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The importance of inter-basin atmospheric teleconnection in the SST footprint of Atlantic multidecadal oscillation over western Pacific

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Abstract

Western Pacific sea surface temperature (SST) multidecadal fluctuations are synchronized to the Atlantic multidecadal oscillation (AMO) phenomenon during the instrumental period. The possible mechanism of the inter-basin synchronization of multidecadal SST variability still remains a matter of discussion regarding the roles of external radiative forcing and internal inter-basin interaction. Here we address this issue using simulations of CMIP5 coupled models and a partially coupled model experiment with prescribed SSTs over the North Atlantic. Observational analysis suggests that in association with the warm AMO phase, prominent SST warming occurs over the western Pacific, accompanied by anomalous low pressures and ascending motion that maintain the warm SST anomalies through positive feedback of local air–sea interaction. The upward motion in the western Pacific corresponds to a significant intensification of Pacific zonal Walker circulation, which is coupled with an increase in the zonal gradient of atmospheric temperature aloft. The CMIP5 model simulated externally forced component of AMO-related changes in western Pacific SST is weak, associated with little change in Pacific zonal circulation showing an absence of anomalous upward motion over the western Pacific, and this is primarily resultant from the negligible changes in the zonal gradient of atmospheric temperature as a direct thermal response to the external radiative forcing. By contrast, the partially coupled model simulation forced by the Atlantic SST variations reasonably reproduces the observed AMO-related changes in western Pacific SST and pan-tropical atmospheric circulation. A surface radiation budget analysis for the western Pacific shows contrasting roles of AMO-related surface incoming solar radiation between the reanalysis/partially coupled model simulation and the forced signal in CMIP5, further confirming the key role of dynamically induced inter-basin atmospheric teleconnection in the multidecadal SST footprint of AMO over the western Pacific.

1 Introduction

Instrumentally observed global sea surface temperature (SST) exhibits strong multidecadal variability superimposed on the secular warming trend. Previous studies have indicated that the Atlantic SST fluctuations play an important role in synchronizing global multidecadal climate variability (Chen and Tung 2018; Sun et al. 2017, 2019; Zhang et al. 2019b). The Atlantic Multi-decadal Oscillation (AMO, also known as Atlantic multidecadal variability) is a multi-decadal scale (50–80 years) oscillation of sea surface temperature (SST) anomalies centered over the North Atlantic Ocean (Enfield et al. 2001; Sun et al. 2015a; Sutton and Hodson 2005; Ting et al. 2009; Zhang et al. 2019b). The AMO varies by about 0.5 °C magnitude and is characterized by a basin-wide spatially coherent pattern (Sun et al. 2018; Zhang

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et al. 2019b). The temporal variations of AMO during the instrumental period are characterized by a warm phase during the 1930s to 1960s and recent decades since the 1990s, and a cold phase during the 1900s to 1930s and the 1960s to 1990s (Enfield et al. 2001; Ting et al. 2009).

The AMO is one of the most important modes of global decadal climate variability and has significant impacts on global and regional climates. Substantial observational and paleoclimate records indicate that the fluctuations of AMO are closely connected to the climate over the Atlantic basin and adjacent continents (Knight et al. 2006; Sutton and Hodson 2005; Zhang and Delworth 2006; Zhang et al. 2019b). In West Africa, the multidecadal variability of precipitation is strongly correlated with AMO, and the effects of multidecadal SST warming/cooling in the North Atlantic on precipitation and temperature over the Continental U.S. and Europe are prominent. There is also a connection between interdecadal variations in Arctic surface temperature and AMO (Chylek et al. 2009). In addition, the AMO also extends its climate impact to East Asia and the Far East region through exciting eastward propagating Rossby wave trains across the Eurasian continent (Li and Bates 2007; Si and Hu 2017; Sun et al. 2015b, 2017; Wu et al. 2016). There are two multidecadal teleconnection patterns associated with the AMO SST forcing in warm and cold seasons, respectively (Sun et al. 2017). The anomalous upper-level divergence over North Atlantic associated with the AMO contributes to the Rossby wave source and climatological westerlies act as a waveguide for the propagation of the Rossby wave trains.

