsoon winds. Percent variances (%) of each EOF mode during the two periods are shown in the upper left of each panel. The region means within the two boxes in panel (b) describe the monsoon variability over the northern and the southern SCS, respectively. (c) The 25-year running linear correlation coefficients of wind speeds between the northern and the southern SCS. Black, red, purple and blue curves are correlation coefficients calculated from datasets of WASWind, ICOADS, CCMP and NCEP-R1, respectively. The horizontal black dashed line indicates the 95% confidence level of the linear correlation. Vertical black dashed lines indicate the years 1979 and 1990.
interdecadal difference of the VEOF1 is consistent with the interdecadal difference of the corNS. The significant anticyclonic structure of the VEOF1 tends to weaken the positive corNS. Anomalies of the VEOF1 (yellow vectors in Figure 1a) are southwesterly anomalies over the NSCS, which weaken the climatological northeasterly monsoons and decrease wind speeds over the NSCS. However, over the SSCS, anomalies of the VEOF1 are not southwesterly. Over the west of the SSCS, anomalies of the VEOF1 are southeasterly, which may exert more influence on wind directions than on wind speeds. More importantly, there are northeasterly anomalies along the northwest coast of Borneo (yellow vectors in Figure 1a), which strengthen the climatological northeasterly monsoons over this region and result in variations opposite to those in the NSCS. In a word, anomalies of the VEOF1 will decrease wind speeds over the NSCS but exert a small or even an opposite influence on wind speeds over the SCSC. Therefore, the significant anticyclonic structure of the VEOF1 tends to weaken the positive corNS. In contrast, the less obvious anticyclonic structure of the VEOF1 during 1953–1979 corresponds to a higher positive corNS.

Therefore, the corNS is a good indicator describing the interdecadal difference in SCSWM interannual variability. A 25-year running correlation analysis presents a more detailed interdecadal variation (Figure 1c). The corNS experiences a great decrease during the late 1970s. This is followed by a short-term oscillation during the 1980s, which is the reason for selecting the chosen periods. After the early 1990s, the corNS decreases again and becomes insignificant. Running correlations from other datasets, including ICOADS, CCMP and NCEP-R1, reveal that the insignificant positive correlation continues until the present. The NCEP-R1 (blue curve) even presents the negative coefficient during the latest decade.

In conclusion, there are interdecadal differences in the interannual variability of the SCSWM. Before the late 1970s, the first leading mode of SCSWM wind vectors is of a weak anticyclonic spatial pattern, and there is high positive linear correlation of wind speeds between the NSCS and the SSCS. After the early 1990s, the first leading mode of SCSWM wind vectors presents a significant anticyclonic structure. The positive correlation of wind speeds between the NSCS and the SSCS becomes insignificant, which continues to the present.

### 3.2 Reasons for interdecadal differences in SCSWM interannual variability

So, are interdecadal differences in the SCSWM interannual variability attributable to interdecadal differences in the tropical WNPAC and the extropical EAWM? Given that percent variances of the first EOF modes are much greater than those of the second EOF modes, and interdecadal differences of the first modes are in general consistent with interdecadal differences of corNS, to address this question we present large-scale circulations correlated with the first EOF modes as well as the WNPAC during two different periods (Figure 2). The WNPAC index is defined as the regional mean vorticity anomalies at 850 hPa in the region $5^\circ$–$20^\circ$N, $120^\circ$–$160^\circ$E, which follows the method proposed by (Wang et al., 2008). The index is multiplied by $-1$, so that the positive index corresponds to the anticyclonic circulation.

The signature of the WNPAC is weaker during 1953–1979 (Figure 2a,c,e) than during 1990–2007 (Figure 2b,d,f), which is indicated by smaller correlation coefficients over the tropical WNP during the earlier period. Especially, correlation coefficients of the WNPAC index with SLP over the tropical WNP are no longer significant at the 95% confidence level during 1953–1979 (Figure 2e). For a quantitative description of WNPAC variations in intensity and zonal location, the meridional mean vorticity and stream function between $5^\circ$–$20^\circ$N at 850 hPa are regressed onto the WNPAC index (Figure 3).

The vorticity anomalies regressed onto the WNPAC index are weaker during 1953–1979 (red curves in Figure 3a) than during 1990–2007 (solid blue curve in Figure 3a). And, vorticity anomalies that are significant at the 95% confidence level (thick segment of the curve) are confined to the east of $120^\circ$E during 1953–1979 but expand westward to the SCS during 1990–2007. Anomalies of stream function regressed onto the WNPAC index are also insignificant over the tropical WNP during 1953–1979 but become significant at 95% level during 1990–2007 (Figure 3b). If the regression analysis is made using a period covering the latest datasets (dashed curves), the result is similar.

