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Multidecadal Variations in the Tropical Western Pacific Driven by Externally-Forced AMV-Like Changes

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Key Points:

- Atlantic Multidecadal Variability (AMV) is mainly correlated with the forced decadal sea surface temperature (SST) variations in tropical western Pacific (TWP) during 1920–2020
- About 43%–49% of forced TWP SST variations, which account for more than half of the total decadal variations, come from the Atlantic Ocean
- The connections between the externally-forced AMV and TWP SST are through the extratropical pathway in the North Pacific

Supporting Information:

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

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Abstract

Multidecadal sea surface temperature (SST) variations in the tropical western Pacific (TWP) have been attributed to nonlinear external forcing and remote influences from the Atlantic Multidecadal Variability (AMV). However, the AMV resulted from both internal variability (IV) and external forcing. Thus, the origins of the TWP SST variations are not well understood. By analyzing observations and model simulations, we show that more than half of the decadal to multidecadal SST variations in TWP during 1920–2020 resulted from external forcing with the forced component correlated with AMV, while the internal component is unrelated to AMV. Furthermore, about 43%–49% of the forced AMV-like SST variations in TWP result from remote influences of the forced AMV in the Atlantic via atmospheric teleconnection over the North Pacific, with the rest from other remote or local processes.

Plain Language Summary

Sea surface temperature (SST) variations in the North Atlantic Ocean and Pacific Ocean are linked on multidecadal time scales. Previous studies have indicated that the Atlantic multidecadal SST variations (referred to as Atlantic multidecadal variability, AMV) not only influence the decadal SST variations in the tropical central-eastern Pacific (referred to as Interdecadal Pacific Oscillation), but also modulate the multidecadal SST variations in the tropical western Pacific (TWP). Since the TWP SST variations can result from both local external forcing and remote influences from AMV, the exact origins of TWP's multidecadal variability remains unclear. Here we analyze observations and model experiments to show that ~56% of the decadal to multidecadal SST variations in TWP during 1920–2020 resulted from nonlinear external forcing, with the rest from internal variability (IV), and the forced SST variations in TWP are correlated with AMV while the IV-induced variations are unrelated to AMV. Both the local external forcing and remote influences from the forced AMV in the Atlantic contribute to the forced multidecadal SST variations in TWP.

1. Introduction

The Atlantic Multidecadal Variability (AMV) and Interdecadal Pacific Oscillation (IPO) are the leading mode of SST multidecadal variations in their respective basins, but the Atlantic and Pacific multidecadal variability are likely linked (Cai et al., 2019; d'Orgeville & Peltier, 2007; Latif, 2001; Nigam et al., 2020). Whether and how the Atlantic Ocean drives the Pacific variability or vice versa is an active research area (Gong et al., 2020; Hong et al., 2022; Wang, 2019). Many studies showed that Atlantic SST variations (mostly AMV) could drive IPO-like variability in the Pacific through atmospheric Walker circulation, with a warm tropical Atlantic often leading to a cold central-eastern tropical Pacific (Kucharski et al., 2016; Li et al., 2016; McGregor et al., 2014; Zhang & Delworth, 2007). Conversely, a warm-phase IPO can also drive a warm-phase AMV through atmospheric teleconnections (e.g., Pacific–North American pattern) (Meehl et al., 2016, 2021). Two-way interactions between the Atlantic and Pacific can arise through internal variability (IV) without external forcing, for example, changes in greenhouse gases or aerosols (Hua et al., 2022).

Recently, Sun et al. (2017) found a link between the AMV and the multidecadal variability in the tropical western Pacific (TWP) since 1900, highlighting the role of dynamically-induced inter-basin atmospheric teleconnection between Atlantic and TWP multidecadal SST variations. However, the AMV since 1870 resulted from both IV and external forcing (Hua et al., 2019; Otterå et al., 2010; Qin et al., 2020a, 2022; Ting et al., 2009). Furthermore, aerosol forcing can generate AMV-like SST variations across global ocean basins (including the TWP) since

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1920, leading to in-phase relationship between Atlantic and Pacific SSTs on multidecadal time scales (Qin et al., 2020b), although historical SST time series in TWP is dominated by the global warming signal (Power et al., 2021). Thus, the exact roles of IV and external forcing in recent TWP SST multidecadal variations, especially their linkage with the internally-generated and externally-forced AMV, are still not well understood.

This study aims to examine and quantify the roles of IV and external forcing and AMV in generating the recent TWP SST multidecadal variations through analyses of a suite of coupled model experiments. We first quantify the internally-generated and externally-forced TWP SST multidecadal variations, and then examine the remote influences from internally-generated and externally-forced components of the AMV in the Atlantic on the TWP SSTs and associated physical processes. Furthermore, we also quantify and compare the relative roles of the local external forcing and remote influence from forced AMV in TWP SST variations, as external forcing can influence the TWP directly through local processes and indirectly or remotely from forced AMV through atmospheric teleconnections. Our results should improve current understanding of TWP SST multidecadal variations, especially the roles of IV, local external forcing and remote influences from AMV.

