Triple-Dip La Niña in 2020-22: Impact of Annual Cycle in Tropical Pacific SST

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Key Points:

- The triple-dip La Niña event in 2020-2022 is associated with the persistent easterly and southeasterly wind anomalies over the tropical Pacific.
- The persistent negative phase of the symmetric mode of annual cycle SST in the tropical Pacific maintains the easterly wind anomalies.
- The contrast of SST between the northern and southern hemispheres provides a favorable background for the southeasterly wind anomalies.

Abstract

The triple-dip La Niña in 2020-22 is characterized by persisting easterly and southeasterly wind anomalies over the tropical central and southeastern Pacific. Our results show that the wind anomalies are associated with two leading modes of the annual cycle (antisymmetric and symmetric modes) of sea surface temperature (SST). The first two modes account for 82.2% and 13.5% of total variances, linking to the seasonal swing of SST distribution in the northern and southern hemispheres and the temporal evolution of El Niño-Southern Oscillation (ENSO), respectively. The persistent negative phase of the symmetric mode enhances easterly wind, while the antisymmetric mode strengthens the southeasterly wind. The negative phase of the antisymmetric mode is regulated by the contrast of SST anomalies between the northern and southern hemispheres. Therefore, both the zonal and the meridional process associated with annual cycle anomalies may play an important role in the evolution of the triple-dip La Niña in 2020-22.

Plain Language Summary

El Niño-Southern Oscillation (ENSO) can be depicted by the interannual variation of the annual cycle sea surface temperature (SST) anomaly, which alternates between El Niño and La Niña. The La Niña phase usually persists for a longer period than the El Niño. The triple-dip La Niña in 2020-22 would be the first three-year La Niña since the 1998-2001 event. Previous studies suggested that the southeasterly wind over the central Pacific in spring would trigger the third-year La Niña in 2022.

In this study, we further point out that the persistent easterly and southeasterly wind anomalies over the tropical central and southeastern Pacific associated with the negative phase of annual cycle modes of SST are conducive to this event. Our results highlight the importance of the inconsistent of SST warming between the north and south Pacific to prolonged La Niña events.

Keywords: Triple-dip La Niña, Annual cycle anomaly, Sea surface temperature

1. Introduction

EI Niño-Southern Oscillation (ENSO) is the most prominent interannual signal of the tropical Pacific and has significant socioeconomic impacts (Timmermann et al., 2018). ENSO is characterized by sea surface temperature (SST) anomalies over the central and eastern equatorial Pacific, which develops during boreal spring and summer, reaches maturity during autumn and winter, and decays in the following spring. Such seasonal evolution is referred to as the ENSO and annual cycle phase-lock phenomena (Chen & Jin, 2020; Galanti E 2000; Jin et al., 1994; Rasmusson & Carpenter, 1982). The characteristics of the annual cycle in the central and eastern equatorial Pacific have been widely discussed (Horel, 1982; T. M. Li & Philander, 1996; Song et al., 2020; Tozuka & Yamagata, 2003; B. Wang, 1994; X. L. Wang, 1994; Shang-Ping Xie, 1994). The annual cycle mode of tropical Pacific SST can be decomposed into symmetric and antisymmetric modes (X. L. Wang, 1994). The symmetric mode directly affects ENSO by changing the zonal SST gradient, while the antisymmetric mode reflects the meridional gradient of SST, which affects

ENSO by modifying the cold tongue (B. Wang, 1994). Tozuka and Yamagata (2003) also investigated the annual ENSO, where the ENSO is interpreted as the interaction between two distinct modes of air-sea interaction: the annual ENSO mode and the interannual ENSO mode. Therefore, the influence of the annual cycle should be considered in the variability and predictability of ENSO (Shin et al., 2021).

