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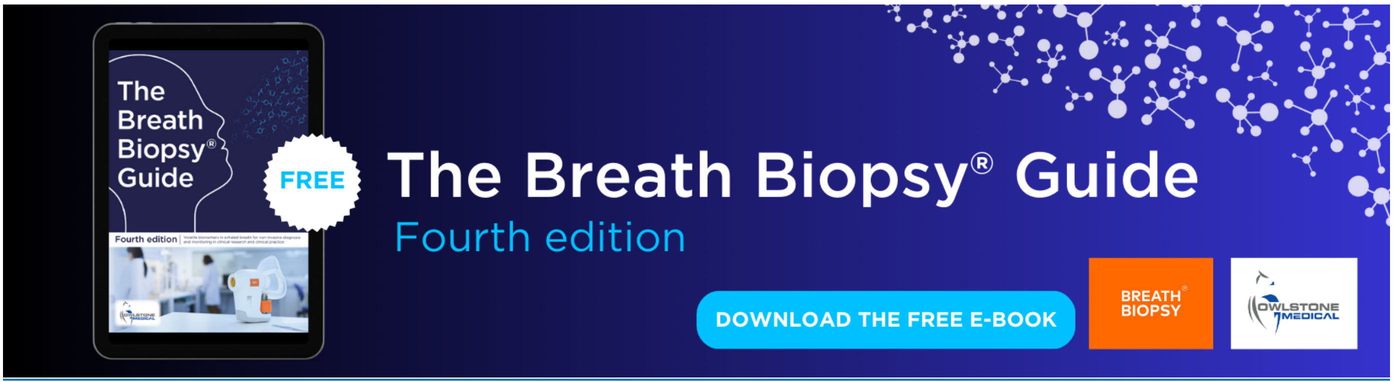

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LETTER

Triple-dip La Niña in 2020–23: understanding the role of the annual cycle in tropical Pacific SST

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Abstract

The triple-dip La Niña in 2020–23 is characterized by persisting southeasterly wind anomalies over the tropical central and eastern Pacific. Our results show that the wind anomalies are associated with the anomalously negative phase of the first two leading modes of the annual cycle (antisymmetric and symmetric modes about the equator) of sea surface temperature (SST) in the tropical Pacific. The two modes account for 82.2% and 13.5% of the total variance, linking to the seasonal swing of SST between the northern and southern hemispheres and the temporal evolution of El Niño-Southern Oscillation, respectively. During 2020–23, the persistently and anomalously negative phase of the symmetric mode enhances easterly wind over the tropical central Pacific, while the antisymmetric mode strengthens the southeasterly wind over the tropical eastern Pacific. The anomalously negative phase of the antisymmetric mode is associated with the contrast of SST anomalies between the northern and southern hemispheres, which provided a favorable background for the triple-dip La Niña in 2020–23.

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, it generally 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-locking phenomena (Rasmusson and Carpenter 1982, Jin *et al* 1994, Galanti and Tziperman 2000, Chen and Jin 2020). The characteristics of the annual cycle in the central and eastern equatorial Pacific have been widely discussed (Horel 1982, Xie 1994, Wang 1994a, 1994b, Li and Philander 1996, Tozuka and Yamagata 2003, Song *et al* 2020). For example, Wang (1994b) suggested that the annual cycle of tropical Pacific SST can be decomposed into quasi-symmetric equatorial-coastal and antisymmetric modes about the equator. The symmetric mode 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 (Wang 1994a). Conversely, ENSO modulates the amplitude of the annual cycle in the central and eastern tropical Pacific through the change of thermocline depth and upwelling (Gu and Philander 1995, Xie 1995). The annual and interannual phenomenon of ENSO are closely linked to each other, as a result of the air–sea interaction between the annual and the interannual mode (Tozuka and Yamagata 2003). Therefore, the influence of the annual cycle of SST should be considered in the variability and predictability of ENSO (Shin *et al* 2021).

ENSO has undergone remarkable changes over the past decades, including the intensity, persistence barrier, asymmetric evolution, and flavor diversity

(Yeh *et al* 2009, Jiang and Zhu 2018, Timmermann *et al* 2018, Hu *et al* 2020, Gan *et al* 2023, Jiang *et al* 2023). For instance, there have been fewer El Niño events and frequent La Niña events since the 1990s (Zhang *et al* 2022). ENSO evolution is asymmetric. For example, La Niña events are usually lasted for two years (Hu *et al* 2014, Luo *et al* 2017, Gao *et al* 2023) or even persisted for three years (triple-dip events), such as the event in 1973–76 and 1998–2001. The persistent cold SST anomalies have been observed in the central and eastern equatorial Pacific since 2020, indicating a new triple-dip La Niña event after 1998–2001 (Jones 2022, Fang *et al* 2023, Zheng *et al* 2023). It has been argued that multi-year La Niña might be related to the westward propagation of cold sea temperature anomaly in the off-equatorial Pacific caused by the reflected Rossby wave on the eastern boundary of the Pacific Ocean, the asymmetric response of the atmosphere due to seasonal cycle in climatology, and inter-basin interaction with the Atlantic and Indian Oceans (Hu *et al* 2014, Gao and Zhang 2016, DiNezio *et al* 2017, Luo *et al* 2017, Zhang *et al* 2019, 2022). For the triple-dip La Niña in 2020–23, both Li *et al* (2022) and Fang *et al* (2023) emphasized the role of persistent easterly wind anomalies, while Hasan *et al* (2022) indicated the contribution of inter-basin interaction. Nevertheless, it is unclear for the role of the annual cycle of SST anomalies in the La Niña in 2020–23, in the context of distinct warming trends in the tropical Pacific (Gao *et al* 2022).