The AMO not only shows strong connections with surface temperature anomalies over the North Atlantic and Eurasian continent but also shows significant footprints of temperature around the globe. Recent studies indicate that the AMO contributes more than the Pacific Decadal Oscillation (PDO) to the global temperature multidecadal variations (Chen and Tung 2018). Several mechanisms have been proposed to understand the remote sea surface temperature (SST) footprint of AMO around the globe. The SST fingerprint over North Pacific and western tropical Pacific can be understood through an inter-basin atmospheric teleconnection pattern (Cai et al. 2019; Nigam et al. 2020; Sun et al. 2017; Wang 2019; Zhang and Delworth 2006), which consists of anomalous low pressure over the North Atlantic and western tropical Pacific and high-pressure anomalies over the northern and eastern Pacific during the warm phase of AMO (Kucharski et al. 2016; Sun et al. 2017). The anomalous high and low pressures over the eastern and western Pacific correspond to multidecadal changes in the Pacific Walker Circulation (PWC) associated with the warming/cooling of Atlantic SST (Kucharski et al. 2011, 2016; Barcikowska et al. 2017; Li et al. 2016; McGregor et al. 2014; Chikamoto et al. 2015; Johnson et al. 2020). A recent study further identified three regions (the north tropical Atlantic, the equatorial Atlantic, and the entire tropical Atlantic) where the SSTs influence the PWC, indicating that both the North Atlantic and equatorial Atlantic may play a role in the inter-basin atmospheric teleconnection (Chikamoto et al. 2020). Several other studies have highlighted the role of the oceanic bridge mechanism in the Atlantic-Pacific trans-basin multidecadal variability, noting that the Arctic Ocean is a critical region as it connects the North Atlantic and North Pacific through water, heat, and salt transport (Hu and Meehl 2005; Johnson et al. 2020; Kucharski et al. 2011; Okumura et al. 2009). Previous studies have also shown a close relationship between the AMO and the multidecadal variability of tropical Pacific ENSO and ITCZ (Levine et al. 2017, 2018), and another study addressed the importance of the Pacific mean state in the remote impacts of AMO on the multidecadal ENSO variability (Kim et al. 2020), since the mean state amplifies/weakens the response of ENSO variability to the AMO. Besides the Pacific Ocean, Indian Ocean multidecadal SST variations are also significantly modulated by the Atlantic-Pacific trans-basin multidecadal variability (Sun et al. 2019), and the Southern Ocean SST is connected to the North Atlantic multidecadal SST changes through the oceanic pathway associated with the changes in Atlantic meridional overturning circulation (AMOC) and ocean heat transport (Sun et al. 2018; Zhang et al. 2019b).

There is no consensus on the driving mechanism of AMO. Substantial theoretical and modeling evidence suggests that the AMO is dominated by changes in the strength of the AMOC and the associated ocean heat transport (Zhang et al. 2019b) and references therein). As the AMOC strengthens (weakens), the northward ocean heat transport increases (decreases), leading to a warm (cold) phase of the AMO. Based on this theory, the AMO can be interpreted as a consequence of internal climate variability arising from oceanic dynamical processes (Delworth and Mann 2000; Knight et al. 2005; O'Reilly et al. 2016). By using proxy records that characterize the strength of AMOC, such as the dominant mode of subsurface seawater temperature, seawater density, sea level gradient, upper ocean heat content, and subpolar sea surface salinity, some observational evidence supports a link between the AMOC strength and AMO (McCarthy et al. 2015; Sun et al. 2018, 2019; Zhang 2017, 2019b). Meanwhile, some studies highlighted the ocean-atmosphere dynamical coupling as the fundamental mechanism explaining the AMO and its linkage to the North Atlantic Oscillation (NAO, the leading mode of atmospheric circulation variability) (Battisti et al. 2018; Delworth et al. 2016; Sun et al. 2015a; Wills et al. 2019). The atmospheric forcing associated with NAO plays a crucial role in the multidecadal variations of AMOC strength, and due to the great inertia of the ocean, the AMOC response is an integral of the NAO forcing and lags the NAO by several years (Delworth et al. 2016; Li et al. 2013; O'Reilly et al. 2019; Sun et al. 2015a, 2018, 2019). The accumulated effect of the NAO forcing induces multidecadal changes in the AMOC strength, which can further lead to AMO, and this mechanism explains the lagged relationship between NAO and AMO at decadal timescales in both instrumental and reconstructed records (O'Reilly et al. 2019; Sun et al. 2018, 2019).