ENSO has become more complex during the last few decades, including the intensity difference, asymmetric evolution, and flavor diversity (Z.-Z. Hu et al., 2020; Timmermann et al., 2018; Yeh et al., 2009). For instance, there have been fewer El Niño events and frequent La Niña events since the 1990s (R.-H. Zhang et al., 2022), and some La Niña events are usually followed by another La Niña (Z.-Z. Hu et al., 2014; Luo et al., 2017) or even persisted three years, such as 1973-76 and 1998-2001. Recently, persistent cold SST anomalies (SSTAs) have been occurring in the central and eastern equatorial Pacific since 2020, and it is another triple-dip La Niña event after 1998-2001 (Cates et al., 2022; Fang et al., 2023; Zheng et al., 2022). It has been argued that multi-year La Niña might be caused by westward propagation of reflected cold ocean temperature anomaly in the off-equatorial Pacific, the asymmetric response of the atmosphere due to climatological seasonal cycle, and inter-basin interaction with the Atlantic and Indian Oceans (DiNezio et al., 2017; Gao & Zhang, 2016; Z.-Z. Hu et al., 2014; Luo et al., 2017; C. Zhang et al., 2019; R.-H. Zhang et al., 2022). Both X. Li et al. (2022) and Fang et al. (2023) emphasized the role of persistent easterly wind anomalies in the triple-dip La Niña in 2020-22, while Hasan et al. (2022) indicated the contribution of inter-basin interaction. But it is unclear for the role of the annual cycle anomalies in the La Niña in 2020-22, in the context of heterogenic warming trends in the tropical Pacific (Gao et al., 2022).

The evolution of ENSO is related to the zonal SST gradient across the tropical Pacific, however, due to the differences in land and sea distribution and heat content, the warming trend in the northern hemisphere is stronger than in the southern hemisphere (Cavalieri et al., 1997; Flato & Boer, 2001), and increasing meridional temperature gradient may strengthen cross-equatorial winds. The cross-equatorial winds can affect ENSO variation (Shang-Ping Xie et al., 2018), leading to a "La Niña-like" change in the tropical Pacific (S. Hu & Fedorov, 2018). Recently, Fang et al. (2023) argued that the meridional processes in the eastern Pacific are important to trigger a third-year La Niña event in 2022-23. The meridional processes seem associated with the antisymmetric mode of annual cycle SST which could be an important factor in the occurrence of the triple-dip La Niña in 2020-22. In the present study, we intend to examine the interannual variability of annual cycle SST in the tropical Pacific associated with ENSO, and try to discuss its role in the triple-dip La Niña event in 2020-22, as well as the contribution of the meridional SST gradient.

2. Data and Methods

We use the daily Optimum Interpolation SST (OIv2.1) records from the National Oceanic and Atmospheric Administration (NOAA) with a 0.25°×0.25° grid in a period of 1982-2022 (Reynolds et al., 2007). The atmospheric components are from the daily JRA-55 Reanalysis dataset, released by the Japanese Meteorological Agenda, with a horizontal resolution of 1.25°×1.25° for the period of 1982-2022 (Kobayashi et al., 2015). The monthly mean outgoing longwave radiation (OLR) is provided by NOAA, with a horizontal resolution of 2.5°×2.5° (Liebmann & Smith, 1996).

Here, the period of the annual cycle is defined as from July to June of the next year. Empirical orthogonal function (EOF) analysis is applied to show the annual cycle modes of climatological SST in the tropical Pacific. The climatology is defined as the 30-yr average between 1991 and 2020. The statistical methods used include Student's t-test, partial correlation, and linear regression. The ENSO events are defined when the 3-month running-mean Niño 3.4 index (averaged SSTA in the region of 5°S-5°N, 120°W-170°W) is above the threshold of 0.5°C for 5 consecutive months, consistent with the NOAA Climate Prediction Center's definition. Here, winter is defined from December to February of the next year (DJF). The results are not sensitive to the selections of different data sets and different periods of climatology.

3. Time evolution of triple-dip La Niña in 2020-22

Figure 1a shows that the Niño 3.4 index has been in a negative phase since the middle of 2020. Except for the summer of 2021, the index value was lower than the threshold of -0.5°C from the mid of 2020 until the end of 2022, implying a triple-dip La Niña event. The fluctuations of the Niño 3.4 index and SSTAs along the equatorial Pacific are coherent with the variations of zonal wind anomalies along the equator

(Figure 1). For example, the strengthening of the easterly wind over the central tropical Pacific in the autumn of 2020 is linked to the decline of the Niño 3.4 index, and SST cooling in the central and eastern tropical Pacific, sustaining the cold SST condition by the Bjerknes positive feedback (Bjerknes, 1969). On the other hand, there have also been meridional wind anomalies over the central tropical Pacific since the winter of 2019 (Figure 1a). It seems also important in triggering and evolution of a La Niña event (Fang et al., 2023).

