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Key Points:

- The stronger (weaker) the tropical cyclones (TCs) over the western North Pacific (WNP), the more the eastern (central)-Pacific La Niña months
- The TCs over the WNP affect La Niña flavor by modulating the Walker circulation and thermocline
- TCs are shown to be essential to improve the prediction skill of the two flavors of La Niña events during the peak time

Supporting Information:

Supporting Information may be found in the online version of this article.

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Feedback of Tropical Cyclones Over the Western North Pacific on La Niña Flavor

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Abstract The relationship between La Niña and tropical cyclone (TC) activity has not received as much attention as that between El Niño and TCs; in particular, the important role of TCs in affecting La Niña flavor has not been reported. This study reveals a clear feedback of TCs over the western North Pacific (WNP) on La Niña flavor by modulating the Walker circulation and thermocline. When strong WNP accumulated cyclone energy (ACE) occurs 3 months earlier, the center of sea surface temperature (SST) anomalies shifts to the equatorial eastern Pacific, favoring the development of eastern-Pacific (EP) La Niña. In contrast, weak WNP ACE is associated with central-Pacific (CP) La Niña, and the influence of WNP TCs on the intensity of CP La Niña may be larger than for EP La Niña. More evidence is provided in the predictions of EP and CP La Niña events using the ACE + SST model.

Plain Language Summary This study reveals the feedback of tropical cyclones (TCs) over the western North Pacific (WNP) on the eastern-Pacific (EP) and central-Pacific (CP) La Niña. Generally, if the accumulated cyclone energy of WNP TCs is strong (weak), the anomalous Walker circulation is suppressed (enhanced) and the east-west thermocline gradient decreased (increased), sea surface temperature (SST) anomalies center is located in the equatorial eastern (central) Pacific 3 months later, favoring the development of EP (CP) La Niña. Most noteworthy is that the pathway that TCs affect thermocline during two flavors of La Niña is different from that during El Niño. Moreover, this feedback is independent of the local SST, zonal wind, and the Madden-Julian Oscillation. Besides, a model based on TC energy and SST gives better predictions of the peak of the two flavors of La Niña than current models, and TC energy is the major contributor to this improvement. The findings of this study will help to enhance our understanding of La Niña events and improve their prediction.

1. Introduction

The El Niño-Southern Oscillation (ENSO) is a perennial topic of study because of its widespread influence (Bjerknes, 1969; Ding et al., 2017; Feng et al., 2019; Ham & Kug, 2016; Jin, 1997; McPhaden, 2012; Wu et al., 2018; X. Han & Wang, 2021). Currently, there is no unified conclusion on the influencing factors of ENSO. As the cold phase of ENSO, La Niña events are divided into two flavors based on the location of sea surface temperature (SST) anomalies (SSTA) center: the eastern-Pacific (EP) and central-Pacific (CP) La Niña (Ashok et al., 2007; Kao & Yu, 2009). In the past few decades, the impact of La Niña on tropical cyclones (TCs) has been widely reported (B. Wang & Chan, 2002; Camargo & Sobel, 2005; Chand et al., 2013; Guo & Tan, 2021; R. Q. Han et al., 2016; Sobel & Maloney, 2000; Zhao et al., 2019). Some studies (C. Z. Wang et al., 2013; H. K. Kim et al., 2020) revealed the distinct influence of CP and EP La Niña events on TCs over the western North Pacific (WNP): During the boreal summer, when an EP La Niña occurs, the number of TCs over the northwestern and northeastern Pacific increases; when a CP La Niña occurs, the number of TCs over the southeastern Pacific decreases significantly.

Currently, the feedback of TCs on ENSO has been the subject of much research, although the focus has generally been on case studies of particular TCs (Keen, 1982; Lian et al., 2019; Sriver et al., 2013). After Camargo and Sobel (2005) first found that the WNP TC signal leads Niño indices and came up with the hypothesis that TCs affect ENSO (Sobel & Camargo, 2005), Q. Y. Wang et al. (2019) systematically studied the important role of the preceding (3 months earlier) WNP TC activity in ENSO intensity on interannual timescales at the first time. Furthermore, WNP TCs are also demonstrated to affect El Niño flavor (Q. Wang & Li, 2022a, 2022b). Q. Y. Wang et al. (2019) mentioned that there is an essential impact of WNP TCs on La Niña intensity, but the corresponding details weren't shown. Meanwhile, El Niño and La Niña are asymmetric, including their dynamic mechanisms and impacts (Camargo et al., 2007; Hoerling et al., 1997; R. H. Zhang et al., 2015; Xie et al., 2018; Z. Z. Hu et al., 2017). It's also true to the different flavors of La Niña (C. Z. Wang et al., 2016; Yang et al., 2018). Therefore, it's necessary to examine whether WNP TCs can affect La Niña flavors, which will help to enhance our understanding of La Niña events and improve their prediction.

