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Key Points:
• The projected changes in the WNPAC during El Niño decaying summers are uncertain among different climate models
• The uncertainty of El Niño→northwestern Pacific climate relationship projection is determined by the El Niño decaying pace under global warming
• Changes in El Niño decaying pace depend on the strength of wintertime WNPAC

Supporting Information:
• Supporting Information S1

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Abstract
Based on 34 coupled models from Phase 5 of the Coupled Model Intercomparison Project, we found that the projected changes in the western North Pacific anomalous anticyclone (WNPAC) during El Niño decaying summers show large spread among the models due to different decaying paces of El Niño. Models with a slower (faster) decaying El Niño are followed by weakened (intensified) tropical central Pacific cooling, which further drives a weaker (stronger) WNPAC through inducing weakened (intensified) descending Rossby waves to its west. The decaying pace of El Niño is dominated by the wintertime WNPAC because the easterly surface wind anomalies to its southern flank are critical to El Niño demise. Both the El Niño-related sea surface temperature anomaly and the precipitation sensitivity to such kind of sea surface temperature anomaly under global warming could affect the wintertime WNPAC.

Plain Language Summary
The western North Pacific anomalous anticyclone (WNPAC) is the key atmospheric circulation system that connects El Niño and East Asian climate variability. Understanding how the WNPAC will change in the future is of vital importance to people living in East Asia-western Pacific region. There is extensive literature on the topic of changes in the WNPAC in response to global warming but how such kind of connection would change under global warming remains inconclusive. The causes of uncertainty in the WNPAC projection and the dominant mechanisms remain unknown. Based on 34 state-of-art climate coupled models, we show evidence that uncertainty in El Niño projection is a source of uncertainty in the WNPAC projection. Our results highlight the importance of a reliable projection of El Niño decaying pace to the projection of climate variability over the western Pacific and East Asia.

1. Introduction
The western North Pacific anomalous anticyclone (WNPAC) is a key bridge that links El Niño–Southern Oscillation (ENSO) and the East Asia-western North Pacific (WNP) monsoon (Zhang et al., 1999; Chang et al., 2000; Wang et al., 2000; Wang et al., 2013; Li et al., 2017; Zhang et al., 2017). It starts to establish in El Niño-developing autumn, forms in El Niño mature winter, and maintains into the post El Niño summer (Stuecker et al., 2015; Wu et al., 2017), which has striking impacts on the regional and global climate. For example, in winter, the WNPAC would transport more anomalous moisture to increase the rainfall over southeastern China. While in summer, it brings excessive water vapor into East Asia, enhances precipitation, and leads to extreme rainfall and flooding along the Meiyu/Baiu front over there (Chang et al., 2000; Wang et al., 2000; Zhang et al., 2017).

Theories on the formation and maintenance of the WNPAC are well addressed. During El Niño mature winter, the WNPAC is stimulated by remote El Niño forcing from the central and eastern tropical Pacific and maintains into the following spring through the local air-sea interactions (Wang et al., 2001; Wang et al., 2003; Wu et al., 2017). The maintenance mechanisms of the WNPAC during El Niño decaying summer are different from those during El Niño mature winter (Wang et al., 2013; Wu et al., 2009; Wu et al., 2010; Xie et al., 2009). During El Niño decaying phase, warm sea surface temperature anomalies (SSTAs) over the tropical Indian Ocean (TIO) could trigger a warm Kelvin wave that propagates eastward to the WNP, suppresses local convection by inducing divergence in the Ekman layer, and maintains an anomalous...
anticyclone (Kosaka et al., 2013; Ohba & Ueda, 2006; Wu et al., 2009; Wu et al., 2010; Xie et al., 2009). The tropical central eastern Pacific cooling during El Niño decaying summer could reduce convection in the tropical central Pacific (TCP) and increase convection in the Maritime Continent via shifting the Walker circulation (Chung et al., 2011; Sui et al., 2007). The suppressed convection in the central Pacific can emanate descending Rossby waves to its west to strengthen the WNPAC. Meanwhile, the enhanced convection in the Maritime Continent can also strengthen the WNPAC via inducing equatorial easterlies to generate off-equatorial anticyclonic shear over the Philippine Sea (Wang et al., 2013; Xiang et al., 2013). The equatorial easterlies can accelerate the demise of El Niño in turn, which is helpful for the tropical central eastern Pacific cooling. Hence, the decaying pace of El Niño plays an important role in maintaining the WNPAC in summer. A fast decaying El Niño with tropical central eastern Pacific cooling leads to a significant WNPAC, whereas a slow decaying El Niño with tropical central eastern Pacific warming is associated with a disappeared or western part weakened WNPAC (Chen et al., 2012; Chen et al., 2016; Jiang et al., 2019; Zhou et al., 2019).