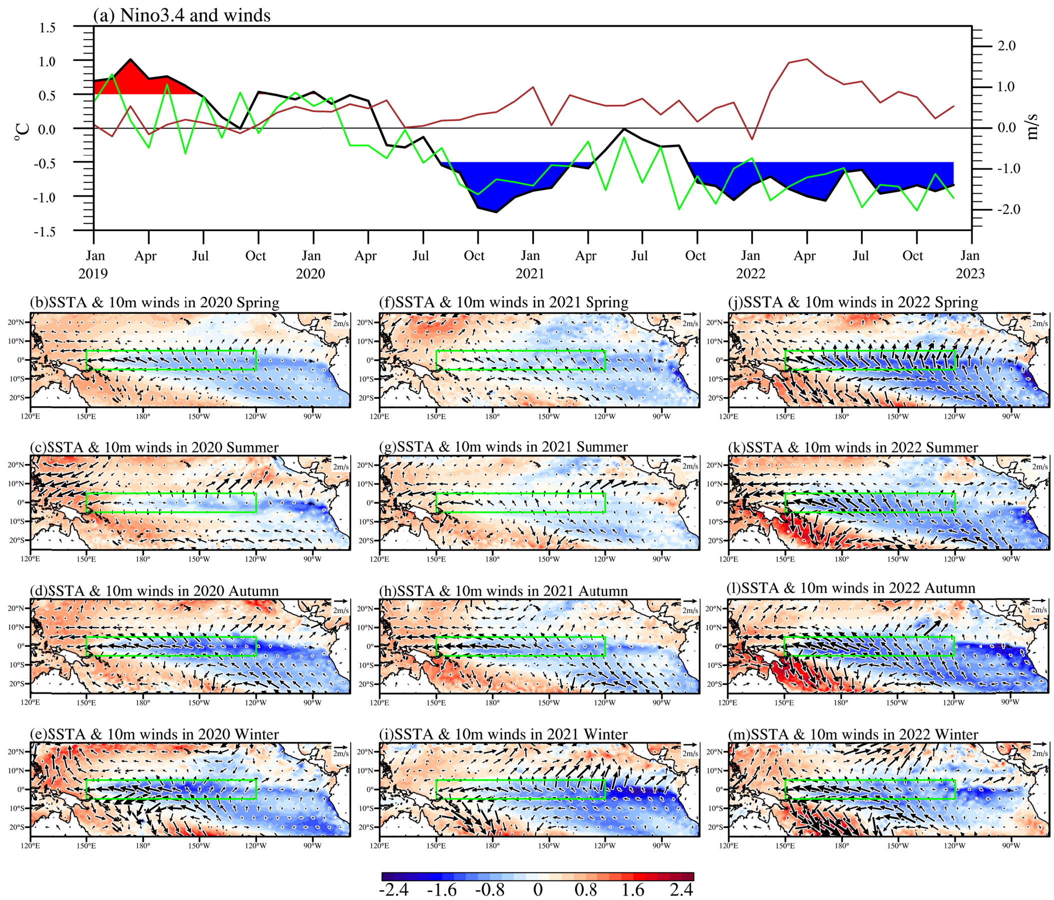

Figure 1. (a) Time series of Niño3.4 index (black line), averaged zonal wind anomaly (green line) and meridional wind anomaly (brown line) in the region of green box (5°S-5°N, 150°E-120°W) during 2019-2022. Horizontal distributions of seasonal SSTA (shading; ℃) and 10m winds anomalies (vector; m/s) for (b-e) 2020, (f-i) 2021, (j-m) 2022.

In autumn 2020, a La Niña pattern developed, characterized by strong trade wind over the central equatorial Pacific and southeasterly wind over the southeastern Pacific (Figure 1d). A similar anomaly pattern occurred in autumn 2021 and autumn 2022 (Figure 1h, l). There was a turning point in the summer of 2021, and the cold SSTA weakened, accompanied by weak southeasterly wind over the central equatorial Pacific (Figure 1g). The southeasterly wind further strengthens in the next season (Figure 1h). Thus, the easterly over the central equatorial Pacific and southeasterly wind anomalies over the southeastern Pacific could be the important factors for the evolution of the triple-dip La Niña in 2020-22.

