Are Greenhouse Gases Changing ENSO Precursors in the Western North Pacific?*

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ABSTRACT

Using multiple observational and model datasets, the authors document a strengthening relationship between boreal winter sea surface temperature anomalies (SSTAs) in the western North Pacific (WNP) and the development of the El Niño–Southern Oscillation (ENSO) in the following year. The increased WNP–ENSO association emerged in the mid-twentieth century and has grown through the present, reaching correlation coefficients as high as ~ 0.70 in recent decades. Fully coupled climate experiments with the Community Earth System Model, version 1 (CESM1), replicate the WNP–ENSO association and indicate that greenhouse gases (GHGs) are largely responsible for this observed increase. The authors speculate that shifts in the location of the largest positive SST trends between the subtropical and tropical western Pacific impact the low-level circulation in a manner that reinforces the link between the WNP and the development of ENSO. A strengthened GHG-driven relationship with the WNP provides an example of how anthropogenic climate change may directly influence one of the most prominent patterns of natural climate variability, ENSO, and potentially improve the skill of intraseasonal-to-interannual climate prediction.

1. Introduction

Studies focusing on long-lead prediction of El Niño–Southern Oscillation (ENSO) have isolated several key patterns across the North Pacific Ocean. Using a linear inverse model (LIM), Penland and Sardeshmukh (1995) identified an “optimal structure” of sea surface temperature anomalies (SSTAs) across the North Pacific Ocean during the northern spring, which often precedes a full-fledged ENSO event during the following winter. This optimal SSTA structure has been examined in

a series of follow-up studies on ENSO precursors; most notably, Vimont et al. (2001, 2003a,b), Anderson (2003), and Alexander et al. (2010) have advanced and popularized the “seasonal footprinting mechanism” (SFM) as a plausible process, from which North Pacific atmospheric variability during the preceding winter/spring eventually influences tropical SSTAs across the equatorial Pacific Ocean and the development of ENSO in the following year.

In the SFM hypothesis, the North Pacific Oscillation (NPO), the second leading pattern of wintertime mid-to-high latitude atmospheric variability over the North Pacific (Rogers 1981; Linkin and Nigam 2008), imparts a surface wind stress that changes the surface heat fluxes and underlying SSTAs. This SSTA footprint can then last into the following summer in the subtropics and potentially impact equatorial zonal wind stress anomalies. Alexander et al. (2010) argue that the wind–evaporation–SST (WES) feedback (e.g., Xie and Philander 1994) and

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off-equatorial Rossby waves could subsequently impact tropical low-level winds and the equatorial thermocline, initiating the onset of ENSO. In addition, Anderson (2004) and Anderson and Maloney (2006) show that wind stress anomalies induced by the NPO may also have a concurrent influence on subsurface temperatures and heat content across the central and eastern tropical Pacific, which can persist and subsequently influence the overlying SSTAs throughout the following year. The occurrence of tropical wind stress anomalies is often interpreted as the stochastic forcing of ENSO (Alexander et al. 2008).

Two subtropical–tropical patterns are strongly related to NPO variability and are both significantly correlated to ENSO up to 6–12-month lead time. Both are identified using a maximum covariance analysis (MCA) of low-latitude low-level winds and SSTA: the Pacific meridional mode (PMM), which is based on the eastern half of the North Pacific (Chiang and Vimont 2004; Chang et al. 2007), and, more recently, the analogous western North Pacific (WNP) pattern located in the western part of the basin (Wang et al. 2012). Both the PMM and WNP are linked to an SSTA dipole with significant anomalies off the equator in the Northern Hemisphere subtropics with opposing SSTAs located in the deep tropics. The meridional SSTA gradient is accompanied by a pattern of low-level winds, which are most significant in the eastern tropical Pacific (the PMM) or the western tropical Pacific (the WNP).

Using reconstructed dynamic heights from Roundy and Kiladis (2007), Wang et al. (2012) show that the WNP, along with associated western Pacific wind anomalies (Fig. 1a), is related to the level of oceanic Kelvin wave activity through the following year and may instigate ENSO (McPhaden 2004; Roundy and Kiladis 2007). Correspondingly, the WNP-related SSTA and wind stress anomalies appear to be more strongly linked to the development of ENSO by the following winter than the PMM SSTA pattern (see Fig. 4 of Wang et al. 2012).