The evolution of ENSO is usually related to the zonal SST anomaly (SSTA) gradient across the tropical Pacific. However, due to the differences in land-sea distribution and heat content, the warming trend in the northern hemisphere is stronger than in the southern hemisphere (Cavalieri *et al* 1997, Flato and Boer 2001), and the increasing meridional temperature gradient may strengthen cross-equatorial winds. The cross-equatorial winds can affect ENSO variation (Xie *et al* 2018), leading to a 'La Niña-like' change in the tropical Pacific (Hu and Fedorov 2018). Recently, Fang *et al* (2023) argued that the meridional wind stress anomaly in the eastern Pacific is important to trigger a third-year La Niña event in 2022–23. We speculated that the meridional SST gradient is possibly 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 2020–23. In the present study, we examine the interannual variability of annual cycle SST in the tropical Pacific associated with ENSO, and discuss its role in the triple-dip La Niña event in 2020–23, as well as the contribution of the meridional SST gradient.

2. Data and methods

We use the daily Optimum Interpolation SST (OIv2.1) from the National Oceanic and Atmospheric Administration (NOAA) with a 0.25° × 0.25° grid in a period of 1982–2022 (Huang *et al* 2021). The atmospheric variables are from the daily JRA-55 Reanalysis, released by the Japanese Meteorological Agency, with a horizontal resolution of 1.25° × 1.25° during 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 and Smith 1996). The monthly subsurface ocean data from the NCEP Global Ocean Data Assimilation System (GODAS; Behringer 2007) are used for the heat budget analysis in the present study.

Here, the period of the annual cycle is defined as from July to June of the next year. The climatology is defined as the 30 yr average between 1991 and 2020. Empirical orthogonal function (EOF) analysis is applied to reveal the annual cycle modes of climatological SST in the tropical Pacific and its climatological principal component (CPC). The observed SSTs in each year are projected into the first two EOF modes to obtain the PCs in each year. The PC anomaly (PCA) is defined as the departure between PC in each year and CPC.

The annual declination of the Sun moves between 23 °26′N and 23 °26′S, which is calculated according to the following equation (Yu 2006):

$$\delta = 0.006918 - 0.399912 \times \cos b + 0.010257 \times \sin b - 0.006758 \times \cos 2b + 0.000907 \times \sin 2b$$

where $b = 2 \times \pi \times N/365$, δ is the declination and N is the Julian day (e.g. $N = 1$ on January 1, $N = 365$ on December 31).

The used statistical methods include Student's *t*-test, partial correlation, and linear regression. The La Niña event is defined when 3 month running-mean Niño 3.4 index (averaged SSTA in the region of 5°S–5°N, 120°W–170°W) is below the threshold of −0.5 °C for five consecutive overlapping seasons, consistent with the NOAA Climate Prediction Center's definition. Here, the boreal spring, summer, autumn and winter are referred to the season from March to May, June to August, September to November and December to February (DJF) of the next year, respectively.

Here we diagnose the oceanic mixed layer heat budget to examine the contributions of different physical processes during the La Niña evolution. The mixed layer depth (MLD) is defined as the depth where the sea temperature is 0.5 K lower than the SST (Cronin *et al* 2008, Liu *et al* 2021). In the mixed layer, sea temperature and salinity are fully mixed due to the wind perturbation and buoyancy loss. The MLD in the tropical Pacific has a seasonal variation, deeper in winter and shallower in summer, and the average depth in Niño 3.4 region is about 74.4 m (figure not shown). The oceanic mixed layer heat budget is diagnosed using the GODAS monthly data with the following equation (Hu and Fedorov 2018):

$$T'_t = -\left\{\left(\bar{u}T'_x + u'\overline{T_x} + u'T'_x\right) + \left(\bar{v}T'_y + v'\overline{T_y} + v'T'_y\right) + \left(\bar{w}T'_z + w'\overline{T_z} + w'T'_z\right)\right\} + \frac{Q'_{\mathrm{net}}}{\rho C_p H} + R$$

where T, u, v, and w correspond to the potential temperature, zonal, meridional, and vertical current velocities averaged over the mixed layer, respectively. Q_{net} is net surface heat flux. The terms $\rho = 1025\ \mathrm{kg\,m^{-3}}$, $C_p = 3850\ \mathrm{J\,kg^{-1}\,K^{-1}}$, and H are the reference density of seawater, the specific heat of seawater, and the MLD, respectively. Bars and primes denote climatologic mean variables and anomaly departures from climatological means, respectively. R represents any unresolved processes like turbulent mixing.