2. Data and Methods

2.1. Data

The WNP TC data (1970–2018) are from the International Best Track Archive for Climate Stewardship data set, provided by the National Oceanic and Atmospheric Administration (NOAA). The interpolated outgoing longwave radiation data (1979–2018) from NOAA are used to calculate the Madden-Julian Oscillation (MJO) index (Wheeler & Hendon, 2004). Monthly 2° × 2° and daily 2.5° × 2.5° SST data sets (1970–2018) are from the Extended Reconstructed Sea Surface Temperature (ERSST) V5 data set (Huang et al., 2017) and the ERA Interim data set of the European Centre for Medium-Range Weather Forecasts, respectively. The ENSO forecast data (2002–2018) are from the International Research Institute for Climate and Society, Columbia University. A monthly 2.5° × 2.5° wind data set (1970–2018) is obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research reanalysis data set (Kalnay et al., 1996). Monthly 0.5° × 0.5° ocean variables (1970–2010) are from the Simple Ocean Data Assimilation product (Carton & Giese, 2008). Three-month running mean is applied to all monthly data sets. Unless otherwise stated, all figures related to SST here are obtained using the ERSST V5 data set.

2.2. Definitions of La Niña Events and Flavors

La Niña events are defined when the Niño-3.4 (N3.4) index in five consecutive overlapping 3-month periods is ≤−0.5°C (http://ggweather.com/enso/oni.htm); and the N3.4 index is the running 3-month mean of SSTA in the N3.4 area (5°S–5°N and 120°–170°W). During La Niña events, the months with N3.4 index at or below −0.5°C are identified as La Niña months. Based on the method proposed by Kug and Ham (2011), EP (CP) La Niña events are defined when the normalized Niño-3 (Niño-4) SSTA is less than −0.5 and less than the normalized Niño-4 (Niño-3) SSTA. Here, Niño-3 (5°S-5°N, and 90°–150°W) and Niño-4 (5°S–5°N and 160°E−150°W) SSTA are defined as the average during December-February. Thus, there are 5 EP and 13 CP La Niña events (Table S1 in Supporting Information S1).

2.3. Definitions of Accumulated Cyclone Energy

The accumulated cyclone energy (ACE; Bell et al., 2000; Q. Y. Wang et al., 2019) is defined as the sum of the squares of the estimated maximum sustained surface wind speed (in $knot^2$) for all TCs occurring in each 2° × 2° grid cell over all 6-hr periods. Then the WNP ACE index is the anomaly of the sum of the ACE for all grid cells in the key region 10°–25°N, 130°–155°E during La Niña (Q. Y. Wang et al., 2019). Strong (weak) ACE is defined when the ACE index is ≥0.5 (≤−0.5) standard deviations.

2.4. Other Notes

In ACE + SST model (Q. Wang & Li, 2022b), the predictor variables are the standardized ACE anomalies and SSTA; the dependent variable is SSTA 3 months later; in the ACE (SST) model, the predictor variable changes to the standardized ACE anomalies (SSTA). Brief introductions of models are given in the Supporting Information S1. The modeling base period is from 1970 to 1999; SSTA and ACE anomalies in the model are obtained relative to the base period. The hindcasting period starts from 2000, unless otherwise stated. This study also employed the partial correlation and regression analyses.

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3. Influence of the WNP TCs on Two Flavors of La Niña Events

The center location of SSTA during November-January can be captured well by the preceding WNP ACE (here, i.e., ACE in August-October), regardless of whether it is an EP or CP La Niña (Figures 1a–1d). The intensities of EP and CP La Niña events related to the preceding ACE are both weakened, with the reduction in intensity of EP La Niña greater than that of CP La Niña, which suggests that the influence of the preceding WNP ACE on the intensity of CP La Niña may be larger than that of EP La Niña. The N3.4 SSTA, tropical western Pacific (10°S–10°N and 120°–160°E) SSTA, zonal wind anomalies over the tropical Pacific (10°S–10°N and 120°E–120°W) and MJO are usually regarded as important factors affecting ENSO and TCs (Camargo et al., 2009; J. H. Kim et al., 2008; McPhaden, 1999; Puy et al., 2016; Weisberg & Wang, 1997; Yang et al., 2018). Hence, we further check the roles of these four factors in the influence of WNP ACE on La Niña flavor. After removing the signal of N3.4 SSTA from the preceding ACE (Figures 1e and 1f), the modulation of EP and CP La Niña by the preceding ACE changes little, except for the weakening of intensity. After removing the signal of SSTA in the tropical western Pacific from the preceding ACE, the modulation of EP and CP La Niña by the preceding ACE also hardly changes (Figures 1g and 1h). The impact of tropical Pacific zonal wind anomalies is similar to that of N3.4 SSTA (Figures 1i and 1j). After removing the MJO signal, the modulation of EP and CP La Niña by the preceding ACE is almost unchanged (Figures 1k and 1l and Figure S1 in Supporting Information S1).