In this study, we report new observational and modeling evidence that, since the mid-twentieth century, there is a growing association between the WNP and the development of ENSO in the following year. This stronger relationship between the WNP and ENSO appears to be linked to increased greenhouse gases (GHGs) in the atmosphere, and it may reflect the energetic west-to-east development of (noncanonical) ENSO in recent decades (Wang and An 2002; Guan and Nigam 2008). Furthermore, a greater link between the WNP and ENSO one year later provides a plausible pathway by which anthropogenic climate change may influence ENSO and perhaps provide greater predictive skill in seasonal ENSO outlooks. To facilitate our analysis, various reanalysis and model datasets are utilized and introduced in

section 2. Results are presented in section 3. A summary and some conclusions are provided in section 4.

2. Data sources

To mitigate potential errors in historical SST data and reanalysis methods, three monthly SST datasets are utilized: 1) the Hadley Centre SST (HadSST) (Rayner et al. 2003), 2) the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) version 3b (Smith et al. 2008), and 3) the Kaplan long-term SST anomalies (Kaplan et al. 1998). Atmospheric winds are obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Global Reanalysis (NCEP1) that begins in 1948 (Kalnay et al. 1996).

In addition, to examine the long-term changes in the WNP and ENSO, historical simulations with the Community Earth System Model, version 1 (CESM1), are analyzed. The CESM1 is the latest generation of fully coupled community climate models that have evolved over 30 years (Neale et al. 2010; Hurrell et al. 2013). Deser et al. (2011) showed that the Community Climate System Model, version 4 (CCSM4)—the predecessor of the CESM1 but sharing the same ocean model—demonstrates significantly improved ENSO variability, possibly due to the inclusion of convective momentum transport and a dilution approximation for convective available potential energy (Neale et al. 2008), as well as an improved Parallel Ocean Program, version 2 (POP2), ocean component (Danabasoglu et al. 2011). The Pacific Northwest National Laboratory (PNNL) and NCAR jointly performed CESM1 experiments for the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012).

This study uses three CMIP5 sets of “historical” single-forcing experiments that are driven by 1) greenhouse gas forcing only (GHG), 2) aerosol forcing only (Aerosol), and 3) natural forcing only including solar and volcano (Natural). Each experiment produced a two-member ensemble initialized from long-stable pre-industrial (1850) control runs up to 2005. In addition, we utilize a 350-yr fully coupled CESM1 simulation without any external forcings (i.e., no anthropogenic, solar, or volcanic forcings), referred to as the control simulation. This long-term control simulation is used for the depiction of natural variability. Moreover, Atmospheric Model Intercomparison Project (AMIP)-style runs are used to test the impact of observed SSTs on the overlying atmosphere. Because the CESM1 has yet to complete a set of AMIP runs at the time of this manuscript, we use the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies

FIG. 1. (a) MCA2 of WNP SSTA and surface wind anomalies in DJF adopted from Wang et al. (2012). The principal component (PC) time series of MCA2 is used as the WNP index. Outlined areas represent an alternative WNP index domain and the Niño-3.4 index domain. (b) The 25-yr sliding correlations between the WNP (DJF) and Niño-3.4 (DJF+1yr) indices using three SST datasets. Years on the x axis represent the final year of the 25-yr sliding window. The top of gray area indicates the 99% significance level. (c) As in (b), but for the three CESM1 experiments.

(GISS) model, called ModelE (Schmidt et al. 2006) from the CMIP5 archive.

3. Results

a. Strengthening of the WNP (DJF) and ENSO (DJF+1yr) association

Throughout this analysis, the WNP index is based on the second leading MCA mode of the western North Pacific SSTA and anomalous surface winds [as defined in Wang et al. (2012)], but the major findings are also reproduced using a simple index of the areal average SSTA. To align with above-average anomalies associated with the areal average WNP index, the positive phase of the MCA-based WNP is defined by the anomalous pattern of SST and winds shown in Fig. 1a. Figure 1b shows the 25-yr sliding correlation between the WNP index during boreal winter [December–February (DJF)] and the Niño-3.4 index (average SSTA for 5°S–5°N, 170°–120°W) during the following winter (DJF+1yr). The x axis corresponds to the final year of each correlation window. Here, the WNP and Niño-3.4 indices are linearly detrended within each 25-yr moving window in order to examine the interannual correlations between the WNP and ENSO, irrespective of multidecadal or longer trends. We note that either removing a single fixed trend over the entire analysis period or keeping the trend results in similar increases in the correlation with a difference less than 0.1 (not shown).