Changes in the WNPAC in response to global warming has been a research focus due to the great influence of the WNPAC on East Asian climate. However, analyses based on climate models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) show diverse conclusions. For example, analysis of the Geophysical Fluid Dynamics Laboratory CM2.1 model showed that the WNPAC during post El Niño summer tends to weaken in a warmer climate (Zheng et al., 2011). The TIO response to ENSO is enhanced under global warming, which is conducive to strengthening the ENSO-WNPAC teleconnection (Hu et al., 2014; Tao et al., 2015). On the contrary, there is also evidence demonstrating that the summertime WNPAC tends to weaken because of the weakening of the atmospheric response to global warming (He et al., 2019; Jiang et al., 2018). Why did the diagnoses of CMIP5 models show such large diversity in the conclusion? We review the main conclusions, models used in these researches, and the suggested mechanisms in Table S1 in the supporting information. Inspection on Table S1 reveals one limitation of the existing studies: No effort has been devoted to understanding the causes of uncertainty in the WNPAC projection.

Hence, we aim to answer the following questions in this study: (1) What is the major cause of the intermodel spread in the WNPAC projection? (2) What are the fundamental mechanisms that dominate the model spread? We show evidences that models with a slower (faster) decaying El Niño are followed by weakened (intensified) TCP cooling, which further drives a weaker (stronger) WNPAC through inducing weakened (intensified) descending Rossby waves to its west, hence reducing the uncertainty in the projection of El Niño decaying paces helps to improve the projection of WNPAC and thereby East Asian-western Pacific climate variability.

2. Data and Methods

In this study, 34 coupled models from CMIP5 (see Table S2 for more details) are chosen for analyses. Only one member (realization r1i1p1 run) for each model is used to give equal weight to models. The monthly mean outputs are analyzed and all the datasets are interpolated onto 2.5° × 2.5° grid before analysis.

Since we focus on interannual variability, the linear trend, annual cycle and a 13-year running mean are removed to extract interannual signals. We perform regressions of interannual anomalies against the December (Year 0) to February (Year 1) \[D(0)JF(1)\]. Hereafter, numerals “0” and “1” denote the developing and decaying years of El Niño, respectively; mean Niño3.4 index (SST anomalies averaged over 5°S to 5°N, 120°-170°W) to measure the sensitivity of the atmospheric circulation response to the ENSO-related SST anomalies. Most of the models used in this study can simulate the ENSO phase locking with the maximum of Niño3.4 index appearing in November (0) to February (1) (figure not shown). Only the positive phase of ENSO is analyzed for simplicity. To avoid the influence of the asymmetries between El Niño and La Niña, the linear impact of negative D(0)JF(1) Niño3.4 index (i.e., the influence of La Niña events) is removed before regression. The regressions are calculated for each model respectively, and then the multimodel ensemble mean (MME) is obtained through averaging the regressed patterns to reduce model bias.

The Historical experiment from 1971 to 2000 is defined as current climate, while the Representative Concentration Pathway 8.5 (RCP8.5) experiment from 2070 to 2099 is referred to as a warmer climate in the future. Changes in El Niño-induced variability in the future is defined as difference of the regressed
Figure 1. Intermodel EOF analysis of Δvorticity at 850 hPa in JJA(1). (a) First intermodel EOF patterns of Δvorticity (shading, units: 10^{-6} s^{-1} K^{-1}) with explained variance noted in the top right and the MME of 34 models of Δvorticity (contours, units: 10^{-6} s^{-1} K^{-1}, dashed lines denote negative values). (b) Standardized PC1 of intermodel EOF1. Models with PC1 < -0.2 belong to Group A, and models with PC1 > 0.2 belong to Group B. (c) ΔWNPAC index in JJA(1) (y axis) as a function of PC1. Black line denotes the linear fitting between the horizontal and vertical coordinates. The correlation coefficient is 0.92, significant at the 99% confidence level.
anomalies between the RCP8.5 and the Historical experiment. For simplicity, we use the symbol \( \Delta \) to represent change in the El Niño-induced anomalies \( X \), that is, \( \Delta X = X_{\text{RCP8.5}} - X_{\text{Historical}} \).