Occurrence frequencies of EP and CP La Niña months and the total value of the corresponding preceding WNP ACE anomalies are also examined. Results indicate that EP La Niña months occur more frequently (~2.2 times) than CP La Niña months when preceding strong ACE occurs (Figure S2a in Supporting Information S1). This ratio (~2.2) is evidently smaller than the ratio (~3.4) of the total value of the corresponding preceding ACE anomalies between EP and CP La Niña (Figure S2b in Supporting Information S1). This indicates that CP La Niña months can occur with preceding strong ACE, but the strength of the preceding ACE is weaker than that before EP La Niña months. In contrast, when the preceding ACE is weak, CP La Niña months occur more frequently (~4.4 times) than EP La Niña months (Figure S2a in Supporting Information S1). This ratio (~4.4) is also smaller than the ratio (~5.7) of the total value (both are negative) of the corresponding preceding ACE anomalies between CP and EP La Niña (Figure S2b in Supporting Information S1), which indicates that EP La Niña months can occur when the preceding ACE is weak, but the strength of the preceding ACE is stronger than that associated with CP La Niña months. Overall, the stronger (weaker) the preceding ACE, the greater the occurrence frequency of EP (CP) La Niña months.

4. La Niña Events Related to the Preceding ACE Strength

To further check the feedback of the WNP ACE on the La Niña flavors, three La Niña cases are studied, including mean La Niña (composite of SSTA in the La Niña months, Figure 2a), La Niña_strong ACE (La Niña associated with preceding strong ACE, Figure 2b) and La Niña_weak ACE (La Niña associated with preceding weak ACE, Figure 2c).

For intensity, La Niña_strong ACE (La Niña_weak ACE) is weaker (stronger) than the La Niña mean state. For the location of SSTA center, differing from the center location of SSTA (equatorial central Pacific) during the mean La Niña (Figure 2a), the center during La Niña_strong ACE is located in the equatorial eastern Pacific (Figure 2b). However, the center location during La Niña_weak ACE (Figure 2c) is similar to that during the mean La Niña, in the equatorial central Pacific. After removing the influence of the N3.4 SSTA, tropical western Pacific SSTA, tropical Pacific zonal wind anomalies and MJO, the center position of SSTA hardly changes, except for the decreasing of intensity (Figure S3 in Supporting Information S1). Overall, when the preceding ACE is strong (weak), the centers of SSTA during La Niña months are located in the equatorial eastern (central) Pacific, supporting the development of EP (CP) La Niña.

5. Atmospheric and Oceanic Bridges

TCs have significant impacts on their environment (Sobel & Camargo, 2005; Wada & Chan, 2008). Walker circulation and thermocline are considered as the important atmospheric and oceanic bridges (Li et al., 2019) which WNP TCs affect ENSO (Q. Wang & Li, 2022b; Q. Y. Wang et al., 2019). Here further investigates the possible mechanisms that WNP TC affect La Niña flavor via these two bridges. In the La Niña_strong ACE, because the preceding WNP ACE are stronger than in the mean La Niña (ACE anomalies are 667.0 vs. −303.5 knot^2), the anomalous 850-hPa easterlies to the south of the key ACE region is weakened, even disappeared; And the descending branch located in the Northern Hemisphere of anomalous Hadley-like circulation changes to ascend (Figure S4 in

