Enhanced correlation between ENSO and western North Pacific monsoon during boreal summer around the 1990s

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ABSTRACT

The correlation between summertime Niño3.4 index and western North Pacific (WNP) summer monsoon index has strikingly enhanced since the early 1990s, with nonsignificant correlation before the early 1990s but significant correlation afterward. This observed interdecadal change around the 1990s may be associated with more frequent occurrences of central Pacific (CP) El Niño and the interdecadal changes in ENSO-associated SST anomalies. During the post-1990s period (the pre-1990s period), highly noticeable tropical Atlantic (Indian) Ocean SST anomalies tend to co-occur with the summertime Niño3.4 SST anomalies. The concurrent tropical Atlantic (Indian) Ocean SST anomalies could constructively reinforce (destructively mitigate) the WNP monsoon circulation anomalies induced by the summertime Niño3.4 SST, thus boosting (muting) the correlation between summertime Niño3.4 SST and WNP monsoon. In addition, the faster decaying pace of preceding-winter El Niño after the 1990s, which may have been mainly induced by the influences from the spring tropical North Atlantic SST anomalies, could also have contributed to the enhanced correlation between the summertime Niño3.4 index and WNP monsoon. These results suggest that the enhanced influences from the tropical Atlantic SST may have triggered the intensified correlation between summertime ENSO and WNP monsoon since the early 1990s.

1. Introduction

The western North Pacific (WNP) monsoon is a major subsystem of the Asian monsoon system (e.g. Wang, Wu, and Lau 2001). During recent decades, the WNP summer monsoon has been found to play more active and dominant roles in the global monsoon system (Lee, Ha, and Jhun 2014; Wang and Yu 2018). Therefore, a better understanding of the WNP summer monsoon variability is essential for us to gain more insight into the climate variability during recent decades.

The interannual variability of the WNP summer monsoon is known to be greatly modulated by ENSO (e.g. Chou, Tu, and Yu 2003; Li and Wang 2005; Gu et al. 2010). Chou, Tu, and Yu (2003) suggested that the processes of both El Niño decay and development could influence the variability of the WNP summer monsoon. During El Niño decaying (developing) years, a weak (strong) WNP summer monsoon tends to be observed after (before) the mature phase of ENSO. There is a growing awareness that ENSO-related SST anomalies could play very important roles in driving the variability of the WNP summer monsoon (e.g. Wang, Wu, and Fu 2000; Li and Wang 2005; Xie et al. 2009; Li et al. 2017). Previous studies have also revealed that interdecadal changes in the relationship between ENSO and the Asian summer monsoon (including the WNP summer monsoon) could be observed since the late 1970s (e.g. Wu and Wang 2002; Wang et al. 2008).

Most of these studies, however, mainly focused on the relationship between the WNP summer monsoon and mature-phase ENSO during the preceding and/or succeeding winter season. The simultaneous
relationship between the summertime ENSO index and the WNP summer monsoon index has been relatively less well investigated in previous studies. In this paper, we demonstrate that the correlation between the summertime Niño3.4 index and the WNP summer monsoon index has enhanced greatly since the early 1990s. The possible reason and mechanism behind this enhancement is discussed.

2. Data and methods

The atmospheric fields are from the monthly NCEP–NCAR reanalysis (Kalnay et al. 1996). The rainfall data are from NOAA’s Precipitation Reconstruction (Chen et al. 2002). The SST data are from ERSST.v5 (Huang et al. 2017).

The WNP summer monsoon index is defined as the difference in 850-hPa zonal wind anomalies between (5°–15°N, 100°–130°E) and (20°–30°N, 110°–140°E), according to Wang and Fan (1999). The Niño3.4 index is defined by the SST anomalies averaged over (5°S–5°N, 170°–120°W), to represent the ENSO intensity.