3. Result

3.1. Time evolution of triple-dip La Niña in 2020–23

Figure 1(a) shows that the Niño 3.4 index has been negative since July 2020. Except for the summer in 2021, the index value is lower than −0.5 °C from July 2020 until at least DJF 2022–23, implying a triple-dip La Niña event. The fluctuations of the Niño 3.4 index and SSTA along the equatorial Pacific are coherent with the variations of 10 m winds 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 the SST cooling in the central and eastern tropical Pacific, sustaining the cold SST condition by the Bjerknes positive feedback (Bjerknes 1969). In addition, the persistent meridional wind anomalies over the central tropical Pacific since 2019 (figure 1(a)) is also an important contribution to the evolution of the La Niña event (Fang *et al* 2023).

In autumn 2020, the La Niña pattern developed, characterized by strong trade wind over the central equatorial Pacific and southeasterly wind over the southeastern Pacific (figure 1(d)). A similar anomaly pattern occurred in autumn 2021 and 2022 (figures 1(h) and (l)). The turning point is observed in the summer of 2021, when the cold SSTA weakened, accompanied by weak southeasterly wind anomaly over the central equatorial Pacific (figure 1(g)). The southeasterly wind strengthened in the following season and persisted to the winter of 2022–23 (figures 1(h)–(m)). Thus, the easterly and southeasterly wind anomalies over the tropical Pacific are linked to the evolution of the triple-dip La Niña in 2020–23.

3.2. Oceanic mixed layer heat budget analysis

To quantify the contribution of the dynamic and thermodynamic processes to the triple-dip La Niña event, we conducted a heat budget analysis of the mixed-layer ocean temperature averaged over the Niño3.4 region during the La Niña development phase (July–October). There was a short warming in the summer of 2021, but the cold condition quickly returned in the autumn of 2021 (figures 1(g) and (h)). Thus, the T'_t was still large in 2021. Subsequently, it maintained a small tendency in 2022 (figure 2), consistent with the small fluctuation of the Niño3.4 index (figure 1(a)).

Overall, the largest contribution to the cooling was from the advection of climatological mean temperature by the zonal current anomaly ($-u'\overline{T_x}$), the zonal advective feedback (figure 2). Meanwhile, the contribution of the Ekman feedback ($-w'\overline{T_z}$) was also relatively strong, especially in 2021 and 2022. In contrast, the role of the thermocline feedback ($-\bar{w}T'_z$) and the vertical nonlinear term ($-w'T'_z$) were not conducive to the development of La Niña, especially in 2022. It implies that the vertical entrainment and diffusion made little contribution to the development of 2020–23 La Niña.

Interestingly, it was noted that the meridional advection terms were also important contributors to the development of cold tendency, especially the linear advection of climatological mean temperature by the meridional current anomaly ($-v'\overline{T_y}$), which stayed in the negative value during 2020–23 (figure 2). The net surface heat flux (Q'_{net}) largely damped La Niña development, in agreement with Zhang *et al* (2007). Therefore, the diagnostic results further suggested that the zonal and meridional advection components over the tropical Pacific play a key role in the triple-dip La Niña evolution, while the vertical entrainment and diffusion play a secondary role.

3.3. Impacts of annual cycle SST modes

The seasonal evolution of SST anomalies shows a zonal and meridional SSTA gradient with negative anomalies confined in the central and eastern tropical Pacific (figures 1(b)–(m)), supported by the heat budget analysis. It has been shown the zonal and meridional SST gradients are closely associated with the first two leading modes of the annual cycle of SST in the tropical Pacific (Wang 1994a, 1994b), implying a possible linkage between the interannual variability of annual cycle SST in the tropical Pacific and prolonged La Niña in 2020–23.

The ENSO seasonality can be described by the first two EOF modes of the annual cycle of the climatological SST in the tropical Pacific (figure 3). The EOF1 shows a meridionally antisymmetric pattern, 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 (Wang 1994a, 1994b, Kim and Chung 2001). Due to the relatively large thermal inertia of the ocean,