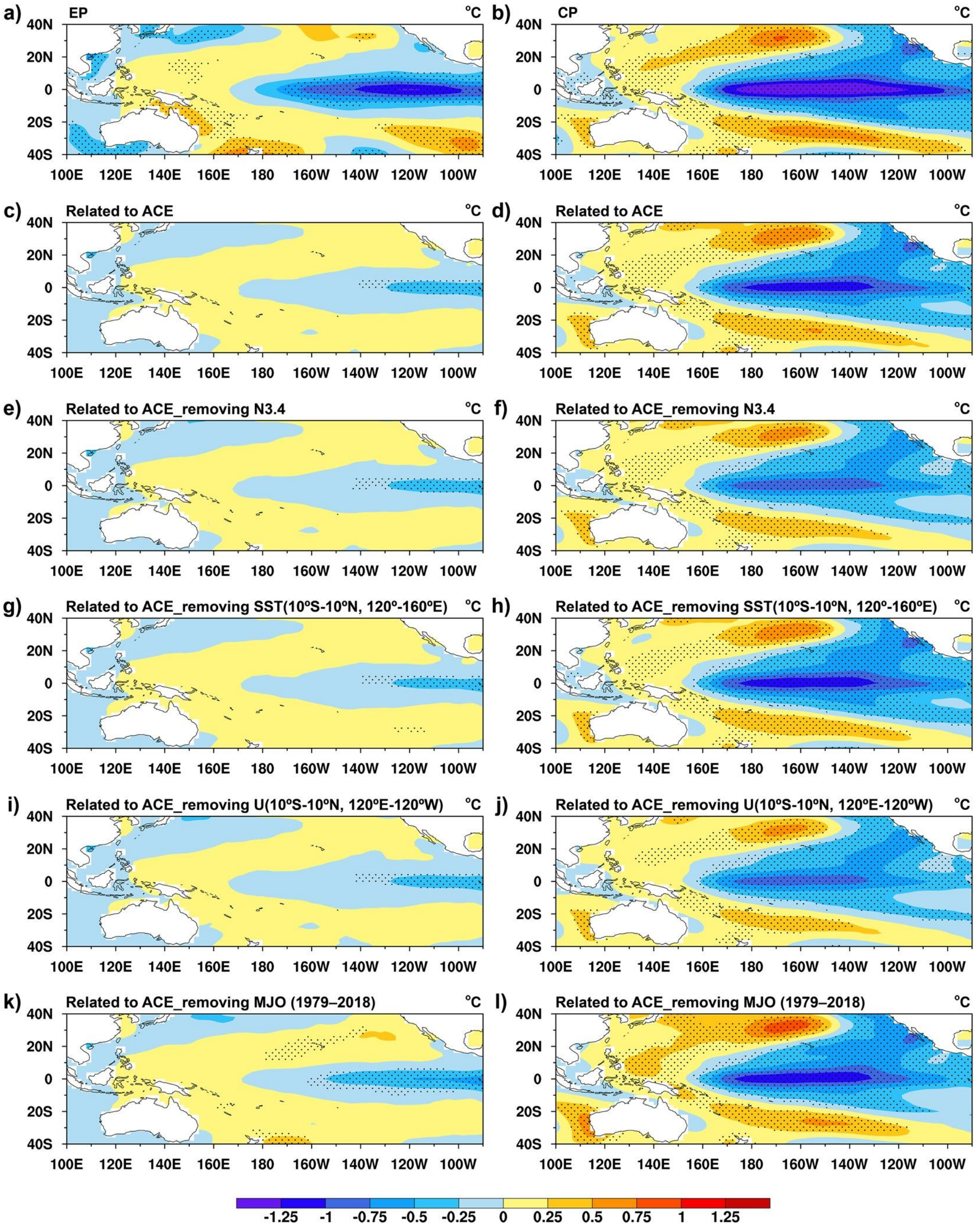

Figure 1. Spatial distribution of sea surface temperature anomalies (SSTA, °C) from November to January during La Niña events. (a) Eastern-Pacific (EP) La Niña from 1970 to 2018; the significance level in stippled regions is ≥95%. Panel (b) same as in panel (a), but for central-Pacific (CP) La Niña. Panels (c and d) as in panels (a and b), but for La Niña events related to the preceding (3 months earlier; i.e., August-October) accumulated cyclone energy (ACE) over the western North Pacific (WNP). Panels (e and f) same as in panels (c and d), but for the preceding WNP ACE are those after removing the Niño-3.4 index. Panels (g and h) as in panels (e and f), but for those ACE after removing the SSTA over the tropical western Pacific (10°S–10°N and 120°–160°E). Panels (i and j) same as in panels (e and f), but for those ACE after removing the tropical Pacific zonal wind anomalies (10°S–10°N and 120°E–120°W). Panels (k and l) same as in panels (e and f), but for those ACE after removing the Madden-Julian Oscillation from 1979 to 2018.

Supporting Information S1). Thus, the anomalous Walker circulation three months before La Niña_strong ACE is weaker, and there is an anomalous updraft over the 140°–170°E (Figure 3a and Figures S5a and S5b in Supporting Information S1); meanwhile, the thermocline over the western Pacific is shallower, the thermocline over the eastern