2. Data, Model Simulations, and Analysis Methods

2.1. Data and Model Simulations

We used monthly SST data from 1920 to 2020 from four observational SST data sets, including the Hadley Center Global Sea Ice and SST version 1 (HadISST1, Rayner et al., 2003), Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5, Huang et al., 2017), Kaplan Extended SST v2 (Kaplan et al., 1998), and COBE-SST version 2 (Centennial in situ Observation-Based Estimate, COBE-SST2) (Ishii et al., 2005). We used their ensemble mean as the observed SSTs to reduce uncertainty (Qin et al., 2020b), as the SST observations are sparse over the tropical and southern oceans.

We analyzed the large ensemble of historical (1920–2005) and future (2006–2100 under RCP8.5) simulations from 1920 to 2100 by the Community Earth System Model Version 1 (CESM1) (i.e., CESM1-LE; Kay et al., 2015). Each of the 40 simulations has the same external forcing, but starts from slightly perturbed initial conditions. We also used the coupled model simulations from the time-series pacemaker experiments by CESM1 (Meehl et al., 2021). The Atlantic pacemaker experiments consist of 10 ensemble simulations, in which time-evolving SST anomalies in the North Atlantic (5°N–55°N, with a linearly tapering buffer zone that extends to equator and 60°N) are nudged to observations (from ERSSTv3b) during 1920–2013, with the rest of the world being fully coupled. All external forcing is identical to the CESM1-LE, besides stratospheric ozone, which is found to be negligible and has minimal effects on the tropical climate (Yang, An, et al., 2020; Yang, Arblaster, et al., 2020). The CESM1 Atlantic pacemaker ensembles simulate the AMV evolution in line with observations, whereas the AMV in the CESM1-LE varies among the individual runs which may differ from the observed AMV cycles during the historical periods.

We also analyzed the idealized Atlantic pacemaker experiments by CESM1 (Meehl et al., 2021; Ruprich-Robert et al., 2017). Two 30-member ensembles of simulations are run for 10 years each simulation with specified idealized AMV (i.e., positive and negative AMV) configurations (see Text S1 in Supporting Information S1). In these simulations, external forcing is fixed at the pre-industrial level, and the specified AMV-related SST anomalies in the North Atlantic are kept constant in time, with the rest of the globe being fully coupled.

2.2. Analysis Methods

To separate the internally-generated (IV) and externally-forced (EX) components in observations, we used the global-mean SST (GMSST) time series from the multi-model ensemble mean (MMM) of all-forcing historical simulations from the Phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016, Table S1 in Supporting Information S1) as the first-order estimate of the forced signal and removed it through linear regression from the observed SSTs at each grid point to produce the residual fields that contain primarily IV (Dai et al., 2015; Hua et al., 2022; Qin et al., 2020a). In this way, we can separate the IV-related and EX-related SST variations over the TWP or the North Atlantic in observations. This regression-based separation method requires that internally-generated variations (such as the internal AMV-related oscillation) are not significantly correlated with the forced signal, which can be achieved by increasing the length of the regression time period (e.g., 1920–

2020) to be much longer than the time scale of the IV (e.g., ~40–60 years for AMV); otherwise, the regressed component (i.e., the EX component) may also contain some internal variations.

We defined the AMV index (AMV) as the linearly detrended, low-pass filtered and area-weighted average of SST anomalies over the North Atlantic Ocean (0°–80°W and 0°–60°N). A Lanczos filter with 19 points and a 13-year cutoff period was used in the low-pass filtering (Hua et al., 2018). The AMV represents the total multidecadal variations (i.e., due to both IV and EX) after removing its long-term linear trend (Qin et al., 2022). Following Qin et al. (2020a, 2022), we defined the internal AMV (AMV_{IV}) as the area-weighted average of the residual SST fields after removing the forced components. To represent the external AMV (i.e., AMV_{EX}), we used the difference between the total and internal AMV. The results are similar when using the linearly detrended SSTs averaged over the North Atlantic derived from the CMIP6 MMM to define the AMV_{EX} (Qin et al., 2022). Similarly, we defined the observed TWP SSTs (termed TWP*) as the linearly detrended, low-pass filtered SST anomalies over TWP (110°E−150°E and 0°–25°N) and then defined the internal TWP SST (termed TWP_{IV}) as the area-weighted average of the residual SST fields after removing the forced components. To examine the relationship between the AMV index and TWP SST in observations, we performed correlation analyses to reveal their association. A correlation coefficient (r) and its significance level were calculated between two time series to quantify their association. The significance level was estimated based on a two-sided Student's t test with an estimated effective degree of freedom to account for autocorrelation (Qin et al., 2020b). We also examined the statistical significance based on the bootstrapping method, which produced similar results (not shown).