A strong increase in correlations between the WNP and ENSO (DJF+1yr) is evident among all three SST datasets (Fig. 1b). This increase is particularly robust for moving windows with 1960 as the initial year. The correlation has increased to as high as 0.7 in the most recent part of the record. This result is robust regardless of the length of the sliding windows (not shown).

Next, the WNP–ENSO association is examined using CESM1 simulations forced by the GHG, Natural, and Aerosol forcings to understand the role of external forcings. Figure 1c shows, for these CESM1 single forcing experiments, the 25-yr sliding correlations between detrended values of the WNP (DJF) and Niño-3.4 indices one year later (DJF+1yr). A considerable amount of decadal variability of the correlation between the WNP and ENSO is observed among the forcing experiments. While the Aerosol and Natural forcing experiments show significant correlations between the WNP and ENSO for brief periods between about 1940/50 through 1960/70, only the GHG forcing reveals strong increase in the correlations that begins during the period around 1950–70 and continues through the present. The GHG-only experiment indicates correlations as strong as ~ 0.9 between the WNP (DJF) and ENSO (DJF+1yr) in the

FIG. 2. Model-based assessment for the occurrence of significant correlations with various time windows as indicated in the x axis computed for the GHG and Natural experiments. The thin vertical lines depict one standard deviation. See text for details.

recent decade while the Natural-only experiment indicates mostly insignificant correlations throughout the analysis period. Because these experiments are free runs, the specific years among the model experiments cannot be directly compared. Thus, the only robust comparison in Fig. 1c is that neither the Aerosol run nor the Natural run produces a sustained period of significant correlations as large, and for as long, as the GHG experiment. This observation is consistent in all members of the ensemble as shown by the figure in the supplemental material for the Natural run.

From a sampling point of view, the low-frequency variability in sliding correlations between any pair of climatic time series often contains apparent periodicities; this is known as the “Slutsky–Yule effect” (Stephenson et al. 1999) and may lead to physical explanations for stochastic noise (Gershunov et al. 2001). Thus, to examine whether the difference between the GHG and Natural experiments is statistically significant, we perform a test following that introduced by Gershunov et al. (2001). A bootstrapping scheme is applied to simulate 500 pairs of correlated white noise time series that mimic the distributions of WNP (DJF) and ENSO (DJF+1yr), using the statistical software R (www.r-project.org). Shown in Fig. 2 is the range of significant correlations within the various time windows starting with 7 yr. Beginning with the 20-yr window, the correlations between the GHG and Natural experiments become distinct. The simulated time series do not provide information on when the correlations

SST Correlation with inverted WNP (DJF)

FIG. 3. (a) Correlation maps of SSTA with the inverted WNP index for (left) 0-lead DJF and (right) 1-yr lead DJF+1yr, using the HadSST and NCEP1 data for the period 1958–2010. All variables are detrended. The Niño-3.4 area is outlined in the right panels. Stippled areas indicate significance at the 99% level with the t test. (b)–(d) As in (a), but for the CESM1 simulations from the GHG, Natural, and Aerosol forcing experiments, respectively, for the period 1958–2005.

become significant, although it can be inferred from Fig. 1c that the most significant correlations of the GHG experiment are concentrated during recent decades.

For verification purposes, Fig. 3a shows one-point correlation maps between SSTA and the WNP index at lead times of zero (left) and one year (right), using HadSST data for the period 1958–2010 (following Wang et al. 2012). The WNP index is inverted, so the map can be interpreted as the negative WNP phase that precedes El Niño. During DJF, strong correlations are evident along the East Asian coastline and along the Kuroshio extension. In the following winter (DJF+1yr), the WNP is related to a significant basin-wide El Niño SSTA pattern. Furthermore, as shown in Figs. 3b–d the correlations between the WNP and SSTA based on the forcing experiments for DJF (left) and DJF+1yr (right) during 1958–2005 bear a strong resemblance with the observations. Key aspects of the