Therefore, we can conclude that the WNPAC is weak and confined to the east of the SCS during 1953–1979 but strengthen and expand westward to the SCS during 1990–2007. Consequently, it can be inferred that the influence of the WNPAC on the SCSWM is stronger during 1990–2007 than during 1953–1979. As mentioned in Section 3.1, the significant anticyclonic structure tends to weaken the positive corNS.

Although previous studies have reported that two interdecadal variations of the WNPAC have occurred during the late 1970s and the late 1990s (Wang et al., 2009; Kim et al., 2017), the 25-year running regression analysis (Figure 3c,d) reveals that the mid-1980s, rather than the late 1970s, is more appropriate to define the time when the first interdecadal variation occurs. Because vorticity anomalies significant at 95% confidence
level begin to happen in the mid-1980s (Figure 3c). And, the stream functions (e.g., the 0.5 contour) also present a significant westward expansion during the mid-1980s. In a word, the weak and eastward WNPAC continues until the mid-1980s, which is an important reason why the corNS experienced an increase during the 1980s, after significantly decreasing during the late 1970s (Figure 1c).

Overall, the interdecadal variation of the WNPAC is an important mechanism to understand the interdecadal difference in SCSWM interannual variability. Next, we focus on the mid–high latitudes, where interdecadal differences are also detectable in Figure 2. For example, correlation coefficients of SLP with SEOF1 and VEOF1 over mainland China were greater during 1953–1979 than 1990–2007. Over the region north of 45°N, there were significant westerly vectors during 1953–1979 which became insignificant during 1990–2007.

To clearly describe the influence of the mid–high latitude EAWM on the SCSWM, the EAWM index (EAWMI) proposed by Shi (1996), which is defined as the land–sea SLP difference between (20°N–50°N, 110°E) and (20°N–50°N, 160°E), is chosen to represent the EAWM variation. There are two reasons for the selection of this index. First, the land–sea contrast is the direct force driving the
monsoon over Asia, and it is easy to understand the physical mechanism of the relationship between the land–sea SLP gradient and the SCSWM. Second, the land–sea contrast is very significant in large-scale circulations correlated with SEOF1 and VEOF1 (Figure 2). A 25-year running analysis (Figure 4) reveals that the EAWMI presents larger interannual variations during 1953–1979 than during 1990–2007, which is the same result as previous studies (He, 2013).

For a confirmation of the relationship between the EAWM and the SCSWM, the principal components of the SEOF1 and VEOF1 are regressed onto the EAWMI. Results show that regression coefficients are all significant at the 95% confidence level. The linear models explain 66% of SEOF1 variance and 59% of VEOF1 variance during 1953–1979, which are greater than, respectively, 50% and 35% during 1990–2007 (Figure 4). Evidently, the influence of the EAWM on the leading EOF modes is stronger during 1953–1979 than 1990–2007.

In the same way, we regress the principal components of the SEOF1 and VEOF1 onto the WNPAC index. During 1953–1979, fractional variances explained by the linear modes are nearly 0.0, indicating that the WNPAC exert little influence on the first EOF mode. During 1990–1979, although the linear model for the SEOF1 is insignificant and explain only 7% of SEOF1 variance, the
linear model for the VEOF1 is significant at the 95% confidence level and explains as much 22% of VEOF1 variance. This result, again, indicates a strengthened influence of the WNPAC on the SCSWM during 1990–2007.

Here, it should be pointed out that the linear correlation between the WNPAC index and the EAWM index is very weak, the value of which is only 0.004 during 1953–1979 and 0.12 during 1990–2007. Obviously, the WNPAC and the EAWM can be approximately considered to be independent of each other. Therefore, their influences on the SCSWM are also independent.