4. Impacts of annual cycle SST modes

The seasonal mean SSTAs in the central and eastern tropical Pacific are negative during 2020-22. Spatially, in addition to the zonal SSTA gradient, there are appreciable meridional SSTA gradients in the tropical Pacific (Figure 1), which may be related to the two leading modes of the annual cycle in the tropical Pacific. Thus, there could be a linkage between the annual cycle of SSTA in the eastern Pacific and prolonged La Niña in 2020-22.

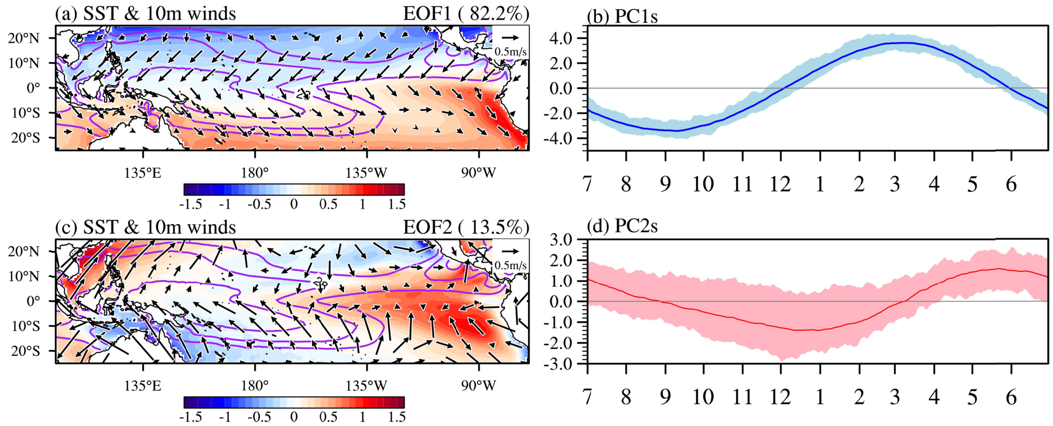

Figure 2. The EOF analysis of tropical Pacific daily mean climatological SST in the region of 100° E-70°W, 25°S-25°N. (a, c) The two leading EOF modes of SST (shading; ℃) and the PCs-regressed surface wind (vectors; m/s). The purple lines in (a, c) indicate the annual mean SST. (b, d) shows the first (PC1, solid blue line) and the second (PC2, solid red line) PC of the annual cycle modes and their interannual variability (blue and red shades) from 1982-2022.

The essential characteristic of the annual cycle SST and ENSO seasonality can be described by the first two EOF modes of the annual cycle of the climatological SST in the tropical Pacific (Figure 2). EOF1 shows an antisymmetric mode, which accounts for 82.2% of the total variance of SST. This mode is associated with the annual cycle of solar radiation and represents the reverse change of SST between the northern and southern hemispheres (Kim & Chung, 2001; B. Wang, 1994; X. L. Wang, 1994). Due to the huge thermal inertia of the ocean, the corresponding principal component (PC1) lags solar radiation for about 2-3 months (Figure 2b) and reaches its peak in March (the winter solstice occurs in late December). At this time, the SST gradient between the northern and southern hemispheres is the largest, and the trans-equatorial northerly wind prevails in the tropical Pacific (Figure 2a). Under the influence of the Coriolis force, the northeast winds turn to northwest winds from the northern hemisphere to the southern hemisphere. In the positive phase of PC1, the weakened southeasterly trade winds off the coast of Peru can reduce the wind evaporation feedback cooling due to reduced wind speed (Shang-Ping Xie & Philander, 1994) and suppress the upwelling of the eastern tropical Pacific. On the other hand, the loading of the annual cycle mode is small in the warm pool region in the western tropical Pacific where SSTs exceed 28℃ and the seasonal variation is weak.

EOF2 represents a symmetric variation to the equator in the central and eastern tropical Pacific (Figure 2c), with main loadings in the eastern equatorial Pacific which is the main region associated with ENSO. This mode reaches its peak in May, lagging PC1 by two months. The center of the warming is around 95°W along the equator, where the thermocline is shallowest (Meyers, 1979).