WNP relationship with SSTA are broadly reproduced, with the exception of opposing correlations in the eastern Indian Ocean. These results demonstrate the performance of CESM1 in simulating ENSO and its precursor SSTA patterns in the WNP.

b. Shifts in the SST trends and the WNP (DJF)–ENSO (DJF+1yr) association

To better understand why the detrended and inter-annual relationship between the WNP (DJF) and ENSO (DJF+1yr) has been increasing, we split the dataset into two halves: 1950–79 and 1980–2008. The year 1950 is chosen as a starting point because of the greater reliability in the observed datasets over the tropical Pacific after that time (Bunge and Clarke 2009; L’Heureux et al. 2012). To further suppress sampling errors, two SST datasets are averaged together (HadSST and ERSST).

FIG. 4. Correlation map of DJF SSTA (shading) and regression of surface winds weighted by the correlation (vector length) against the DJF+1yr Niño-3.4 index during the periods of (a) 1951–79 and (b) 1980–2008, using the NCEP1 wind and averaged HadSST-ERSST data. The plotted values exceed significance at the 95% level. (c) Similar to the 25-yr sliding correlation in Figs. 1b and 1c, but for the DJF surface wind stress (τ_U) [averaged in the yellow box in (a) and (b)] and the DJF+1yr Niño-3.4 index from the three CESM1 experiments. (d) As in (c), but for correlations between τ_U and the inverted DJF WNP index.

Figures 4a and 4b show the DJF SSTA correlation and the low-level wind regression against the DJF+1yr Niño-3.4 index (the length of the vectors are determined by the correlation). Comparing the two halves, the most striking and pronounced change in the recent era is the stronger regression/correlation between ENSO (DJF+1yr) and

the previous DJF low-level wind anomalies curling southward and then eastward in the western equatorial Pacific just north of Papua New Guinea. Also evident is a stronger out-of-phase SSTA correlation between the subtropical western North Pacific and western equatorial Pacific (about 160°E–180°). This result mirrors the inverse

FIG. 5. As in Figs. 4a and 4b, but showing correlations/regressions with the inverted DJF WNP during two periods: (a) 1951–1979 and (b) 1980–2008.

of Fig. 1a and strongly implies that one of the canonical initiating mechanisms for ENSO onset has become more active recently; namely, the generation of oceanic Kelvin waves by wind stress anomalies over the western equatorial Pacific.

The contemporaneous correlations between the DJF WNP index and DJF SSTA and wind anomalies for the two eras are shown in Fig. 5. West of 180°, the shift in the correlation maps between the two eras is less striking compared to that in Fig. 4. However, one of the significant differences is that the equatorial western Pacific wind anomalies have changed from more southerly flow to westerly flow in the recent era (yellow box between 120°E and 180°). Also, the most significant equatorial SSTA correlations in the western Pacific have shifted farther east. East of 180°, the strength of the subtropical North Pacific SSTA correlations has increased in the recent period, while the strength of the equatorial correlations has weakened. Nevertheless, while it appears the WNP SSTA dipole has always been present, the similarity between Figs. 4b and 5b suggest that the precursor pattern of (1 yr prior to) ENSO has become more closely linked to the WNP pattern in recent years, and the associated equatorial wind anomalies imply a significant change in how ENSO is initiated.

Given that low-level wind anomalies in the western equatorial Pacific are optimally situated to influence the generation of oceanic Kelvin waves that affect the development of ENSO, we show in Figs. 4c and 4d the CESM1 25-yr sliding correlations of the detrended surface zonal wind stress averaged for 5°S–10°N, 120°–170°E (τ_U) with the detrended Niño-3.4 (DJF+1yr) and WNP (DJF), respectively. Among all the forcing experiments, only the GHG experiment illustrates the pronounced upward correlation between low-level wind stress in the equatorial western Pacific and the WNP–ENSO beginning in the mid-twentieth century. The increased correlations of the low-level winds provide more evidence for an increased GHG-driven relationship between the WNP and ENSO development by the following year. Noteworthy is that we have also tested the wind field of the twentieth-century reanalysis data (Compo et al. 2011) and found the result (not shown) to be consistent with that of the NCEP1.

c. The changing ENSO precursor pattern

Why are there stronger connections between the low-level winds in the western tropical Pacific and the WNP (DJF)–ENSO (DJF+1yr) index in the recent decades? To further examine the extent to which the low-level