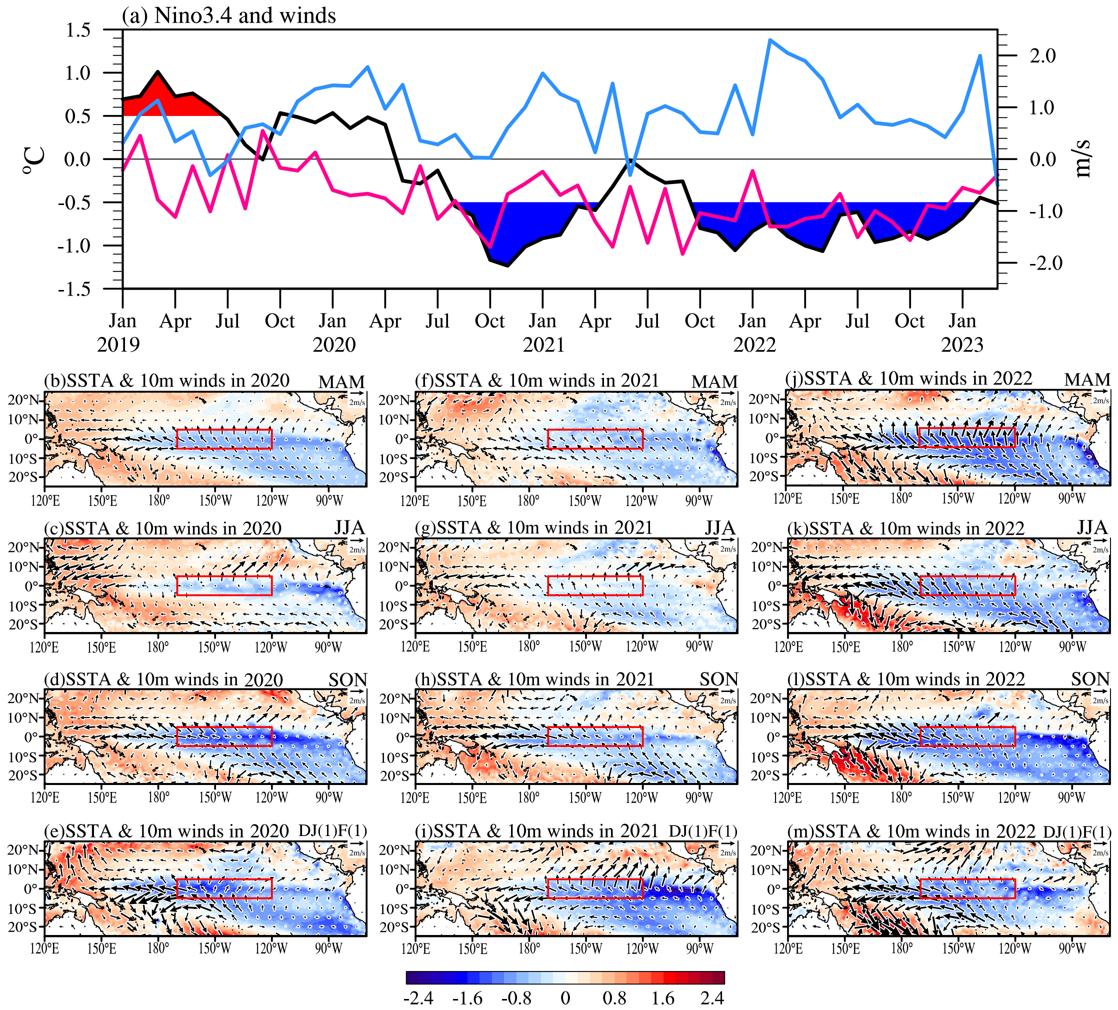

Figure 1. (a) Time series of Niño3.4 index (black line), averaged zonal wind anomaly (red line) and meridional wind anomaly (blue line) in the Niño 3.4 region (red box) during 2019–2022. Horizontal distributions of SST (shading; °C) and 10 m winds (vector; m s^{-1}) anomalies for (b)–(e) 2020, (f)–(i) 2021, (j)–(m) 2022.

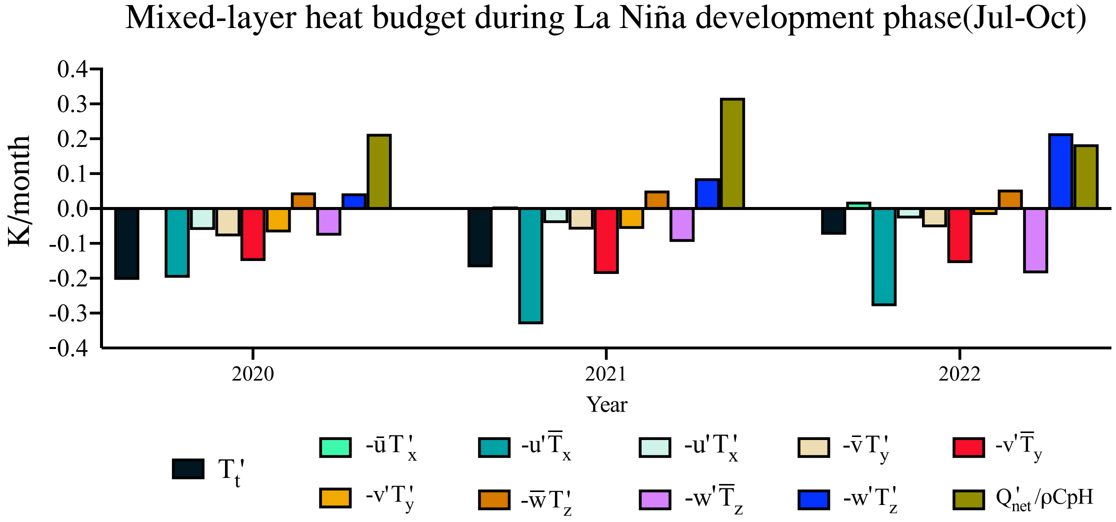

Figure 2. The mixed-layer temperature tendency, the net surface heat flux term, the zonal and meridional advection terms, and vertical entrainment and diffusion terms (unit: K month^{-1}) averaged over the Niño 3.4 region during the La Niña development phase (July–October).