To quantify TWP SST response to AMV-related SST anomalies and examine associated physical processes of AMV's influences, we used the linearly detrended SST and other fields from the ensemble mean of the CESM1 Atlantic pacemaker simulations to represent the AMV-induced variations over TWP and other regions (called AMV-induced), which includes both the forced and internal components. We used the ensemble mean difference between the CESM1 Atlantic pacemaker simulations and CESM1-LE to represent the variations induced by internally-generated AMV (called AMV_{IV}-induced, Hua et al., 2022), as the forcing is identical and thus the forced changes over the Atlantic and other regions should be similar in these experiments. The difference between the AMV-induced and AMV_{IV}-induced variations was considered as the AMV_{EX}-induced changes in the pacemaker experiments. Please note that the Atlantic pacemaker results allow us to examine the TWP SST variations and associated other changes induced by the AMV, AMV_{IV} or AMV_{EX}-related SST changes in the North Atlantic.

3. Results

3.1. Internal and Forced SST Variations in TWP

Observed TWP SST shows decadal to multidecadal variations superimposed on a warming trend from 1920 to 2020, which is reflected mainly in its forced component (Figure 1a). A strong correlation of 0.94 between the observed TWP and its forced component indicates that external forcing is the dominant driver of the decadal SST variations and long-term changes in TWP since 1920. As the correlation between the IV and EX components is weak ($r = 0.26$, $p = 0.39$), using the CMIP6 MMM of GMSST as the estimate of the forced signal should work effectively (otherwise, the two could be difficult to distinguish through regression). After linearly detrending the TWP SST and its forced component, Figure 1b shows that about 56% of the multidecadal SST variations during 1920–2020 in TWP (TWP*) are explained by the nonlinear forced component (TWP^*_{EX}) with a correlation of 0.75 between the two, with the remaining coming from IV.

Previous studies (Sun et al., 2017, 2021) suggested that the AMV (i.e., linearly detrended multidecadal variations in North Atlantic SSTs) drives the multidecadal SST variations in TWP. Our results also show a significant correlation between the detrended TWP SST (TWP*) and AMV ($r = 0.67$, Figure 1b). We further examine the relationship between the AMV and the internal and external components of the TWP SST variations. The correlation with the AMV is strong ($r = 0.72$) for the external component (TWP^*_{EX}) but insignificant ($r = -0.24$, $p = 0.41$) for the internal component (TWP_{IV}, Figure 1b). These results suggest that the internally-generated SST variations in TWP are unrelated to AMV, while the forced SST variations in TWP are correlated with the AMV.

3.2. Footprint of the AMV in TWP SSTs

We also found that multidecadal SST anomalies in TWP are associated with in-phase multidecadal SST anomalies in the Atlantic, with a warm phase of the AMV being associated with warm anomalies in TWP

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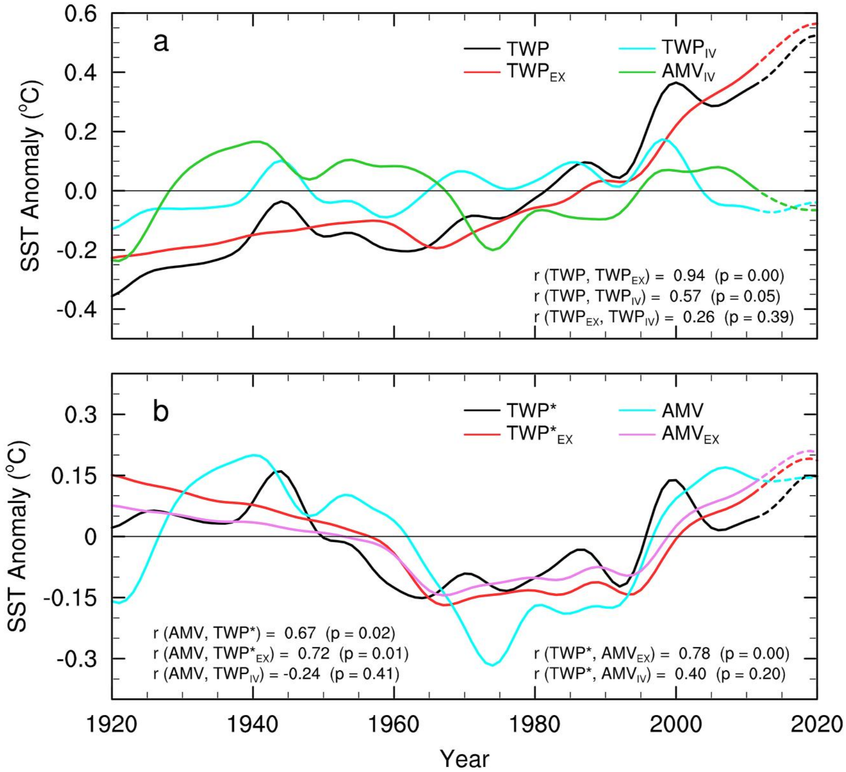