The WNPAC anomaly index is defined as the difference of the El Niño-related zonal wind anomalies at 850 hPa between regions of 20°–30°N, 110°–140°E and 5°–15°N, 100°–130°E as Jiang et al. (2018). An El Niño event is selected when the D(0)JF(1)-mean Niño-3.4 index exceeds 0.5 standard deviations from the time mean of each model, following previous studies (Chen et al., 2016; Jiang et al., 2019; Zhou et al., 2019).

The standard two-tailed Student’s \( t \) test is used to evaluate the significance levels of the results. Moreover, composite analysis is applied to confirm the results (figure not shown).

### 3. Results

#### 3.1. Model Grouping

We first calculate model standard deviations of JJA(1) El Niño-induced relative vorticity (Avorticity) at 850 hPa. The relative vorticity can directly measure the strength of the WNPAC and has been widely used in previous studies (He et al., 2019; He & Zhou, 2014; Terao, 2005; Wu & Zhou, 2015). The standard deviations are large over the WNP region, indicating a large intermodel spread in projecting the WNPAC among CMIP5 models (Figure S1). To further identify the spread, we compute the intermodel empirical orthogonal function (EOF) of Avorticity in JJA(1) over the WNP region (15°–30°N, 90°E to 180°). The first intermodel EOF

Figure 2. Temporal evolution of El Niño-induced SST and atmospheric anomalies for Group A models. SST (shading, units: KK\(^{-1}\)), precipitation (contours, units: mm day\(^{-1}\) K\(^{-1}\)), and 850 hPa wind anomalies (vectors, units: m s\(^{-1}\) K\(^{-1}\)) from D(0)JF(1) to JJA(1): (a, d, and g) the Historical experiment for the period of 1971–2000; (b, e, and h) the RCP8.5 experiment for the period of 2070–2099; (c, f, and i) their differences. The green (purple) lines represent the positive (negative) precipitation anomalies. The contour interval is 1.0 mm day\(^{-1}\) K\(^{-1}\). The wind with magnitude less than 0.2 m s\(^{-1}\) K\(^{-1}\) and more than 1.5 m s\(^{-1}\) K\(^{-1}\) is omitted. The black dots indicate the region where the projected SST changes are significant at the 90% level based on the Student’s \( t \) test.

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The EOF1 explains 28.6% of total variance, displaying a spatial distribution with a meridional dipole pattern over the WNP and tropical western Pacific regions. The PC1 is highly correlated with the $\Delta$WNPAC index at $r = 0.92$ (Figure 1c). The MME of $\Delta$vorticity for 34 models (Figure 1a, contours) and the high correlation coefficients between $\Delta$WNPAC index and PC1 (Figure 1c) indicate that the leading intermodel EOF mode (EOF1) reflects the intermodel diversity of changes in strength of the projected WNPAC. For better understanding, we mainly focus on models with the large differences in the following discussion. We choose 16 models with PC1 less than $-0.2$ and 12 models with PC1 greater than 0.2 to do composite analysis, namely, Group A and Group B (see Table S1 for more details). As expected, Group A models project a weakened WNPAC, whereas Group B models project an intensified WNPAC.