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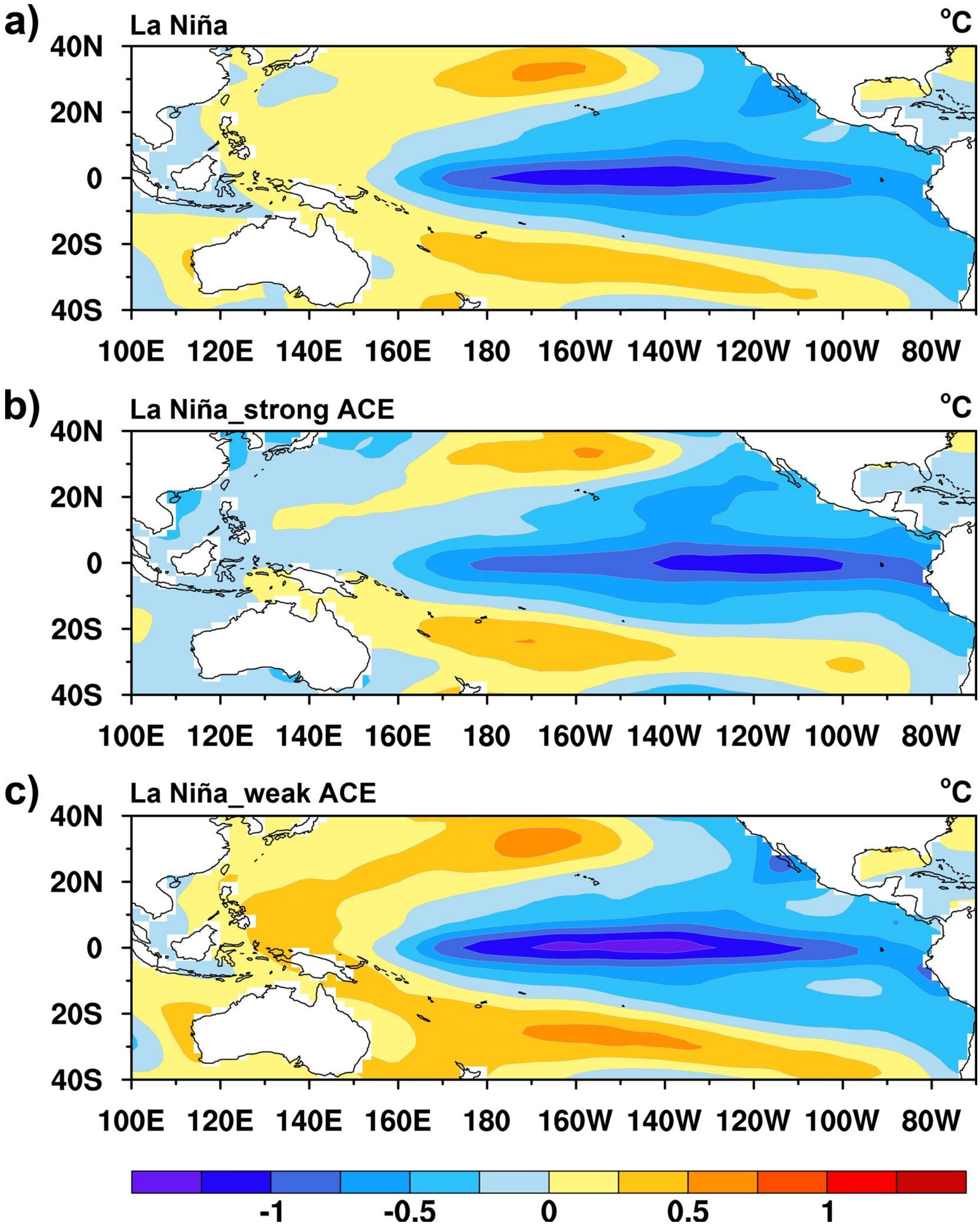

Figure 2. Spatial distribution of sea surface temperature anomalies (SSTA, °C) for three La Niña cases. (a) Mean La Niña; that is, composite of SSTA in all La Niña months. (b) La Niña_strong ACE; that is, composite of SSTA in La Niña months for which strong accumulated cyclone energy (ACE) occurs 3 months earlier. (c) La Niña_weak ACE; that is, composite of SSTA in La Niña months for which weak ACE occurs 3 months earlier.

Pacific deeper, and the east-west thermocline gradient smaller than that in the mean La Niña (Figure 3b and Figures S5d and S5e in Supporting Information S1). These features suppress the westward transport of the cold sea water over the eastern Pacific, and the center of maximum negative SSTA is limited in the equatorial eastern Pacific, supporting the development of EP La Niña. In contrast, in the La Niña_weak ACE, the preceding WNP ACE (−683.0 knot^2) are weaker than in mean La Niña, the anomalous easterlies to the south of the key ACE region and the anomalous Hadley-like circulation with descending branch located in the Northern Hemisphere are both strengthened (Figure S4 in Supporting Information S1), leading a stronger Walker circulation anomaly 3 months before La Niña_weak ACE