FIG. 6. Composite differences of SSTA (shading) and surface wind (vectors) prior to (a) El Niño (DJF-1yr) and (b) La Niña (DJF-1yr) between the two eras of 1951–79 and 1980–2008. (c) Differences between (a) and (b). The wind fields are from NCEP1 while the SSTA fields are averaged from HadSST and ERSST.

wind fields may change the ENSO–WNP link, Fig. 6 presents composites of SSTA and winds one year prior to (a) El Niño and (b) La Niña, using a $\pm 0.5^{\circ}\text{C}$ threshold in the DJF Niño-3.4 index. The composite differences between the two eras, which are not detrended, emphasize the change in the preceding SSTA and winds from the earlier period to the most recent period. This composite stratification allows for an examination of how the precursor SSTs have changed for El Niño and

for La Niña separately. Interestingly, positive SST trends east of Taiwan and/or south of Japan have become greater prior to La Niña whereas these positive trends have become relatively muted prior to El Niño. In the equatorial western Pacific, positive SST trends are stronger prior to El Niño (about 160°E – 180°) relative to those prior to La Niña.

By design, nearly the same relative SST trend differences are revealed in the GISS AMIP ensemble, which

FIG. 7. As in Fig. 6, but for the AMIP runs of the GISS model.

uses HadSST as the boundary condition (Fig. 7). The use of an AMIP simulation allows us to infer how the SSTs of ENSO precondition influence the low-level wind anomalies. While the low-level winds are not identical between Figs. 6 and 7, some commonalities emerge. In particular, prior to El Niño, the low-level flow north of Papua New Guinea is generally westerly and pointed toward the region of largest SST warming located in the equatorial western Pacific (Figs. 6a and 7a). Conversely, prior to La Niña, the low-level flow has become much

weaker north of Papua New Guinea and, in the AMIP run, is actually easterly, curving northward into the region of strong SST warming (Figs. 6b and 7b). That the precursor pattern in the AMIP run is similar to the observed pattern implies that the change in the wind anomalies is primarily due to the change in SSTs.

Figures 6c and 7c show the difference between the precursor (DJF-1) El Niño and La Niña “trend patterns.” These results share strong similarities with the WNP pattern and the precursor ENSO pattern in the

FIG. 8. (a) As in Fig. 1b, but showing the 25-yr sliding correlations of the inverted WNP index (DJF) with the NPO (blue), PMM-wind (green), and PMM-SST (red) indices during DJF. (b) As in (a), but correlated with the Niño-3.4 (DJF+1yr) index. Shading indicates the significance at the 99% level.

recent era, as shown by the correlation maps in Figs. 4b and 5b, with both depicting the SSTA dipole and strong curvature of the winds connecting the subtropical WNP to the equator. The fact that the difference pattern resembles the WNP is suggestive that future work should include an explanation for why the positive SST trend pattern varies between winters (and likely summers) prior to El Niño and La Niña. Ultimately, the recent increase in correlations between ENSO and the WNP, which also occur in the detrended data, cannot be attributable to a single, fixed mean state SST change (i.e., static linear trend pattern).

d. Correlations with SFM-related indices

Wang et al. (2012) noted that the WNP is linked to other Pacific climate patterns related to the seasonal footprinting mechanism, such as the PMM and the NPO. Following Fig. 1b, sliding correlations are computed between the detrended WNP and the DJF averaged values of three other indices of the NPO, PMM-wind, and PMM-SST (Fig. 8a). Here the NPO index is constructed using the second principal component of the North Pacific sea level pressure (Linkin and Nigam 2008) while the PMM indices were provided by Dan Vimont (<http://sunrise.aos.wisc.edu/~dvimont/MModes/Data/>). Over the past 70 years, the relationship between the WNP and PMM has increased modestly and remains significant, while the relationship between the WNP and NPO has decreased since 1990 and is insignificant in the most recent decade. There is significant diversity among the three indices when they are correlated with ENSO a year later, as shown in Fig. 8b. While the NPO has become a less significant ENSO precursor since the 1970s, the correlations between ENSO and the PMM-wind index remain steady and

significant through the analysis period. On the other hand, Furtado et al. (2011) have noted that the southern lobe of the NPO represents a separate but related center of action with regard to its northern counterpart; this southern lobe of the NPO in the vicinity of Hawaii still maintains significant correlations throughout the analysis period (not shown).