Figure 1. (a) Time series of low-pass filtered, annual-mean sea surface temperature anomalies (°C, relative to the mean of the analysis period from 1920 to 2020) averaged over the tropical western Pacific (TWP) (110°E–150°E, 0°–25°N, outlined in Figure 2a) from the observations (TWP, black line), its externally-forced component without detrending (TWP_{EX}, red line) and internally-generated component (TWP_{IV}, bright blue line) in the observations. The green line shows the internally-generated component of the Atlantic multidecadal variability (AMV) index (AMV_{IV}). The last 9 years (marked by dashed lines) are derived with mirrored data in the filtering and thus are less reliable. The correlation coefficients (r) between the TWP and TWP_{EX} or TWP_{IV}, together with the attained significance level (p), are also shown. (b) Same as panel (a), but for the linearly detrended TWP (termed TWP*) and TWP_{EX} (termed TWP^*_{EX}). The bright blue and purple lines show the total AMV index and the externally-forced component of the AMV index (AMV_{EX}), respectively.

(Figures 2a and 2d). The SST anomaly pattern associated with the multidecadal variations in TWP (Figure 2a) roughly matches the AMV-related SST anomaly pattern (Figure 2d), indicating that there exists some spatial similarity between the global SST anomalies associated with the North Atlantic and TWP SST multidedacal variations.

As both IV and external forcing contribute to the AMV (Qin et al., 2020a), we further distinguish the relationships of internally-generated (AMV_{IV}) and externally-forced AMV (AMV_{EX}) with the IV and EX components of TWP SST. Figure 2e shows that the AMV_{IV}-related SST fields (for a warm phase) exhibit a horseshoe-like warming pattern in the North Atlantic, warm anomalies over most the extratropical Pacific (including TWP), and cold anomalies in the South Atlantic and equatorial Pacific, which are consistent with pervious findings (Qin et al., 2022). However, North Atlantic SST anomalies associated with internal multidecadal SST variations in TWP (i.e., TWP_{IV}) show a cooling pattern (Figure 1b) that differs from the AMV_{IV}-related pattern, which shows relatively weak correlation over the TWP (Figure 2e). This further confirms that the IV-induced variations in TWP are not related to internal AMV-like SST anomalies in the Atlantic. In contrast, the AMV_{EX}-related SST anomaly pattern is similar to that associated with TWP_{EX} (Figures 2c and 2f). These results suggest that the observed AMV-like variations in TWP SSTs are externally forced, and the forced TWP SST variations are mainly related to the AMV_{EX}, rather than the AMV_{IV}.

To further this finding, we analyzed the Atlantic pacemaker ensemble simulations to investigate TWP SST's response to Atlantic SST forcing. We notice that the magnitude of TWP SST in observations (dashed green line in Figure 3a) is similar to the TWP SST response to the AMV-related variations in the Atlantic pacemaker

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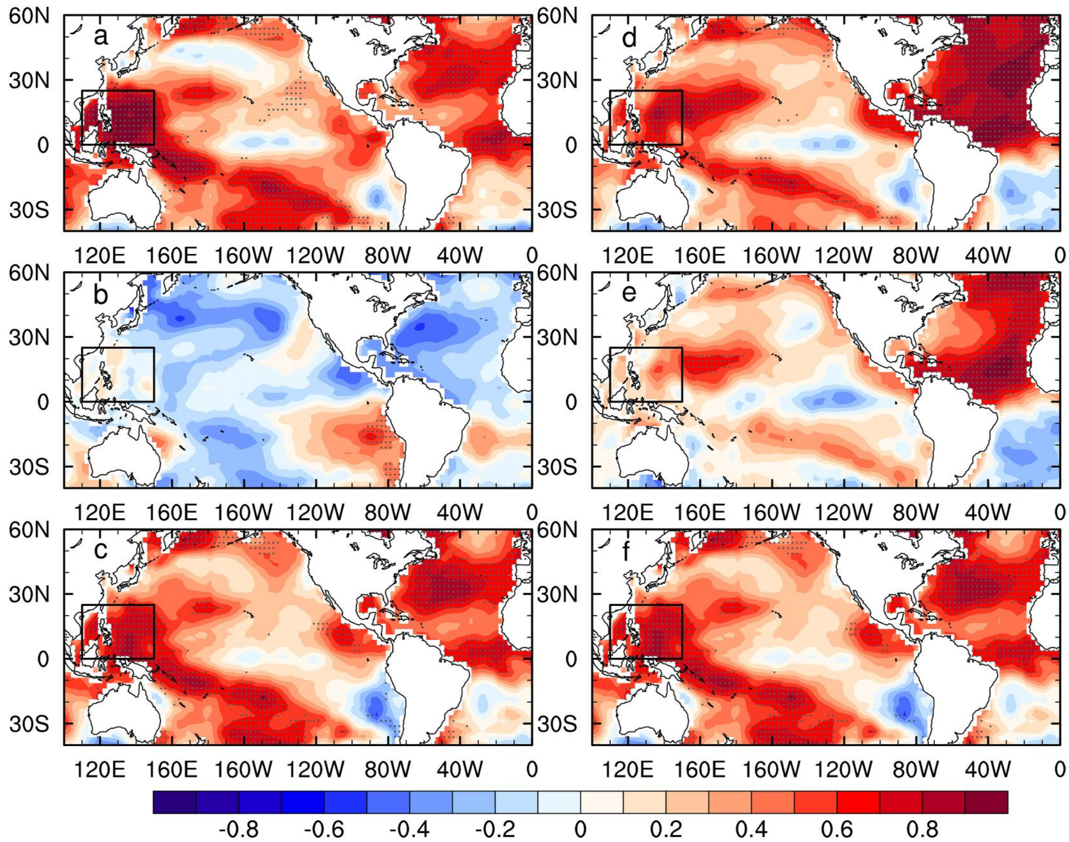