3.2. Changes in the WNPAC in Response to Global Warming

To investigate how the WNPAC might change in response to global warming, the temporal evolution of the MME for Historical experiment, RCP8.5 experiment, and their differences in El Niño-induced wind anomalies at 850 hPa and corresponding precipitation anomalies for Group A and Group B models are shown in Figures 2 and 3, respectively. In the historical simulation of Group A models, the WNPAC persists from D(0)JF(1) to JJA(1) (Figures 2a, 2d, and 2g). In a warmer world, the WNPAC is still evident in D(0)JF(1) but weakens in MAM(1), and even disappears in JJA(1) (Figures 2b, 2e, and 2h). Compared with the historical simulation, cyclonic wind anomalies appear over the tropical WNP region during the mature phase of El Niño, continue to develop in MAM(1), and persist into JJA(1) in the projection (Figures 2c, 2f, and 2i). Hence, the WNPAC projected by Group A models significantly weakens from boreal winter to spring and
disappears in summer. On the contrary, in Group B models, the WNPAC is evident in D(0)JF(1), weakens in MAM(1), and vanishes in JJA(1) in the historical simulation (Figures 3a, 3d, and 3g), whereas it can persist from D(0)JF(1) into JJA(1) in the projection (Figures 3b, 3e, and 3h). Group B models see northeasterly wind anomaly over the southern WNP and the tropical western Pacific from D(0)JF(1) to JJA(1) (Figures 3c, 3f, and 3i), which is in sharp contrast to Group A models (Figures 2c, 2f, and 2i). These results indicate that changes in JJA(1) WNPAC are related to changes in its strength in D(0)JF(1). The enhanced (weakened) WNPAC in D(0)JF(1) is favorable (unfavorable) to the maintenance of the WNPAC in JJA(1).

3.3. Role of Changes in SST Interannual Variability

To reveal the associated changes in SST interannual variability, the temporal evolution of the MME for Historical experiment, RCP8.5 experiment, and their differences in El Niño-related SST anomalies for Group A and Group B models are shown in Figures 2 and 3 separately. For Group A models, the TCP sees warmer SSTAs in JJA(1) under global warming (Figures 2h and 2i, shading), indicating that El Niño-related TCP SSTAs decay more slowly in a warmer climate. The persistence of the warm TCP SSTAs obstructs the further enhancement of the WNPAC via increasing convection over WNP through Rossby wave effects (Figure 2i, contours). In addition, the decreased warm SST anomalies in the equatorial Indian Ocean from MAM(1) to JJA(1) indicate that it will be difficult for the weakened wintertime WNPAC to maintain and intensify due to the weakened TIO capacitor effect in JJA(1) (Figures 2d–2f). For Group B models, significant negative SST anomalies are seen over TCP (Figures 3h and 3i, shading). The enhanced TCP cooling indicates that El Niño decays more rapidly in a warmer climate, which can further strengthen the summertime WNPAC. In the meantime, the equatorial Indian Ocean warming during El Niño decaying phase is not significant, indicating that the Indian Ocean capacitor effect no longer works.

To test the hypothesis that the change in El Niño decaying pace is crucial to the establishment or evanescence of WNPAC during post-El Niño summers, we examined the ENSO cycles represented by Niño3.4 index in Figure 4. The El Niño decaying paces are different between two model groups (Figures 4a and 4b). For Group A models, El Niño in the Historical experiment (Figure 4a, blue line) is stronger in D(0)JF(1) and decays more rapidly than the projection in JJA(1) (Figure 4a, red line). On the contrary, for Group B models, the strength of El Niño keeps unchanged in D(0)JF(1) but decays more rapidly in JJA(1) in the projection (Figure 4c). Hence, under a warmer climate, Group A models projected a longer decaying El Niño, while Group B models projected a shorter decaying El Niño. Such kind of different El Niño decaying paces would have different effects on the establishment of the WNPAC. A more rapid (slower) decaying El Niño would strengthen (weaken) the TCP cooling, suppress more (less) precipitation to its west, generate a stronger (weaker) descending Rossby waves to WNP, and, finally, lead to a strengthened (weakened) WNPAC.

3.4. Mechanisms for changes in the El Niño decaying pace

The TCP SST change is mainly determined by the El Niño decaying pace. To figure out the cause of changes in the El Niño decaying pace, we examined changes in SST anomalies during winter and spring as well. For Group A models, compared with present, the El Niño-induced warm SSTAs in the tropical eastern Pacific significantly decrease from D(0)JF(1) to MAM(1) in the future (Figures 2a–2f), which is further confirmed by Figure 4a. Hence, Group A models project weakened El Niño SST anomalies in winter. The weaker warm SSTAs further suppress the local convective heating over the tropical eastern Pacific, leading to decreased precipitation anomalies (Figures 2a–2f). The weakened condensational heating associated the decreased precipitation is followed by a weakened Gill-response (Gill, 1980), as evidenced by the weakened
northerly component to the western flank of the northern part of the twin cyclonic anomalies (Figures 2a–2f). Hence, the weakened remote forcing from the tropical eastern Pacific will form a weakened WNPAC in D(0) JF(1) over WNP.