Overall, fractional variances explained by the linear modes regarding to the EAWM are greater than those explained by the linear modes regarding to the WNPAC. Therefore, the present analyses demonstrate a critical role of the mid-high latitude EAWM in SCSWM interannual variability. It is interesting to note that the influence of the EAWM on the SEOF1 is greater than that in the VEOF1. It is easy to understand the relationship between the EAWM and SEOF1. The cold surge associated with the EAWM is one of the main causes of strong winds over the SCS—this surge can penetrate the southernmost part of the SCS (even cross the Equator) and induce large wind speeds across the whole of the SCS (Chang et al., 1979; Chang and Chen, 1992). In other word, when the cold surge outbreak, wind speeds over the NSCS and SSSC will increase simultaneously. During the year of a stronger EAWM, there will be stronger and more frequent cold surges, which strengthen wind speeds over both the NSCS and SSSC. Therefore, the larger interannual variation of the EAWM will result in a stronger SEOF1 and a larger positive corNS. However, the VEOF1 contains variations of both wind speed and wind direction. The wind direction is controlled by the direction of pressure gradient. Because the Asian coastline is invariable, in comparison to the magnitude, the direction of the land–sea SLP gradient over the mid-high latitudes changes smaller. The wind direction over the SCS is controlled more by the local SLP gradient than the gradient over the mid–high latitudes. Therefore, the of the EAWM exert a greater influence on the SEOF1 than on the VEOF1.

Additionally, the 25-year running variance of the EAWMI in Figure 4 also partly accounts for the corNS oscillation during the 1980s. The variance of EAWMI experienced the first interdecadal decrease during the late 1970s, which accounted for the interdecadal decrease of the corNS during this time. Then, the decrease in EAWMI variance slowed and even present a weak increasing oscillation during the 1980s. As discussed previously, before the mid-1980s the WNPAC is still weak and confined to the east of the SCS. In combination with the EAWM and WNPAC, the corNS experienced an oscillation during the 1980s. After 1990, the EAWMI variance continued decreasing, while the WNPAC strengthened and expanded westward. Therefore, the EAWM (WNPAC) exert a smaller (greater) influence on the interannual variability of SCSWM and the corNS became insignificant.

4 | CONCLUSION AND DISCUSSION

In the present study, we discuss interdecadal differences in the interannual variability of the SCSWM since 1950.

Previous studies, which used datasets covering only the latest three or four decades, have reported that the first EOF mode of wind vectors over the SCS (VEOF1) presents an anticyclonic spatial pattern. However, results in the present study reveal that the VEOF1 extracted from datasets before 1979 is of a weak anticyclonic structure. In addition, the first EOF mode of scalar wind speeds (SEOF1)—spatial coefficients of which are of the same sign across the whole SCS—is also of a larger percent variance before 1979 than after 1990. Correspondingly, the linear correlation coefficients of wind speeds between the northern and southern SCS (corNS) was positive with significance at the 95% confidence level before the late 1970s but became insignificant after the early 1990s.

Interdecadal variations of both the extropical EAWM and the tropical WNPAC contribute to interdecadal differences in SCSWM interannual variability. The EAWM tends to cause a larger percent variance of the SEOE1 and a larger positive corNS. Because the cold surge of the EAWM can make wind speeds over the NSCS and SSSC increase simultaneously. While, the WNPAC, which exerts anticyclonic anomalies over the SCS, tends to weaken this positive correlation because anomalies associated with the WNPAC will decrease wind speeds over the NSCS but exert a small or even an opposite influence on the SSSC.

The interannual variation of the EAWM before the late 1970s is greater than that after the early 1990s. And the WNPAC was weak and confined to the east of the SCS before the late 1970s but became strong and expanded towards the SCS after the early 1990s. Therefore, before the late 1970s, the signature of the WNPAC in SCSWM interannual variability was weak and the anticyclonic structure of the VEOF1 was insignificant. And, there is a greater percent variance of the SEOE1 and a significant positive corNS before the late 1970s. While, the VEOF1 present a more significant anticyclonic structure and there is smaller percent variance of the SEOE1 and an insignificant corNS. The running analysis also
reveals the 1980s to have been a transitional decade. Because the WNPAC that is weak and confined to the east of the SCS continues until the mid-1980s. While, the decrease in the EAWM interannual variance slowed and even present a weak increasing oscillation during the 1980s. As a result, the corNS presented an oscillation during the 1980s.

Because the SCSWM affects the air–sea exchange and upper ocean circulation over the SCS as well as the precipitation over the coastal region, the findings of the present study are of scientific importance to help understand the interannual variability of ocean and climate over the SCS. In particular, the results in this article show that, when discussing interannual variability before the late 1970s and possibly during certain periods in the future, careful attention may need to be paid to influences from mid–high latitudes, rather than tropical influences alone.

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ORCID

Baochao Liu https://orcid.org/0000-0001-9414-8687

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