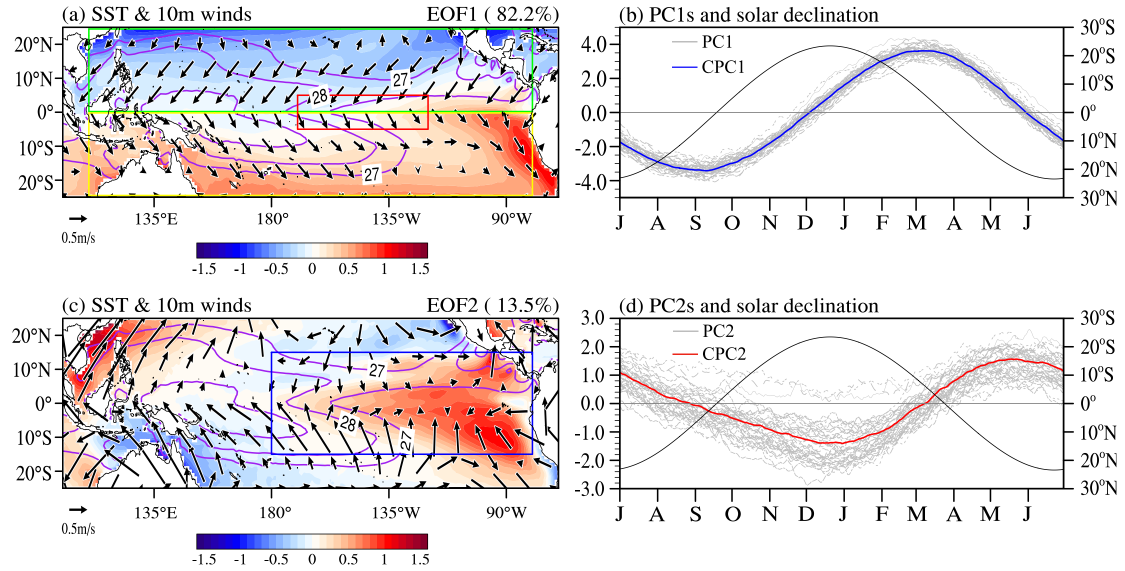

Figure 3. The EOF analysis of tropical Pacific daily mean climatological SST in the region of 100° E–70° W, 25° S–25° N. (a) and (c) The two leading EOF modes of SST (shading; °C) and the climatological principal components (CPCs)-regressed 10 m winds (vectors; m s^{-1}). The purple lines in (a), (c) indicate the climatological annual mean SST. The red, green, yellow, and blue boxes in (a), (c) represent the Niño 3.4 region, northern tropical Pacific region (0°–25° N, 110° E–80° W), southern tropical Pacific region (25° S–0°, 110° E–80° W) and eastern tropical Pacific region (15° S–15° N, 180°–80° W), respectively. Figures (b) and (d) shows the first (CPC1, solid blue line) and the second (CPC2, solid red line) CPC of the annual cycle modes and the PCs of each year (gray lines) from 1982 to 2022. The black line in (b), (d) indicates the annual cycle of solar declination.

the climatological PC1 (CPC1) lags the solar radiation cycle by about 2–3 months (figure 3(b)), and it reaches the peak in March, corresponding to the largest SST gradient between the northern and southern hemispheres and the trans-equatorial northerly wind prevails in the tropical Pacific (figure 3(a)). Under the influence of the Coriolis force, the northeasterly winds turn to the northwesterly from the northern hemisphere to the southern hemisphere. In the positive CPC1, the weakened southeasterly trade winds off the coast of Peru can reduce the wind evaporation feedback cooling with reduced wind speed (Xie and Philander 1994) and suppress the upwelling in 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 °C and the seasonal variation is weak (Wang 1994a).

EOF2 represents a symmetric variation to the equator in the central and eastern tropical Pacific (figure 3(c)), with large loadings in the eastern equatorial Pacific. It accounts for 13.5% of the total variance of SST, and reaches its peak in May, lagging CPC1 by two months. The warming center is located around 95° W along the equator, where the thermocline is shallow (Meyers 1979).