Different from Group A models, changes in the El Niño-induced warm SST anomalies over the tropical eastern Pacific are not significant in D(0)JF(1) and MAM(1) in Group B models (Figures 3a–3f, shading), further confirmed in Figure 4b. However, the responses of both the atmosphere circulation and the precipitation to SSTAs are stronger in the projection (Figures 3a–3f). Such kind of enhanced low-level specific humidity response to interannual SST variability can be explained by Clausius-Clapeyron equation under a warmer climate (Hu et al., 2014). The intensified precipitation further induces a stronger remote forcing on the WNPAC via triggering stronger Gill response. Therefore, although the amplitude of ENSO does not change significantly in Group B models, the effect of ENSO on the northwestern Pacific atmospheric circulation still would strengthen under a warmer climate.

In summary, changes in both El Niño-induced warm SST anomalies in the tropical eastern Pacific and the precipitation sensitivity to the equatorial eastern Pacific SST anomalies could influence changes in the wintertime WNPAC strength. A well-established WNPAC in D(0)JF(1) is beneficial for the rapid decaying of El Niño through enhancing the background northeast wind to its southern flank, thus strengthening the TCP cooling.

4. Summary and Discussion

Understanding how the WNPAC will change in the future is crucial to the East Asian climate projections. Here we show evidence that the uncertainty of El Niño-northwestern Pacific climate relationship projection is determined by the El Niño decaying pace under global warming. A reliable projection of El Niño decaying pace would reduce the uncertainty in the WNPAC projection. The key underlying processes are depicted in Figure 5. A faster (slower) decaying El Niño with stronger (weaker) tropical central Pacific cooling can strengthen (weaken) the summertime WNPAC via emanating intensified (weakened) descending Rossby waves to western North Pacific regions. The change in El Niño decaying pace depends on the strength of wintertime WNPAC. Because the anomalous easterlies to the southern flank of the wintertime WNPAC would enhance the background northeast wind and expedite El Niño demise. Both the El Niño-induced SSTAs and the precipitation sensitivity to El Niño-related SSTAs over topical eastern Pacific under a warmer climate could affect the change in WNPAC in boreal winter.

The contribution of the tropical central Pacific cooling associated with the El Niño decaying pace to the summertime WNPAC has been reported in previous studies (Jiang et al., 2019; Zhou et al., 2019). In this study, we further note that the simulated WNPAC during El Niño mature winter can modulate the decaying pace of El Niño in models and thus influence the simulated WNPAC during El Niño decaying summer indirectly.

In addition to the downwelling Kelvin waves driven by the easterly anomalies to eastern flank of the WNPAC in winter and spring, other factors such as the ENSO meridional width, longitudinal location, ocean-atmosphere coupling, and climate mean states can influence ENSO periodicity (An & Wang, 2000; Capotondi et al., 2006; Kirtman, 1997; MacMynowski & Tziperman, 2008; Timmermann et al., 1999). In a recent study, Lu et al. (2018) formulated a new Wyrtki index to capture the periodicity of ENSO. They proposed that a stronger thermocline and zonal advective feedback would lead to a shorter ENSO period, whereas a lower efficiency of the recharge/discharge mechanism would result in a longer ENSO period. A decadal shift of ENSO decaying effect on the WNPAC around the early 1990s has also been observed in both reanalysis and model simulations (Chen & Zhou, 2014), indicating the potential role of internal decadal variability in the changes of ENSO-WNPAC relationship. These results suggested that the projections of the duration of the El Niño and the associated summertime WNPAC are still uncertain and worthy to be studied in future.
Compared with observations, the El Niño-related summertime WPAC simulated by Group A models in the Historical experiment is closer to that in observations (figure not shown), implying their projection results would be more reliable than Group B models; that is, the summertime WPAC in a warmer world is more likely to weaken. The biases in some models may partly contribute to the intermodel uncertainties in future projection. Approaches to correcting model biases may reduce the uncertainties, and thus increase robustness of climate projection (Li et al., 2016; Zheng et al., 2016), which deserve further study for the projection of the WPAC.

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