Figure 2. (a–c) Maps of correlation coefficients between (a) TWP*, (b) TWP_{IV}, and (c) TWP^*_{EX} indices shown in Figure 1 and local low-pass filtered and linearly detrended sea surface temperature anomalies from observations during 1920–2020. Panels (d–f) same as panels (a–c), but for the correlations with the Atlantic multidecadal variability, AMV_{IV}, and AMV_{EX} shown in Figure 1, respectively. The stippling indicates statistically significant regressions at the 0.05 level. The outlined boxes represent the tropical western Pacific.

simulations (solid green line in Figure 3a) and their correlation is strong ($r = 0.96$), confirming that the AMV drives the decadal variations in TWP. In addition to the impact from the total AMV, how AMV_{IV} affects TWP SST also deserves investigation. We use the SST difference between the CESM1 Atlantic pacemaker and its all-forcing ensemble simulations to examine the AMV_{IV}-related variations (Figures 3c and 3d).

Consistent with previous studies (Hua et al., 2022; Meehl et al., 2021; Ruprich-Robert et al., 2017), warm AMV_{IV} leads to a cold IPO-like SST pattern in the Pacific and a warm anomaly around TWP (Figure 3d). Figure 3c compares the IV-induced TWP SST variations in observations (dashed green line) and AMV_{IV}-induced TWP response in the model simulations (solid green line), which show a moderate correlation of 0.53. Thus, although the AMV_{IV} can contribute to decadal TWP SST variations (Figures 2e and 3d), other processes or inter-basin interactions may also play a role in the internal TWP SST variations (Figures 2b, Cai et al., 2019). For the AMV_{EX}-induced SST variations (Figures 3e and 3f), we found that there exists a strong linkage between the AMV_{EX} and TWP SST. That is, the dominant AMV-like variations in TWP SST are forced and strongly linked to AMV_{EX} (Figures 1b and 3e), while the IV-induced variations in TWP SST contribute less to the total SST variations in TWP (Figure 3c).

3.3. Causes of Decadal SST Variability in TWP

How does AMV_{EX} remotely influence TWP SST? It may be possible that the decadal SST variations in TWP can be linked with the North Atlantic SST through atmospheric teleconnections (Yang, An, et al., 2020; Yang, Arblaster, et al., 2020; Yao et al., 2021). In the North Pacific, the atmospheric circulation shows consistent responses to the AMV_{EX} from the lower to middle troposphere, with anomalous high pressure (Figures 4a–4c) accompanied by pronounced SST warming (Figure 3f, for a warm phase of AMV_{EX}). The warming SSTs and