In addition to the annual cycle of SST in climatology, the first two modes also show distinct interannual variability in each year. The interannual variability of PC1 is quite small compared to PC2 (figure S1(a)), and the PC1 anomaly (PC1A) mainly reflects the change of El Niño-like pattern in annual mean SST anomalies (figure S1(b)). That implies that the antisymmetric mode mainly affects the phase of ENSO via the mean state changes in tropical Pacific SST. PC2 with a large interannual variability in winter (figures 3(d) and S1(a)) and the maximum loading of EOF2 in the central and eastern equatorial Pacific, implying a potential link to ENSO. The correlation coefficient between PC2 anomaly (PC2A) and Niño 3.4 index is +0.84 (figure 4(b)), implying that the interannual variation of EOF2 is associated with the ENSO evolution. Interestingly, PC1A is positively correlated with PC2A (figure 4(c)) which is significant at a 99% level and suggests the strong connection between the two modes on interannual variability.

We compute partial correlation to investigate the connection of PC1A and PC2A with ENSO, represented by the Niño 3.4 index. After excluding the PC1A, the correlations with PC2A show an ENSO pattern (figure 4(e)). The positive phase of symmetric mode is associated with the decrease in the zonal sea level pressure (SLP) gradient, westerly wind anomaly, positive SSTA in the central and eastern tropical Pacific, and the negative phase vice versa. In 2020–22, PC2A was negative and showed a downward tendency with the Niño 3.4 index (figures 1(a) and 5(b)), suggesting that the development of La Niña is related to the strengthening of the trade wind over the central tropical Pacific, which is consistent with the result of heat budget analysis.

When excluding the PC2A, PC1A has a significant partial correlation with the SSTA in the southeastern and northern Pacific. The positive PC1A is associated with an anomalous northwestern–southeastern gradient of SLP in the east of the dateline

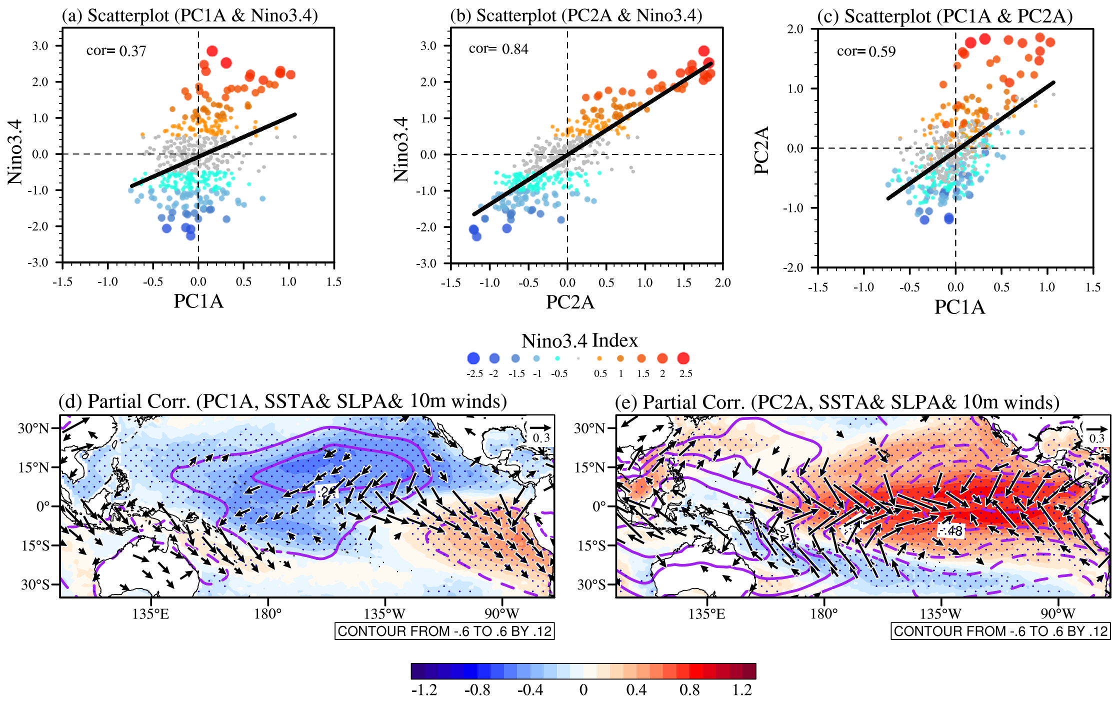

Figure 4. (a)–(c) are the scatterplots of PC1A and Niño 3.4 index, PC2A and Niño 3.4 index, and PC1A and PC2A, respectively. Their linear regression relationship is shown by the black line. The color and size of the dots represent the value of the Niño 3.4 index (greater than 0.5 for red, less than −0.5 for blue, and others for gray). (d) and (e) The partial correlation of PC1A and PC2A with SSTA (shading), SLP anomalies (SLPAs; contour), and 10 m winds anomalies (vectors) from 1982 to 2022. The black vectors for 10 m winds anomalies, contour for SLPA, and stippling for SSTA indicate the region where the correlation coefficient is statistically significant at the 95% confidence level.

(figure 4(d)). 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 (Zhang *et al* 2014, Zhu *et al* 2016). Interestingly, PC1A has been negative since early 2019 (figure 5(a)), 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, suggesting that the antisymmetric (EOF1) mode may also play an important role in the prolonged La Niña event in 2020–23.