The interannual variability of the time series is calculated by applying a 9-year high-pass filter to the anomalies, which are obtained by subtracting the long-term trend and mean seasonal cycle from the original time series. The statistical significance levels in the statistical analysis are determined based on the two-tailed $P$-value using the Student’s $t$-test.

3. Results

Figure 1(a) depicts the time series of WNP summer monsoon index during 1960–2017, which exhibits prominent interannual variability. A 21-year sliding correlation analysis between the WNP summer monsoon index and the summertime Niño3.4 index during June–July–August (JJA) (Figure 1(b)) was used to examine the possible decadal changes in the relationship between the two indexes. The results show highly noticeable interdecadal changes in the correlation coefficients, with vastly enhanced correlations between the two indexes since the early 1990s. The correlation coefficients after the early 1990s increase markedly to be larger than 0.40, and are boosted to being statistically significant (Figure 1(b)). The maximum correlation coefficient (0.70) was found for the year 2004, and the minimum absolute value (0.03) for the year 1976. According to the years (1976 and 2004) with the maximum and minimum 21-year sliding correlations, two periods were selected: P1 (1966–1986, centered in 1976) and P2 (1994–2014, centered in 2004). In the following analysis, we used the selected 21-year period of P1 (P2) to denote the pre-early-1990s period (post-early-1990s period).

During 1966–86, there are no notable signals of significant correlations in the tropical central and eastern Pacific (Figure 2(a)), consistent with the fact that the examined correlation coefficient between the two indexes is nonsignificant during this period (Figure 1(b)). During 1994–2014, significantly positive correlations dominate the tropical central Pacific region (Figure 2(b)), confirming that the examined correlation is markedly enhanced during this period (Figure 1(b)). In addition, the negative correlations in the tropical Atlantic strengthen substantially during 1994–2014 (Figure 2(b)). Furthermore, the maximum positive correlations occur in the central tropical Pacific region rather than in the eastern tropical Pacific region (Figure 2(b)), which is a reminder of the possible different influences of these two different types of El Niño. The WNP summer monsoon variability during 1994–2014 might be more influenced by the central Pacific (CP) type El Niño (Kao and Yu 2009). Previous studies have revealed an increasing frequency in the emergence of these CP-type El Niño events during recent decades (e.g. Yu, Lu, and Kim 2012; Yu et al. 2015). Therefore, the observed intensified correlation between summertime ENSO SST and WNP summer monsoon after the 1990s may also be associated with the increasing frequency of CP-type El Niño.

But why can different correlation coefficients between the WNP summer monsoon and summertime Niño3.4 index be found before and after 1990s? The different ENSO-associated SST anomalies during different decades may be the reason. In the following, we report the results of regression analysis (Figures 3 and 4) and compare different characteristics during P1 and P2.

Obvious SST anomalies can be observed for the period 1966–86 in the tropical North Indian Ocean (Figure 3(a)), but they weaken substantially during 1994–2014. Meanwhile, negative tropical Atlantic SST anomalies, absent during 1966–1986 (Figure 3(a)), become highly noticeable (Figure 3(b)). Negative SST anomalies in the tropical eastern Indian Ocean (TEIO) could be found in both periods (Figure 3(a,b)), which have been considered a major factor for interdecadal change in southern China summer rainfall (Chen et al. 2017). Because the differences in TEIO SST anomalies are relatively small compared with those in tropical Atlantic and North Indian Ocean SST anomalies between P1 and P2, the TEIO SST anomalies may not be the most important factor triggering the interdecadal change examined here. Prominent tropical North Indian Ocean (Atlantic) SST anomalies can be seen to generally co-occur with summertime Niño3.4 SST anomalies before (after) the early 1990s. These different configurations of ENSO-associated SST anomalies in other ocean basins (e.g. the Indian and Atlantic oceans)
during different decades may exert different influences on the WNP summer monsoon, thus resulting in different correlations between the WNP summer monsoon and summertime Niño3.4 index. The regressed 850-hPa cyclonic circulation anomalies over the WNP region are much weaker during 1966–86 (Figure 3(a)) than those during 1994–2014 (Figure 3(b)), supporting a weaker impact of summertime Niño3.4 index on the circulation anomalies of the WNP summer monsoon during P1. Similar conditions could also be observed in the regressed rainfall anomalies (Figure 3(c,d)), with non-obvious (highly noticeable) rainfall anomalies in the WNP summer monsoon region during 1966–86 (1994–2014).