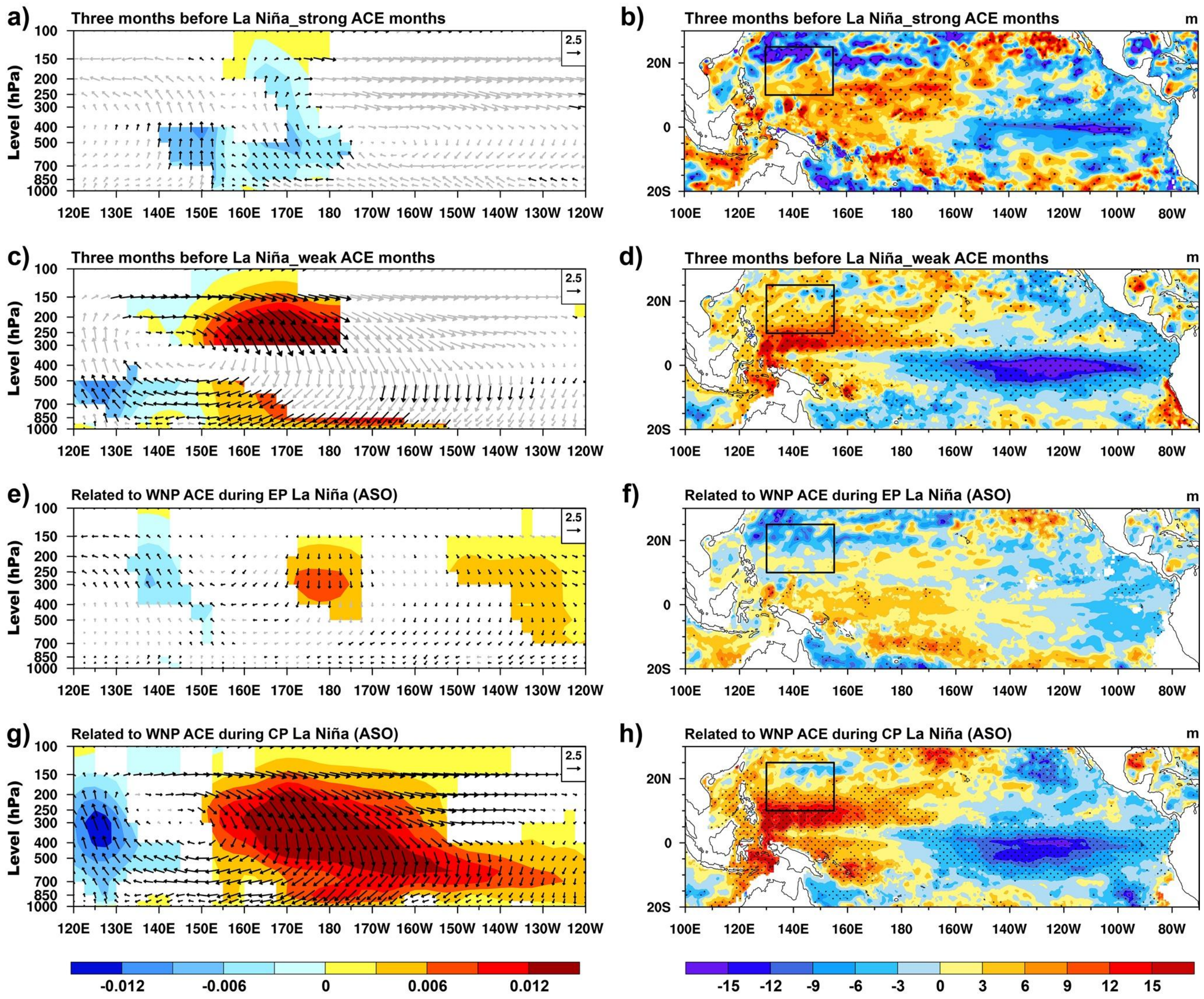

Figure 3. Anomalous vertical p-velocity, the wind and the depth of the 20°C isotherm. (a) Vertical p-velocity (shading, Pa s^{-1}) and the wind (vectors) anomalies in the vertical-zonal plane over 5°S−5°N 3 months before the La Niña_strong ACE (same as in Figure 2b) months in the period 1970–2018. Panel (b) same as in panel (a), but for the depth of the 20°C isotherm anomalies (shading, m) in the period 1970–2010. Panels (c and d) same as in panels (a and b), but for La Niña_weak ACE months (same as in Figure 2c). Panel (e) same as in panel (a), but for the vertical p-velocity and the wind anomalies associated with the simultaneous accumulated cyclone energy (ACE) from August to October during eastern-Pacific La Niña. Panel (f) same as in panel (e), but for the depth of the 20°C isotherm anomalies. Panels (g and h) same as in panels (e and f), but for central-Pacific La Niña. In the left panels, vectors are obtained by the zonal wind anomalies and magnified vertical p-velocity (×(−200)). Shading and black vectors indicate significance above the 95% confidence level using Student's *t*-test. In the right panels, the stippled regions denote statistical significance above the 95% confidence level. The black rectangles denote the key ACE regions (10°–25°N and 130°–155°E).

(Figure 3c and Figures S5a and S5c in Supporting Information S1); And the east-west thermocline gradient becomes greater (Figure 3d and Figures S5d and S5f in Supporting Information S1). These features enhance the westward transport of the cold sea water over the eastern Pacific, and the center of maximum negative SSTA can reach to the equatorial central Pacific, supporting the development of CP La Niña. More evidence can be found in the change of anomalous walker circulation and thermocline related to WNP ACE during EP and CP (mean ACE anomalies are −22.2 vs. −653.7 knot^2) La Niña events (Figures 3e–3h).

Differing from El Niño, because of the negative ACE anomalies during EP and CP La Niña (in this case, WNP TCs have no evident influence on the Kelvin wave propagation, Q. Wang & Li, 2022b), the change in thermocline is mainly related to Ekman pumping resulting from the anomalous Walker circulation related to TCs during EP and CP La Niña: It's evident that the change in thermocline anomalies follows the change in sea surface pressure anomalies related to the WNP TCs (Figure S6 in Supporting Information S1).