The antisymmetric mode is associated with the seasonal evolution of the SST between the northern and southern hemispheres, which can be 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 (figure S3(a)). The index shows a persistently negative value during the triple-dip La Niña in 2020–23 (figure 5(a)).

It has been shown the warming trend is larger in the northern hemisphere than in the southern hemisphere (Fox-Kemper 2021). There is a La Niña-like trend in the tropical Pacific, and the trend is larger in the northern tropical Pacific than in the southern tropical Pacific, especially in the last 20 years (figure S2). The SSTA in the southern tropical Pacific has even shown a cooling tendency in recent years (figure 5(a)), as a result, the negative $SSTA_{S-N}$ persists and induces an anomalous meridional gradient of SLP in the east of the dateline (figure 5(c)). The anomalous SLP gradient is favorable for maintaining the anomalous southeasterly over the eastern tropical Pacific during 2020–23. The southeasterly wind anomalies over the southeastern Pacific enhance the wind speed and cool down SST (figure not shown) which in turn further strengthen southeasterly wind (figure 4(d)), due to the wind-evaporation-SST feedback (Xie *et al* 2009). Thus, the spatially heterogeneous warming trends may provide a favorable background for the triple-dip La Niña in 2020–23. The anomalous SLP gradient and the cross-equatorial meridional wind associated with negative $SSTA_{S-N}$ also produce an anomalously asymmetric vertical circular circulation, which causes a strengthening of the Hadley cell over the eastern tropical Pacific. The anomalous downward (upward) motion over the eastern south (north) Pacific is in agreement with the OLR anomalies (figure 5(c)). The anomalous asymmetric Hadley cell is related to the effect of the ENSO and climatological background