Different joint effects of the tropical Pacific SST anomalies and concurrent tropical Indian Ocean (Atlantic) SST anomalies before (after) the early 1990s are apparent. During 1994–2014, both the warm Niño3.4 SST anomalies and concurrent cold tropical Atlantic SST anomalies (Figure 3(b)) tend to foster a strong WNP summer monsoon. This takes place via a Gill-type response of the warm Niño3.4 SST.

Figure 1. (a) Time series of WNP summer monsoon index and JJA Niño3.4 index on the interannual timescale during 1960–2017. (b) 21-year sliding correlation coefficients between WNP summer monsoon index and JJA Niño3.4 index. The red dots in (b) indicate the correlation is significant at the 95% confidence level.
anomalies, causing cyclonic circulation anomalies over the WNP region and triggering a strong WNP summer monsoon (e.g. Gu et al. 2010). Meanwhile, it is through the trans-basin atmospheric zonal vertical circulation anomalies that the cold tropical Atlantic SST anomalies may also be helpful to a strong WNP summer monsoon (e.g. Hong, Chang, and Hsu 2014). During 1994–2014, remarkable anomalous atmospheric downward motion (denoted by negative 850-hPa velocity potential anomalies) over the tropical Atlantic could be observed (Figure 3(d)), which is absent for the period 1966–86 (Figure 3(c)). These observed atmospheric downward motions over the tropical Atlantic are closely related with the cold SST anomalies there during 1994–2014 (Figure 3(b)). Compared with the motion during 1966–86, the anomalous atmospheric upward motion over the central equatorial Pacific is substantially enlarged to cover a greater area in the WNP region during 1994–2014, thus being able to exert an intensified impact on the WNP summer monsoon by inducing a low-level cyclonic anomaly to the west according to the process described in Hong, Chang, and Hsu (2014). Consequently, the effects from the warm Niño3.4 SST anomalies and concurrent cold tropical Atlantic SST anomalies may constructively interfere, producing an intensified impact of the summertime Niño3.4 SST anomalies on the WNP summer monsoon and a larger correlation between them after the early 1990s.

Different from the conditions during 1994–2014, the effects on the WNP summer monsoon from the warm tropical Indian Ocean SST and warm Niño3.4 SST anomalies during 1966–86 (Figure 3(a)) may be opposite and tend to cancel each other out. The warm Indian Ocean (Niño3.4) SST anomalies tend to weaken (strengthen) the WNP summer monsoon. It is through a remote Gill-type response that the warm SST anomalies in the western tropical Indian Ocean could cause easterly wind anomalies and anticyclonic circulation anomalies over the WNP region (e.g. Xie et al. 2009). Therefore, the effects from the warm Niño3.4 SST anomalies and concurrent warm tropical Indian SST anomalies may destructively interfere, producing a reduced impact of the summertime Niño3.4 SST anomalies on the WNP summer monsoon before 1990s. For this reason, the correlation coefficients between the WNP summer monsoon and summertime Niño3.4 index are low and nonsignificant before the 1990s.

In addition, the changes in the decaying pace of preceding-winter El Niño may also contribute to the enhanced correlation between summertime Niño3.4 index and WNP summer monsoon after the 1990s. The warm Niño3.4 SST anomalies in the preceding winter tend to decay faster during P2 than during P1 (Figure 4). Significant cold Niño3.4 SST anomalies could be observed in JJA during P2 (Figure 4(b)) but not during P1 (Figure 4(a)). During both P1 and P2, warm Niño3.4 SST anomalies in the preceding winter could induce weak WNP summer monsoon during
the following JJA. Thus, large positive correlations could be expected to occur with the co-existence of the weak WNP summer monsoon and significant cold Niño3.4 SST anomalies in JJA during P2, but not during P1.