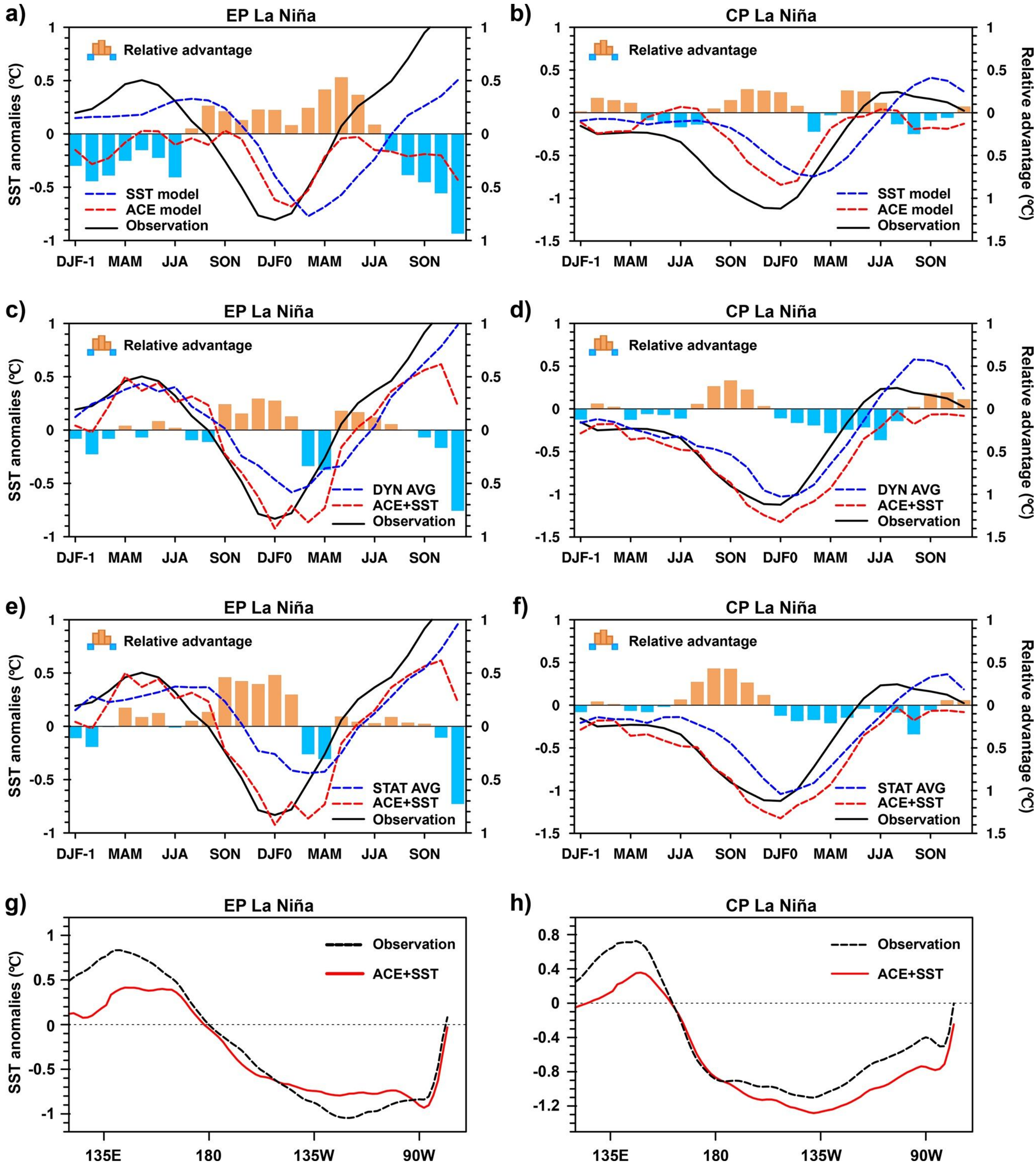

Figure 4.

6. The ACE + SST Model Can Predict Well the La Niña Flavor

Whether La Niña flavor can be hindcasted based on the WNP ACE is a touchstone for the role of WNP ACE in setting La Niña flavor. Hence, based on the preceding ACE and SST, a modified empirical model, ACE + SST, is employed to predict SSTA in the tropical equatorial Pacific.

First, single factor models are employed to distinguish the roles of ACE and SST in the ACE + SST model. As seen in Figures 4a and 4b, the La Niña predicted by the SST model reaches its peak 3 months after the observations, while the ACE model can reduce this error to 1-(0-) month lag for EP (CP) La Niña; furthermore, the advantage in intensity of the ACE model is evident when the EP and CP La Niña start to weaken from its peak. It's clear that the ACE + SST model gives better predictions of the peak time and intensity of N3.4 index than the SST and ACE models for both EP and CP La Niña (Figures 4a–4d). The improvement with the ACE + SST model is not just the superposition of the linear actions of the ACE and SST models, which implies there is a non-linear interaction between ACE and SST.