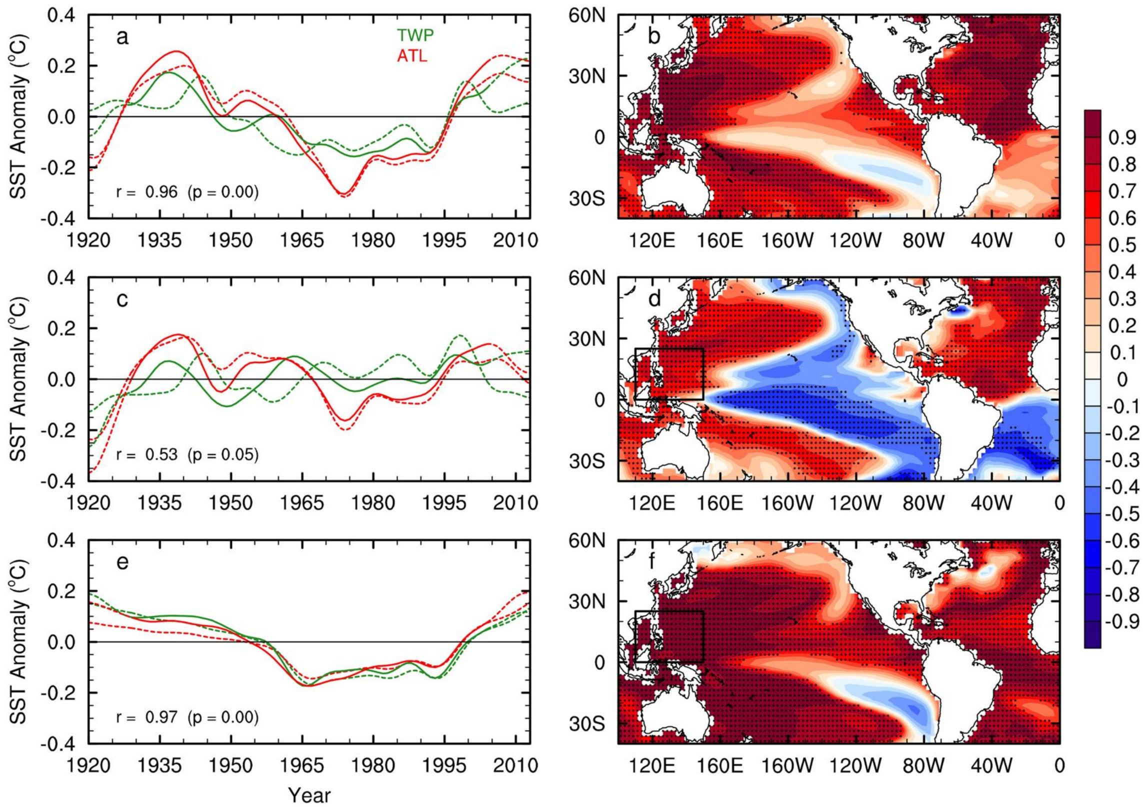

Figure 3. (a) Time series of low-pass filtered and linearly detrended annual-mean sea surface temperature (SST) anomalies (°C, relative to the mean of 1920–2013) averaged over the tropical western Pacific (TWP) (solid green line) and North Atlantic (solid red line) from the CESM1 Atlantic pacemaker ensemble simulations from 1920 to 2013. Also shown are the correlation coefficient between the two solid lines. The dashed green and dashed red lines show, respectively, the observed TWP SST anomaly (i.e., TWP*, black line in Figure 1b) and SST anomalies over the North Atlantic (i.e., Atlantic multidecadal variability, bright blue line in Figure 1b) after detrending and smoothing. Note that there exist slight differences between the solid (i.e., ERSSTv3b) and dashed (i.e., ensemble mean of HadISST1, Kaplan, ERSSTv5 and COBE) red lines. (b) Maps of correlation coefficients between the solid red line in panel (a) and local low-pass filtered and linearly detrended SST anomalies for the Atlantic pacemaker simulations, which represents the AMV-induced SST variations. The stippling indicates statistically significant regressions at the 0.05 level. (c, d) Same as panels (a, b), but with the ensemble difference of the CESM1 Atlantic pacemaker minus all-forcing ensemble simulations, so that it represents the unforced internal Atlantic SST variations (i.e., AMV_{IV}-induced variations). Panels (e, f) same as panels (a, b), but for the AMV_{EX}-induced variations, which are the differences between the AMV-induced and AMV_{IV}-induced SST variations.

enhanced vertical motion over the tropical Atlantic are associated with anomalous descent over the tropical Pacific with accelerated trade winds there through Walker circulation connections (Figure 4). Furthermore, the warming in the North Atlantic Ocean could enhance local convection and increase subsidence in the North Pacific, contributing to the anomalous North Pacific high pressure through extratropical pathway (Sun et al., 2017). The anomalous high pressure could weaken the Aleutian low and subtropical North Pacific westerlies, leading to enhanced surface warming around the subtropics through the wind–evaporation–SST (WES) feedback (Xie et al., 2010). The anomalous low-level southwesterly winds over the TWP (Figures 4a and 4b) can contribute to the warming there over TWP through thermal advection. The diagnosis of the mixed-layer heat budget (see Text S1 in Supporting Information S1) indicates that the SST anomaly in TWP is mainly induced by anomalous surface heat flux and meridional temperature advection (Figure S1 in Supporting Information S1).

Consistent with the AMV_{EX}-induced variations (Figure 4a), the North Pacific exhibits a positive sea level pressure (SLP) anomaly for a warm phase of the AMV and AMV_{IV} (Figures S2–S3 in Supporting Information S1). The anomalous high pressure can weaken the Aleutian low and subtropical North Pacific westerlies. The SLP responses also exhibit anomalous high pressure around TWP (for a warm phase). That is, the connections between the AMV (or AMV_{EX} and AMV_{IV}) and TWP SST are established through the North Pacific. Previous studies suggest that the AMV (for a warm phase) could produce anomalous high pressure over the North Pacific and enhance local warming through inter-basin atmospheric teleconnection (Sun et al., 2021). The subtropical North Pacific SST warming could lead to wind convergence and anomalous cyclonic circulation and low pressure