The two leading modes explain 95.7% of the total variance of annual cycle SST, which can capture the basic characteristics of the climatological seasonal evolution of SST in the tropical Pacific. To obtain the interannual variation of the annual cycle, the observed SSTs in each year are projected into the EOF1 and EOF2 of climate state (shading in Figure 2b, d). Here, PC1A (PC2A) is defined as the difference between PC1 (PC2) for each year and climatic PC1 (PC2). Since PC2A shows large interannual fluctuations in the winter and the largest loading of EOF2 is in the central and eastern equatorial Pacific, thus this mode is related to ENSO. The correlation coefficient between PC2A and Niño 3.4 index is 0.84 (Figure 3b), implying that the interannual variation of EOF2 is associated with the ENSO evolution. Interestingly, PC1A is positively correlated with PC2A (Figure 3c) which is significant at a 99% level and suggests some non-orthogonality between the interannual modulation of symmetric mode and antisymmetric mode of annual cycle anomalies.

We compute partial correlation to investigate the relationship of the PC1A and PC2A with ENSO events. When excluding the PC1A component, PC2A shows an ENSO pattern (Figure 3e). The positive (negative) phase of symmetric mode (EOF2) is associated with the decrease (increase) in the zonal pressure gradient, westerly (easterly) wind anomaly, and positive (negative) SSTA in the central and eastern tropical Pacific. During the last three years, PC2A was in a negative phase and showed a downward trend just like the Niño 3.4 index (Figures 1a, 4b), meaning that the development of La Niña is related to the strengthening of the trade wind over the central tropical Pacific.

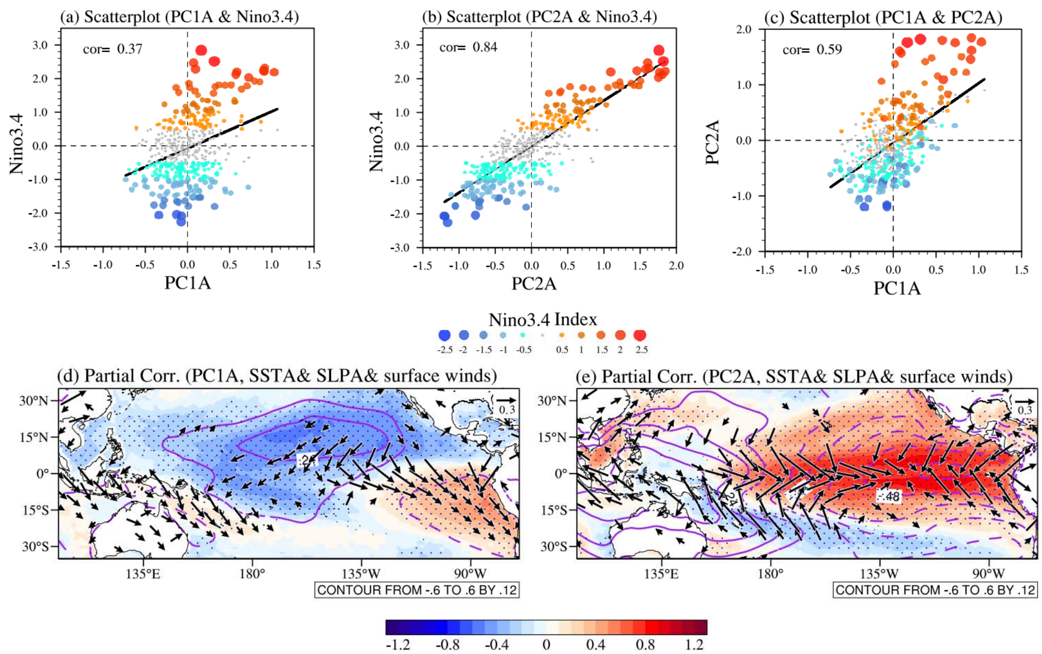

Figure 3. (a-c) are the scatterplots of PC1A and Niño 3.4 index, PC2A and Niño 3.4 index, and PC1A and PC2A, respectively. Their linear relationship was shown by the black line. The color and size of the dots represent the value of the Niño 3.4 index (greater than 0.5 for red, less than -0.5 for blue, and others for gray). (d-e) The partial correlation of PC1A and PC2A with SSTA (shading), SLPA (contour), and surface winds (vectors) from 1982-2022. The black vector arrows, contour, and stippling indicate the region where the correlation coefficient is statistically significant at the 95% confidence level.