ACE + SST model are then compared with the 18 dynamical and 8 statistical models. The ACE + SST model also performs better for peak time and intensity of N3.4 than the average of the dynamical/statistical models (Figures 4c–4f). However, the dynamical and statistical models have better prediction skill in the period when the EP and CP La Niña start to weaken from their peak, which may result from the SST persistence in the ACE + SST model in this period. Furthermore, ACE + SST model can also capture well the position and intensity of SSTA center during EP and CP La Niña from November to January, except for a slight eastward shift of the center during EP La Niña and an overestimate of the center intensities of EP and CP La Niña (Figures 4g and 4h and Figure S7 in Supporting Information S1). This larger predicted error in EP than CP La Niña may further imply that the preceding WNP ACE has a larger influence on the intensity of CP La Niña than on EP La Niña.

7. Conclusion and Outlook

This study explores the feedback of the WNP TCs on La Niña flavor from the perspective of ACE. When the preceding ACE is strong (weak), the anomalous Walker circulation is suppressed (enhanced) and the east-west thermocline gradient decreased (increased), the center of maximum SSTA is limited in the equatorial eastern Pacific (can reach to the equatorial central Pacific), which favors the development of EP (CP) La Niña events. Thereinto, WNP TCs affect Walker circulation by changing the lower-level anomalous winds and Hadley-like circulation; The modulation of TCs on thermocline results from the Ekman pumping during EP and CP La Niña, which is different from that during El Niño. The influence of the preceding TCs on the intensity of CP La Niña may be larger than for EP La Niña. Moreover, the N3.4 SSTA, tropical western Pacific SSTA, tropical Pacific zonal wind anomalies and MJO do not change this feedback. In addition, ACE + SST model can capture well the spatial pattern, time and intensity of the peak of the two La Niña flavors, WNP ACE is essential to improve the prediction skill.

This study shows the accumulated effects of WNP TCs may be an important stochastic forcing of the development of La Niña flavors on the interannual timescale, which will help to enhance our understanding of La Niña flavor and improve its prediction. However, a few points need to be clarified: First, this study mainly explores the feedback of WNP TCs on the development of La Niña flavor rather than its trigger, that is, TCs could affect La Niña flavor, but this flavor is not leaded by TCs. Second, the predicted results from ACE model don't mean that the ACE is the main contributing factor of La Niña flavor. There is a non-linear interaction between WNP ACE and other factors. The analysis presented here is not sufficient to distinguish completely the independent role of WNP ACE from these factors. These need to be further verified in a fully coupled model, but will be a huge challenge because the current models do not simulate well the interannual variabilities of either TC activity or ENSO (Fang & Zheng, 2021; Ren et al., 2020; Vidale et al., 2021; Z. Z. Hu et al., 2019). Third, there are still some impactors of ENSO and TCs are not covered in this study, including the remote SST (Ding et al., 2019), westerly wind burst (Chen et al., 2015; Z. Z. Hu et al., 2012), Pacific meridional mode (H. J. Zhang et al., 2020), monsoon (Harr & Wu, 2011; Wu et al., 2012) and so on. Much research is necessary to solve these issues.

Figure 4. Observed and predicted sea surface temperature anomalies (SSTA, °C) during eastern-Pacific (EP) and central-Pacific (CP) La Niña events. (a) Niño-3.4 index during EP La Niña in the hindcasting period 2002–2018. Black solid line is observations. Blue (red) dashed line is the prediction by the SST (accumulated cyclone energy, ACE) model. Bars indicate the amplitude of the models' relative advantage (relative advantage $_{\text{model A} \rightarrow \text{model B}}$ = |Model A − Observation| − |Model B − Observation|) between the average of the SST and the ACE model. Orange bars indicate that the ACE model performs better than the SST model, while blue bars indicate that the SST model is superior. DJF-1 and DJF0 represent December-February in the previous year and the year of peak La Niña, respectively. Panel (b) same as in panel (a), but for CP La Niña. Panels (c and d) same as in panels (a and b), but for the ACE + SST model and the average of dynamical models. Blue dashed line is the average prediction by dynamical models, and red dashed line is that for the ACE + SST model. Orange bars indicate that the ACE + SST model performs better than the average of dynamical models, while blue bars indicate that the average of dynamical models performs better. Panels (e and f) same as in panels (c and d), but for the ACE + SST model and the average of statistical models. (g) Zonal distribution of the SSTA along 5°S–5°N during EP La Niña from November to January in the hindcasting period of 2000–2018. Black dashed line indicates observations and red line indicates the prediction from the ACE + SST model. Panel (h) same as in panel (g), but for CP La Niña.

Data Availability Statement

Tropical cyclone data is available online at https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r00/access/netcdf/; outgoing longwave radiation data at https://psl.noaa.gov/data/gridded/data.interp_OLR.html; monthly sea surface temperature (SST) data at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html/; daily SST data at https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/; the multi-model El Niño-Southern Oscillation forecast data at https://iri.columbia.edu/~forecast/ensofcst/Data/; monthly wind data set at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.pressure.html; and ocean variables at http://apdrc.soest.hawaii.edu/datadoc/soda_2.2.4.php.

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