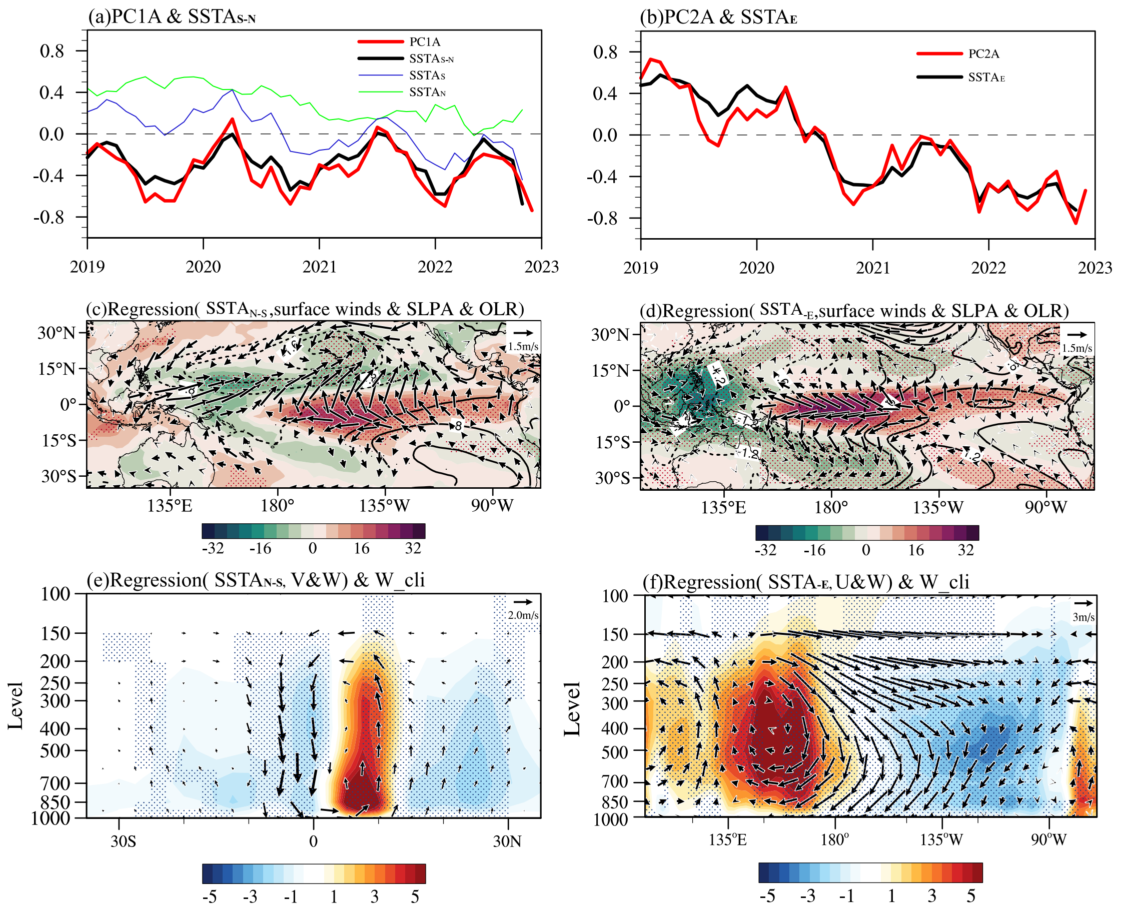

Figure 5. (a) The time series of SSTA in the northern tropical Pacific ($SSTA_N$, averaged in 0°–25°N, 110°E–80°W; green line) and SSTA in the southern tropical Pacific ($SSTA_S$, averaged in 25°S–0, 110°E–80°W; blue line) and the difference between them ($SSTA_{S-N}$; black line) and PC1A (red line) during 2019–2022; (b) the time series of SSTA in the eastern tropical Pacific ($SSTA_E$, averaged in 15°S–15°N, 180°E–80°W; black line) and PC2A (red line) during 2019–2022. The $SSTA_{N-S}$ regressed (c) SLPA (contour; hPa), OLR anomalies (OLRAs, shading; W m^{-2}) and 10 m winds anomalies (vectors; m s^{-1}) from 1982 to 2022; the negative phase of $SSTA_E$ ($SSTA_{-E}$) regressed (d) SLPA, OLRA and 10 m winds anomalies from 1982 to 2022. The $SSTA_{N-S}$ regressed (e) meridional circulation (vectors; m s^{-1}) in the eastern Pacific (averaged in 180°E–80°W); the negative phase of $SSTA_E$ ($SSTA_{-E}$) regressed (f) zonal circulation in the tropical Pacific (averaged in 5°S–5°N). The shading in (e) and (f) represent the climatological vertical velocity (omega*-100 Pa s^{-1}) during the July–October. The stippling and vector and contour in (c)–(f) indicate the region where the regression coefficient is statistically significant at the 95% confidence level.

SST (Guo and Tan 2018), which in turn feeds back to ENSO via the wind-evaporation-SST feedback and other atmosphere-ocean dynamics (Li *et al* 2023).

On the other hand, the change of symmetric mode is associated with the seasonal evolution of SSTA in the eastern tropical Pacific ($SSTA_E$; 15°S–15°N, 180°E–80°W). The correlation coefficient between $SSTA_E$ and PC2A is +0.92 and significant at a 99% level (figure S3(b)). The index is negative since the summer of 2020 (figure 5(b)), linked to the strengthened trade wind over the central tropical Pacific via increasing the zonal SLP and SST gradient (figure 5(d)). The anomalous easterly wind and SLP gradient are accompanied by strengthened Walker circulation and enhanced convection over the Maritime Continent. Thus, both the zonal and meridional advection components are conducive to the triple-dip La Niña in 2020–23 under the favorable background of antisymmetric mode anomaly.

4. 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 2020–23 (Fang *et al* 2023). The oceanic heat budget analysis also indicates the important role of zonal and meridional advection components. In this work, from the annual cycle SST perspective, we further analyze the connection of the triple-dip La Niña event in 2020–23 with the anomalies of leading annual cycle modes. We propose that the easterly and southeasterly wind anomalies over the central and southeastern Pacific are associated with the anomalies of two leading annual cycle modes of SST.

The large loading of symmetric mode is mainly in the central and eastern tropical Pacific reflecting 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 loading of antisymmetric mode 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 two modes are both in negative phases since 2020 and are favorable for the development of the triple-dip La Niña event. Thus, our results may provide an implication for understanding the triple-dip La Niña event from the annual cycle variation perspective.

The triple-dip La Niña event in 1998–2001 is also corresponding to the negative phase of PC2 (figure S3(b)). It enhanced the zonal SSTA gradient, strengthened the trade winds over the central and eastern equatorial Pacific, and favored the growth of negative SSTA and La Niña conditions. However, the amplitude of PC1 was small (figure S3(a)). As a result, the last triple-dip La Niña event was probably mainly caused by the symmetric mode anomaly of annual cycle SST. However, there is a relatively larger difference between the PC1 during 1999–2001 and 2020–2022 with a La Niña-like SST anomalies in the tropical Pacific (figure S4). It further implies that the antisymmetric mode of the annual cycle can influence the phase of ENSO via the change of annual mean SST (figure S1(b)).

It has been suggested that the multi-year La Niña events may also be affected by interdecadal variations, such as the Pacific decadal oscillation (PDO; Mantua and Hare 2002). Statistically, multi-year La Niña events are favorable to occur during a negative phase of the PDO (Park *et al* 2021). Similar to PC1A, the PDO index has been in a negative phase since 2019, which possibly provides a favorable background for the easterly and southeasterly wind anomalies over the central and southeastern Pacific (figure S5). On the other hand, the spatial heterogeneity of warming trends may affect the SST contrast between the southern and northern hemispheres, which modulate ENSO evolution as well (Hu and Fedorov 2018).

Data availability statements

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 US NOAA is downloaded from https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html. The monthly GODAS data are available at www.cpc.ncep.noaa.gov/products/GODAS. The PDO index is downloaded from (www.ncei.noaa.gov/access/monitoring/pdo). 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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Conflict of interest

The authors declare that they have no conflict of interest.

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