By comparison, the PMM–SST index correlations remain largely insignificant until a strong shift around 1995, after which the PMM wind and SST indices come into greater alignment. The greater PMM–SST correlations in the recent era may also be suggested in Fig. 4b by the stronger subtropical eastern Pacific SSTA correlations prior to ENSO. However, the lack of strong correspondence in the correlations of the NPO and PMM indices with the preceding results makes them unlikely candidates to explain the influence of GHG on the increasing WNP–ENSO relationship. Yet, these correlations still imply that the PMM is playing a greater role in more recent decades, both in its contemporaneous relationship with the wintertime WNP pattern and its antecedent connection with ENSO.

e. The role of multidecadal variability

Using the 350 years of the CESM1 preindustrial control simulation representing coupled climate variability, we can diagnose how the WNP–ENSO relationship may have evolved in the absence of external perturbations (i.e., without anthropogenic and natural forcings). To examine multidecadal variability associated with tropical and subtropical SSTA, which can arise without external forcing (e.g., Wittenberg 2009), we first apply a 30-yr low-pass filter to SSTA. Shown in Fig. 9a is the correlation map of the low-passed SSTA correlations with the low-passed WNP during DJF, portraying the

CESM1 350-year control run
(preindustrial)

FIG. 9. Correlation of 30-yr low-pass DJF SSTAs with (a) low-pass WNP from the 350-yr control run of CESM1. (b) Low-pass WNP SST from yellow box in (a) (black line) and the 25-yr sliding correlations between the detrended, nonfiltered WNP and Niño-3.4 (DJF+1yr), following Fig. 1b but centered here (red dotted line). (c) EOF1 of 30-yr low-pass SSTA. (d) PC1 time series where the dashed lines indicate the threshold for warming-cooling periods. (e) As in Fig. 5c, but for the difference of pre-El Niño and pre-La Niña between the PC1 warming and cooling periods [see (d)]. The dotted area in (a) indicates the 99% significance level taking into account the reduced degree of freedom due to low-pass filtering.

low-frequency variability. The result reveals the familiar WNP SSTA dipole shown in Fig. 1a. Figure 9b shows the low-passed WNP time series (black line) against the 25-yr sliding correlations (red dotted line) between the detrended, nonfiltered DJF WNP index and the detrended, nonfiltered Niño-3.4 index (DJF+1yr). Interestingly, the internal multidecadal variability present in the WNP region tightly corresponds with natural decadal changes in the interannual WNP–ENSO relationship.

An empirical orthogonal function (EOF) analysis is then applied to the 30-yr low-pass filtered SSTA. Both the first EOF pattern (Fig. 9c) and principal component (PC) time series (Fig. 9d) closely resemble the SSTA correlations with the WNP shown in Figs. 9a and 9b, respectively. The resemblance indicates that the fluctuations of

the WNP SSTA dipole is tied to the dominant mode of North Pacific low-frequency (30 yr) variability, echoing the findings presented earlier using a shorter historical record. Using the PC1 index values greater/less than ± 0.3 ($\sim 1\sigma$ of the normalized PC series) for the definition of warming (cooling) periods, we categorize El Niño (La Niña) events in each period using the $\pm 0.5^\circ\text{C}$ threshold. We then compute the El Niño (La Niña) composite differences between the warming and cooling periods following Fig. 6c (Fig. 7c). The result (Fig. 9e) reproduces the WNP SSTA dipole similar to that in Figs. 6c and 7c and is associated with equatorward surface wind anomalies from southeastern Asia that curve eastward over the equatorial western Pacific. These results suggest that, while the WNP dipole pattern appears to persist

throughout both warm and cold periods, the connection of the WNP pattern with ENSO development a year later strengthens during warmer periods.

Therefore, changes in the WNP–ENSO correlation are manifest in multidecadal natural variability without any external–anthropogenic forcings. However, we note two differences from the GHG-related simulations: 1) the maximum sliding correlations in Fig. 9b barely exceed 0.5 during the 350 yr while those in the GHG-only experiment reach 0.9 (Fig. 1c), and 2) the maximum amplitude between the WNP warming and cooling periods in Fig. 9b is only 0.5°C while the GHG-forced warming since 1960 is $\sim 1.2^{\circ}\text{C}$ (not shown). It is therefore conceivable that increased GHGs are driving a rapid and unprecedented change in the western North Pacific SSTs that accounts for the recent strengthening of the WNP–ENSO relationship.