When excluding the PC2A component, PC1A has a significant partial correlation with the SSTA in the southeastern and northern Pacific. The positive phase of PC1A is associated with an anomalous northwestern-southeastern gradient of SLP in the east of the dateline (Figure 3d). The anomalous SLP gradient is associated with the northwesterly wind anomalies over the southeastern Pacific, which reduces the southeasterly trade winds and suppresses the upwelling along the coast of Peru. Previous research has emphasized the contribution of SSTA in the southeastern Pacific in the evolution of ENSO (H. Zhang et al., 2014; Zhu et al., 2016). Interestingly, the PC1A has been in the negative phase since early 2019 (Figure 4a), which is conducive to the persistent southeasterly wind prevailing over the southeastern Pacific. The southeasterly wind anomalies over the southeastern Pacific favor the persistence of La Niña condition. This suggests that the antisymmetric (EOF1) mode may also play a role in the prolonged La Niña event in 2020-22.

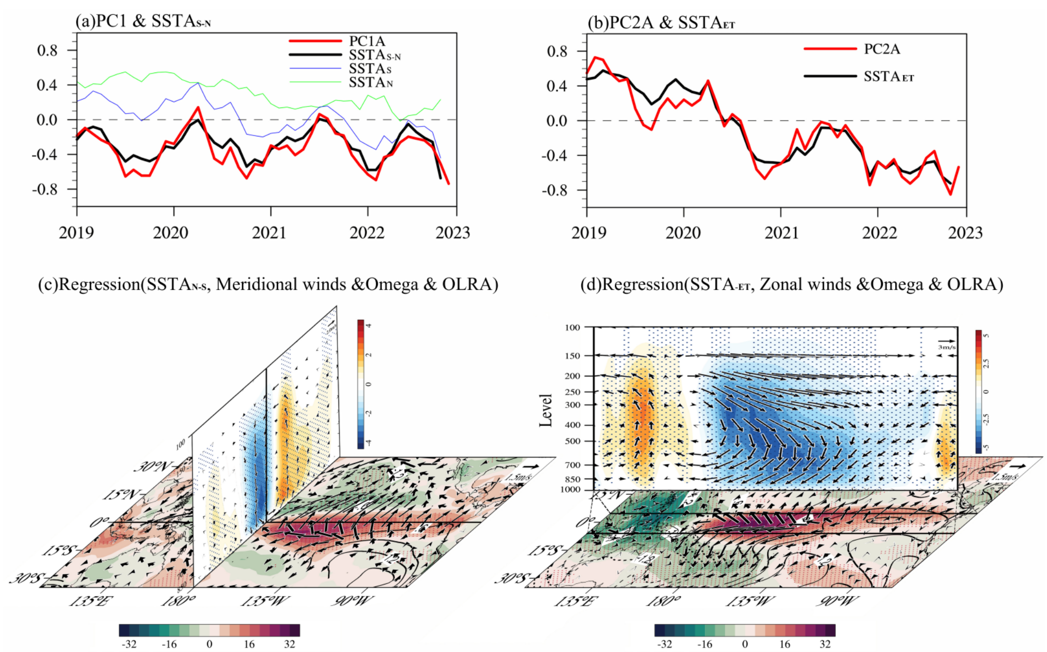

Figure 4. (a) The time series of SSTA in the northern tropical Pacific (SSTA_N, averaged in 0°-25° N, 110°E-80°W) and SSTA in the southern tropical Pacific (SSTA_S, averaged in 25°S-0, 110°E-80° W) and the difference between them (SSTA_{S-N}) and PC1A during 2019-2022; (b) The time series of SSTA in eastern tropical Pacific (SSTA_{ET}, averaged in 15°S-15°N, 180°E-80°W) and PC2A during 2019-2022. The SST A_{N-S} regressed (c) pressure velocity (vertical shading; omega*-100Pa/s), meridional circulation (vectors; m/s) in the eastern Pacific (averaged in 180° E-80°W), SLPA (contour; hPa) and OLRA (horizontal shading; W/m^2) from 1982 to 2022; the SSTA_{-ET} regressed (d) pressure velocity, zonal circulation in the tropical Pacific (averaged in and 5°S-5°N), SLPA and OLRA from 1982 to 2022. The stippling and vector and contour in (c-d) indicate the region where the regression coefficient is statistically significant at the 95%

confidence level.

The antisymmetric mode is associated with the seasonal evolution of the SST between the northern and southern hemispheres, which is represented by the SST difference between the southern (25°S-0,110°E-80°W) and northern (0-25°N, 110°E-80°W) tropical Pacific (SSTA_{S-N}). The correlation coefficient between $SSTA_{S-N}$ and PC1A during 1982-2022 is 0.82 and significant at a 99% level. The index is negative in the recent three years (Figure 4a), which is consistent with the triple-dip La Niña in 2020-22.