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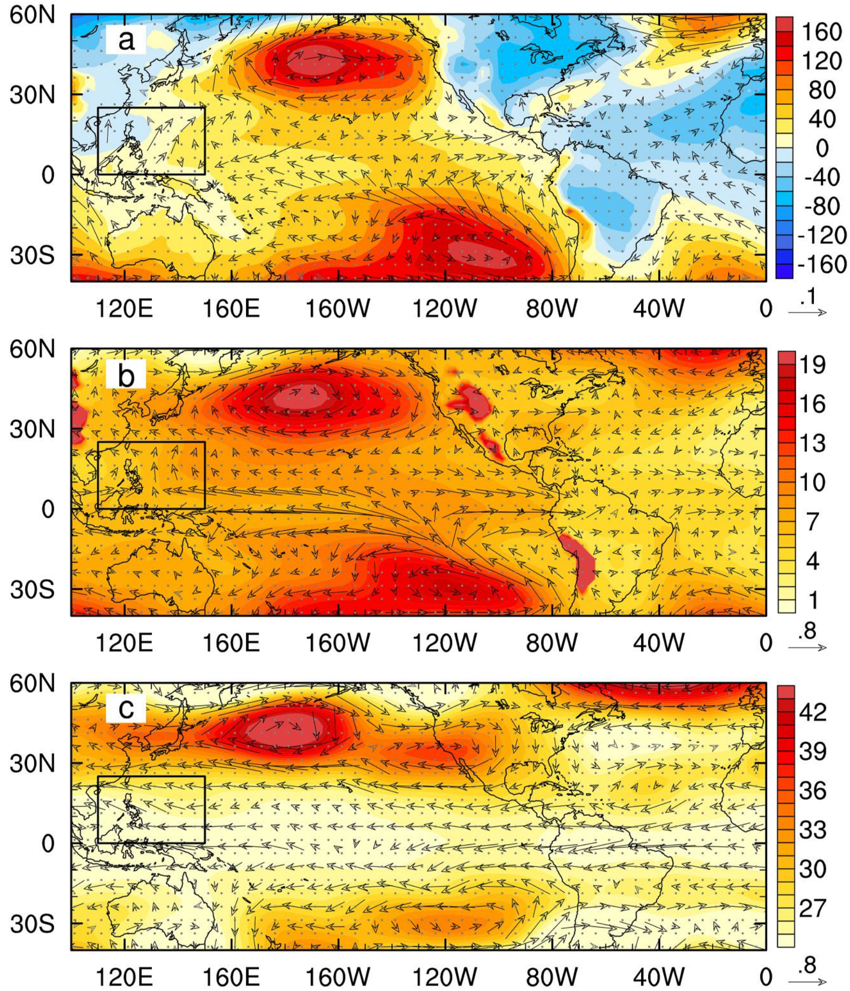

Figure 4. (a) Regression pattern of local low-pass filtered sea level pressure (shading, hPa) and wind stress (vectors, dyn cm^{-2}) onto the AMV_{EX} index (solid red line in Figure 3e) in the CESM1 Atlantic pacemaker simulations. The black stippling indicates statistically significant regressions at the 0.05 level. Panels (b, c) same as panel (a), but for the (b) 850 hPa, (c) 500 hPa winds (vectors, m s^{-1}) and geopotential height (shading, m).

around TWP through SST–SLP–cloud–longwave radiation positive feedback (Sun et al., 2017). However, there exist some differences in SLP responses in TWP between our results and previous findings (Figures S2a–S3a in Supporting Information S1). The differences presumably result from different model setup (i.e., using fully coupled atmosphere–ocean model or equivalent slab–ocean model in the previous studies) and different representation of the inter-basin teleconnections. To reduce model uncertainty and ensure the robustness of our findings, we also examined similar Atlantic pacemaker simulations using another model IPSL-CM6A-LR (Boer et al., 2016). This model also simulates increased SLP in the North Pacific and around TWP driven by the AMV, AMV_{IV} and AMV_{EX} (Figure S4 in Supporting Information S1). Together, these results suggest that the AMV contributed to TWP SST decadal variations through the atmospheric teleconnection over the North Pacific in the coupled models.

3.4. Roles of Local and Remote Influences of External Forcing

It is noteworthy that external forcing can generate AMV-like variations not only in the North Atlantic (i.e., AMV_{EX}), but also over other ocean basins (including the TWP) since 1920 (Qin et al., 2020a). It is thus unclear whether the forced AMV-like SST variations in the TWP mainly come directly from the local external forcing, or from the remote influence of the AMV_{EX}. Furthermore, our results suggested that the AMV contributed to TWP SST decadal variations through the atmospheric teleconnection over the North Pacific. That is, the remote

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influences from the North Pacific due to external forcing may also contribute to the TWP SST variations. However, Qin et al. (2020b) have shown that the decadal SST variations over the North Pacific in response to external forcing are relatively weak. Thus, the forced TWP SST variations mainly come from local external forcing and remote influences from the Atlantic Ocean. We use two modeling approaches to estimate the relative roles of local responses and remote influences of the external forcing. We assume that the atmospheric teleconnection pathways from the North Atlantic to the TWP are similar for both internal and forced SST variations, and the magnitudes of the TWP SST response to a unit AMV forcing is approximately the same regardless whether the AMV is forced or internal.