4. Concluding remarks

While the WNP index is significantly correlated to the development of ENSO by the following winter, the analysis presented here further suggests that this relationship between the WNP and ENSO has significantly increased since the mid-twentieth century. The stronger WNP–ENSO association occurs on interannual time scales based on detrended data and so is not the direct result of the SST warming trends. CESM1 single forcing experiments suggest that the increased relationship is forced by increasing GHGs in the atmosphere. The recent era is characterized by strengthening of the low-level wind anomalies in the equatorial western Pacific one year prior to ENSO, and an AMIP-style run implies that this strengthening is due to shifts in the location of positive SST trends relative to El Niño or La Niña (1 yr previously). Prior to El Niño, the region of positive SST trends occurs near the typical region of above-average SSTA in the western equatorial Pacific whereas, prior to La Niña, positive SST trends reinforce the above-average SSTA near southeastern Asia.

It is hypothesized that this shift in SST trends, which sharpens and amplifies the above-average SST region of the WNP dipole, is conducive to a stronger WNP–ENSO relationship on interannual time scales. Analysis of the 350-yr CESM1 preindustrial control simulation reveals that fluctuations in the leading North Pacific SSTA pattern of multidecadal (30 yr) variability mirror the variability in the correlations between the WNP and ENSO. While the control simulation only reflects coupled climate variability without external forcings, CESM1 suggests that anthropogenic forcings, particularly GHGs, have facilitated and likely accelerated such a WNP–ENSO relationship. In recent decades, both the GHG-forcing

experiment and the observations indicate unprecedented correlations within 0.7–0.9 between WNP and ENSO in the following winter.

The intensification of the relationship between WNP and ENSO due to GHGs elicits several interesting questions that are not pursued here. In the present study, we have reported findings based CESM1 historical experiments and show the difference in SST trends, which are linked to an intensified WNP–ENSO relationship. However, a clear mechanism to explain these trends remains elusive and motivates further investigation. Equatorial SST anomalies in the eastern Pacific are evident in the precursor patterns, which may have some impact on the WNP region. Also, as shown in Wang et al. (2012), anomalies in the WNP are associated with low-level equatorial winds that may impact the frequency of oceanic Kelvin waves and facilitate the development of ENSO one year later. During the negative WNP phase, westerly wind anomalies in the tropical western Pacific could lead to more activity that could trigger El Niño, and during the positive WNP phase easterly wind anomalies potentially encourage the development of La Niña by precluding Kelvin wave activity. Thus, the increased low-level zonal wind anomalies in recent decades strongly evoke the possibility that ENSO onset may increasingly be driven by wind stress anomalies in the western Pacific generating oceanic Kelvin waves. Recently, Stevenson et al. (2012) suggested enhanced Kelvin wave activity under high CO_2 simulations, which implies a greater role for stochastic triggering of El Niño events.

What is more, the stronger WNP–ENSO relationship does not appear to be accompanied by an increasing correlation between the NPO and WNP; rather, that correlation is decreasing. However, the relationships of PMM with both WNP and ENSO are increasing. These results imply that the seasonal footprinting mechanism (SFM) may have changed characteristics in relation to GHG and SST trends in the WNP. Future work should also consider the changing (and/or persistent) role of internal atmospheric processes, such as the North Pacific Oscillation, upon surface and subsurface temperatures in setting the stage for ENSO (see Anderson 2004; Anderson and Maloney 2006). Along those lines, possible changing roles of other internal atmospheric processes in setting the stage for ENSO should be taken into account as well.

Finally, these results—with a focus on the year prior to ENSO events—provide an important example of how lower-frequency changes, such as anthropogenic climate change, can directly impact intraseasonal-to-interannual climate variations. Provided that prediction tools can adequately capture the WNP–ENSO connection, if

GHGs are increasing the WNP–ENSO relationship then this may suggest potentially more skillful ENSO forecasts at 1-yr lead and increased confidence in seasonal predictions during the decades to come.

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