As suggested in previous studies, both winter warming in the western Indian Ocean (WIO) SST (Kug and Kang 2006) and spring warming in the north tropical Atlantic (NTA) SST (Ham et al. 2013) could contribute to the cooling in the equatorial central-eastern Pacific in El Niño decaying summers. The SST warming in the WIO and NTA could be observed during both periods (Figure 4), with no obvious differences in the NTA SST anomalies.

**Figure 3.** Regression with respect to JJA Niño3.4 index for JJA SST anomalies (shading; units: °C °C⁻¹) and 850-hPa wind (vector; m s⁻¹ °C⁻¹) during (a) period P1 and (b) period P2, and for JJA rainfall anomalies (shading; mm d⁻¹ °C⁻¹) and 850-hPa velocity potential (contours; solid for positive and dashed for negative values; units: 10⁶ m² s⁻¹ °C⁻¹) during (c) period P1 and (d) period P2. Only values at or above the 90% confidence level are shown. The green box in (c, d) denotes the core rainfall region of the WNP summer monsoon.
between them. However, Wang, Yu, and Paek (2017) suggested the spring NTA SST warming might only have exerted significant influences on the following ENSO after the early 1990s and not before, possibly due to the warmer mean background SST in the North Atlantic since the 1990s. For the WIO SST, the warming tends to persist for a longer time from the preceding winter to the following summer during P1 (Figure 4(a)). In contrast, the WIO SST warming during P2 starts to decay after spring and nearly disappears during JJA (Figure 4(b)). The influences from the warm WIO SST anomalies during P2 might be relatively weak because of its shorter persistence time. Therefore, the spring NTA SST anomalies might be the main driver for a faster ENSO decaying pace during P2, which is consistent with results presented in Wang, Yu, and Paek (2017). During P1, although warm WIO SST warming could be observed, we could not find significant cold Niño3.4 SST anomalies during JJA (Figure 4(a)), suggesting that the warm WIO SST might be not the most dominant factor to determine the ENSO evolution process during P1.

4. Conclusions and discussion

Statistical analyses were applied to show that the relationship between the summertime Niño3.4 SST and WNP summer monsoon has intensified markedly since the early 1990s. The correlation between the summertime Niño3.4 index and the WNP summer monsoon index is nonsignificant before the early 1990s, but strikingly intensified and significant after the early 1990s. The observed interdecadal change in the relationship between the two indexes might be associated with the decadal changes in the ENSO-associated SST anomalies. Before (after) the 1990s, highly noticeable tropical Indian (Atlantic) Ocean SST anomalies tend to co-occur with the summertime Niño3.4 SST anomalies. The concurrent tropical Indian (Atlantic) Ocean SST anomalies may destructively mitigate (constructively reinforce) the WNP summer monsoon circulation anomalies induced by the summertime Niño3.4 SST, thus muting (strengthening) the relationship between the summertime Niño3.4 index and WNP summer monsoon. In addition, a faster decaying pace of preceding-winter El Niño after the 1990s, which may be mainly induced by the influences from the spring tropical Atlantic SST anomalies, could also contribute to the enhanced correlation between the summertime Niño3.4 index and WNP monsoon. These results highlight the intensified influences from the tropical Atlantic SST in triggering a stronger summertime ENSO–WNP monsoon connection since the 1990s.