First, we used the idealized AMV pacemaker runs to estimate the magnitudes of the TWP SST responses resulting from the AMV (e.g., using difference between AMV+ and AMV− experiments). In general, the TWP SST responses to a given AMV of 1.0°C is ~0.56°C. Second, we used the Atlantic time-varying pacemaker runs to examine the TWP SST changes between the warm and cold phases of the AMV (e.g., based on the ensemble mean difference between the Atlantic pacemaker simulations and historical all-forcing runs). We focus on the period between 1970 and 1993 (for a cold phase) and 1995–2013 (for a warm phase). The TWP SST responses to a given AMV of 1.0°C is also ~0.56°C. Overall, the TWP SST responses to a given AMV of 1.0°C is about 0.56°C. To find out to what extent the observed forced TWP SST variations (i.e., TWP^*_{EX}) are driven by the local processes and remote influences from the Atlantic Ocean, we examine the SST changes between the cold (1965–1995) and warm (1920–1950 and 2005–2020) phases of the TWP^*_{EX} in the observations. We used the SST difference between the cold and warm phases to represent the total forced TWP SST changes. The TWP SST response to AMV_{EX} forcing is estimated by multiplying the 0.56°C response per 1.0°C AMV SST forcing by the AMV_{EX} value, which represents the remote influence from the AMV_{EX}. And the residual represents the influence from local processes over the TWP. Overall, the estimated AMV_{EX}-related TWP forced SST variations accounts for ~43–49% of the multidecadal changes, with the remaining coming from local processes.

4. Conclusions and Discussion

Our results suggest that more than half of the multidecadal SST variations during 1920–2020 in TWP can be explained by the nonlinear forced component. These decadal variations resemble the AMV in time, indicating that the AMV-like variations in TWP SST may be linked to AMV. We further used Atlantic pacemaker simulations to show that the externally-forced AMV (AMV_{EX}) can cause AMV-like variations in TWP. The AMV_{EX} influences the Pacific Ocean through the atmospheric connections. In general, the warm phase of the AMV_{EX} is associated with the weakening of the Aleutian low and warm anomalies over the North Pacific, and contributes to the warming around TWP through southerly advection.

As external forcing can influence the forced AMV-like TWP SST variations directly through local processes (i.e., local external forcing) and remotely from forced AMV, we further quantify the relative roles of the local external forcing and remote influence from forced AMV on TWP SST variations. Our results show that the estimated AMV_{EX}-related forced SST variations accounts for ~43–49% of the multidecadal changes in TWP, with the remaining coming from other remote or local processes. In our study, we assume that the remote influences of external forcing come mainly from the forced AMV, as the local North Pacific decadal variations in response to external forcing are relatively weak (Qin et al., 2020b). However, there's no denying that the atmospheric circulation changes due to external forcing in the Pacific may influence the TWP SST variations, further efforts to distinguish the local external forcing and remote influences could advance our understanding of decadal variability in the TWP.

In our study, we found that the decadal variations in TWP are influenced by the AMV_{EX}, rather than the AMV_{IV}. However, there exist some differences between the AMV_{IV}-related and AMV_{EX}-related SST and atmospheric circulation variations in model simulations. For example, the South Atlantic has the same sign as the North Atlantic for the AMV and AMV_{EX} signals in CESM1, while it has an opposite sign of the North Atlantic for the AMV_{IV}-induced variations. On the one hand, the SST patterns (in particular over the entire Atlantic) in response to AMV_{IV} and AMV_{EX} are different. The IV underlying AMV_{IV} originates mainly from the Atlantic, while the external forcing underlying AMV_{EX} may exist in and outside the North Atlantic (e.g., including the TWP), which could lead to different atmospheric responses under the two AMV cases. Furthermore, the models may overestimate the forced response or underestimate the IV, as we only consider the approximate linearity of the AMV

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forcing to TWP. Further efforts to reduce the model biases could help improve simulations of decadal variability in the Pacific and Atlantic Oceans.

Data Availability Statement

HadISST data (Rayner et al., 2003) can be obtained from the Met Office Customer Centre website. ERSST data (Huang et al., 2017) can be obtained from the National Oceanic and Atmospheric Administration (NOAA) website. Kaplan Extended SST data (Kaplan et al., 1998) can be obtained from the NOAA website at https://psl.noaa.gov/data/gridded/data.kaplan_sst.html. COBE SST data (Ishii et al., 2005) can be obtained from the NOAA website at https://psl.noaa.gov/data/gridded/data.cobe.html. Data sets from CMIP6 simulations (Eyring et al., 2016) are available at the Earth System Grid Federation (ESGF). The CMIP6 models used in this study can be found in Table S1 in Supporting Information S1. The CESM1-LE ensemble simulations (Kay et al., 2015) can be obtained from the University Corporation for Atmospheric Research (UCAR) website. The Atlantic pacemaker simulations and idealized AMV experiments (Meehl et al., 2021) can be downloaded from the UCAR website.

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