In addition to that the overall warming trend is larger in the northern hemisphere than in the southern hemisphere (IPCC, 2021), the SSTA in the southern tropical Pacific ($SSTA_S$) has even shown a cooling trend in recent years (Figure 4a), as a result, the negative $SSTA_{S-N}$ persists and induces an anomalous meridional gradient of SLP in the east of the dateline (Figure 4c). The anomalous SLP gradient is favorable for maintaining the anomalous southeasterly over the eastern tropical Pacific in the recent three years. The southeasterly wind anomalies over the southeastern Pacific enhance the wind speed and cool down SST (Figure not shown) which (Figure 3d) can in turn further strengthen southeasterly wind, a wind-evaporation-SST feedback (Shang-Ping Xie et al., 2009). Thus, the spatially heterogeneous warming trends may also have an impact on the triple-dip La Niña in 2020-22. The anomalous SLP gradient and the cross-equatorial meridional wind associated with negative $SSTA_{S-N}$ also produce an anomalous vertical circular circulation, which causes a weakening of the Hadley cell.

The anomalous downward (upward) motion over the eastern south (north) Pacific is in agreement with the OLR anomalies (Figure 4c).

On the other hand, the symmetric mode is associated with the seasonal evolution of SST in the eastern tropical Pacific (15°S-15°N, 180°E-80°W). The correlation coefficient between SSTA_{ET} and PC2A is 0.92 and significant at a 99% level. The index is negative since the summer of 2020 (Figure 4b), linked to the strengthened trade wind over the central tropical Pacific via increasing the zonal SLP gradient (Figure 4d). The anomalous easterly wind and SLP gradient also strengthen the Walker circulation, accompanied by increased convection over the Maritime Continent. Thus, both the zonal wind associated with the symmetric and the meridional wind associated with the antisymmetric mode are conducive to the triple-dip La Niña in 2020-22.

5. Summary and Discussion

It has been pointed out that the persistent southeasterly winds over the tropical Pacific played a crucial role in the triple-dip La Niña in 2020-22 (Fang et al., 2022, 2023). From the annual cycle SST perspective, we further analyzed the connection of the triple-dip La Niña event in 2020-22 with the anomalies of leading annual cycle modes. We argued that the easterly and southeasterly wind anomalies over the central and southeastern Pacific were associated with the anomalies of two leading annual cycle modes of SST.

The annual cycle SST in the tropical Pacific can be largely described by antisymmetric and symmetric modes. The symmetric mode with loading mainly in the central and eastern tropical Pacific links to the temporal evolution of ENSO. Its positive (negative) phase is associated with weakened (enhanced) zonal SLP gradient and reduced (strengthened) trade winds over the central and eastern equatorial Pacific, and El Niño (La Niña) condition. While the antisymmetric mode with loading mainly in the off-equatorial Pacific reflects the seasonal meridional migration of SST between the northern and southern hemispheres. In its positive (negative) phase, the north-to-south SST gradient decreases (increases), which is associated with the weakening (strengthening) of the southeasterly wind over the southeastern and central and eastern equatorial Pacific, favorable for the growth of positive (negative) SSTA and El Niño (La Niña) in the central and eastern equatorial Pacific. The modes are both in negative phases since 2019 and are favorable for the development of the triple-dip La Niña event.

The spatial heterogeneity of warming trends may affect the SST contrast between the southern and northern hemispheres. That may modulate ENSO evolution (S. Hu & Fedorov, 2018). In the scenario of the increase in the SST contrast between the north and south Pacific in the future warming, more frequent prolonged La Niña events might be expected.

Acknowledgments

This study was jointly supported by the National Natural Science Foundation of China (41830969, U2242205), the S & T Development Fund of CAMS (2022KJ008), and the Basic Scientific Research and Operation Foundation of CAMS (2021Z004).

Data Availability Statement

The daily SST of the NOAA OIv2.1 SST high-resolution dataset is downloaded from https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html. The monthly mean outgoing longwave radiation (OLR) from the U.S. NOAA is downloaded from https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html. The JRA - 55 reanalysis dataset is obtained from the National Center for Atmospheric Research, Computational and Information Systems Laboratory (https://doi.org/10.5065/D6HH6H41).

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