Previous studies have reported that CP-type El Niño has occurred more frequently in recent decades (e.g.
Yu, Lu, and Kim (2012; Yu et al. 2015). The emergence of CP-type El Niño may also have a close association with the influence from the tropical Atlantic SST (e.g. Ham et al. 2013; Yu et al. 2015; Wang, Yu, and Paek 2017), possibly involving a closer connection between ENSO and tropical Atlantic SST anomalies during recent decades. The phase change of the Atlantic Multidecadal Oscillation (AMO) (from a negative to positive phase) around the early 1990s may have contributed substantially to the enhanced influence of the tropical Atlantic on the Pacific climate during recent decades. For the tropical Indian Ocean SST, there are three possible reasons for the weakening of its association with the summertime Niño3.4 index after the 1990s. First, it may also be closely associated with the more frequent occurrence of CP-type El Niño. Previous results have revealed that tropical Indian Ocean SST anomalies exhibit a stronger connection with eastern Pacific (EP) El Niño than with CP El Niño (e.g. Yuan, Yang, and Zhang 2012). Thus, the increased frequency of CP-type El Niño during recent decades may have reduced the connection between the tropical Indian SST anomalies and summertime Niño3.4 index after the 1990s. Second, the faster decaying pace of El Niño during recent decades may have greatly weakened the warm tropical Indian Ocean SST anomalies in summer (Chen et al. 2018). In contrast, a later-decaying El Niño may support the tropical Indian SST anomalies in persisting for a longer time and to be more significant during the summer (e.g. Ren et al. 2016), which is also apparent in Figure 4. This is also consistent with the first reason, considering that CP El Niño tends to have a shorter lifetime and decays more rapidly than EP El Niño. Third, the intensity of the JJA tropical Indian SST variability has been observed to have weakened noticeably since the 1990s (Chen et al. 2018), which may also have mitigated the climatic influences from the summertime tropical Indian SST anomalies during recent decades.

In addition, it should be noted that zonal wind anomalies associated with the WNP summer monsoon could also feed back to ENSO and influence the following ENSO evolution (e.g. Weisberg and Wang 1997; Kim and Lau 2001). Fan et al. (2018) suggested that the AMO could modulate these ENSO–summer monsoon interactions significantly, with a stronger summer monsoon feedback to ENSO during positive AMO phases. Thus, it is also possible that the intensified correlation between summertime ENSO index and WNP summer monsoon results from stronger ENSO–monsoon interactions during recent decades, which needs to be investigated in more detail future studies.

Recent studies have shown an intensified impact of summertime ENSO Modoki SST anomalies on tropical cyclone (TC) genesis over the WNP after the early 1990s (Cao, Wu, and Xiao 2018; Liu and Chen 2018). The present results support the enhanced influence of summertime ENSO SST on WNP summer monsoon after the early 1990s. All of these results suggest that summertime ENSO SST anomalies may have been able to exert much greater influences on regional climate in the WNP region during recent decades, including both WNP TC and monsoon activities. These results should have important implications for WNP TC and monsoon outlooks based on climate predictions and projections. Considering that the WNP summer monsoon is an important medium for ENSO to influence WNP TC genesis, it may also be possible to understand the intensified relationship between summertime ENSO and WNP TC genesis number from the perspective of a stronger ENSO–WNP summer monsoon connection/interaction after the 1990s, which is another perspective different from the views of Cao, Wu, and Xiao (2018) and Liu and Chen (2018).

The present results suggest that enhanced influences from tropical Atlantic SST anomalies may have triggered the intensified correlation between summertime ENSO and WNP monsoon since the early 1990s. More studies are needed in the future to better understand the inter-basin interactions (interactions among the tropical Pacific, Atlantic and Indian Ocean basins) and their interdecadal changes, which are essential to better understand the variability in the Pacific climate, including the WNP summer monsoon and ENSO.

Acknowledgments

We thank the anonymous reviewers for their comments and suggestions, which helped to greatly improve the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Key Research and Development Program of China [grant number 2018YFC1506903]; the National Natural Science Foundation of China [grant number 41776031]; the Guangdong Natural Science Foundation [grant number 2015A030313796]; the program for scientific research start-up funds of Guangdong Ocean University, and the Foundation for Returned Scholars of the Ministry of Education of China.

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