On the other hand, some studies have shown an externally forced component in the AMO (Bellucci et al. 2017; Booth et al. 2012; Otterå et al. 2010). These studies have suggested that the radiative effect of aerosols may have contributed to the AMO-related SST fluctuations in the North Atlantic. However, the aerosol-forcing mechanism fails to explain the observed anticorrelation between multidecadal tropical North Atlantic surface and subsurface temperature variations and the anticorrelated multidecadal variations between upper and deep subpolar North Atlantic seawater temperature (Kim et al. 2018; Zhang 2008, 2013, 2017). The aerosol-forcing mechanism has recently been applied to explain the inter-basin connection between Atlantic and Pacific multidecadal SST variations. Different from the previously suggested inter-basin atmospheric teleconnection mechanism (Li et al. 2016; McGregor et al. 2014; Sun et al. 2017), it has been suggested that the aerosol forcing can generate AMO-like variations of surface temperature globally, leading to the in-phase relationship between Atlantic and Pacific SSTs at multidecadal timescales (Qin et al. 2020). Nevertheless, some recent studies have further shown that the inter-basin teleconnection between the Atlantic and Pacific exists not only in the surface layer but also in the subsurface layer (Cai et al. 2019; Kucharski et al. 2016; Li et al. 2016; Wu et al. 2020) and highlighted the role of inter-basin atmosphere–ocean coupling in the remote influence of AMO on the Pacific Ocean. Therefore, to better understand the origin of the Atlantic-Pacific inter-basin teleconnection, it is necessary to compare the contributions of the atmospheric teleconnection mechanism and aerosol-forcing mechanism in the connection between AMO and Pacific SST.

This study aims to investigate the relative roles of external forcing and internal atmosphere–ocean dynamics in the inter-basin teleconnection from the Atlantic to the Pacific Ocean, with a focus on the western Pacific basin, which shows the most prominent in-phase relationship with the AMO at multidecadal timescales (Chen and Tung 2018; Qin et al. 2020; Sun et al. 2017; Wu et al. 2020). In this study, we combine the data from observations, reanalysis, and simulations from the CMIP5 multimodel ensemble and Atlantic Pacemaker experiments to examine the externally forced and internally generated components of the AMO SST footprint over the western Pacific and associated atmospheric circulation changes.

2 Data and methodology

2.1 Data

Observation/reanalysis data are employed to analyze the spatial-temporal features of the AMO-related variations in the SST and associated atmospheric circulation anomalies. Atmospheric data sets are derived from the 20th-century reanalysis (20CR) data (Compo et al. 2011) for the period 1900–2013. The 20CR data assimilates observed surface variables including surface pressure from ISPD version 3.2.9, SSTs from Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 2 and monthly COBE-SST2 sea ice. The AMO index is defined as the area-weighted average of detrended SST anomalies over the North Atlantic region, similar to the definition of AMO in the previous study (Clement et al. 2015). Others (Trenberth and Shea 2006) defined the AMO as the difference between the North Atlantic and global mean SST (Supplementary Fig. S1). The AMO indices based on the two definitions are in phase with each other, showing high agreement for both the unfiltered and filtered data ($r = 0.90$ and 0.95, respectively). For the comparison of the results between observations/reanalysis and the CMIP5/partially coupled model simulations, we use the area-weighted average of detrended North Atlantic SST for the definition of AMO. The SST data is derived from the Extended Reconstruction SST version 5 (ERSST v5) data set (Huang et al. 2017) for the period 1900–2013. The long-term linear trend is removed to isolate the multidecadal fluctuations, and accordingly, all data in the observations/reanalysis and simulations are detrended for ease of comparison. In this study, the variables in reanalysis and model simulations are regressed onto the AMO index to investigate their responses to the AMO.

2.2 Evaluating the role of external radiative forcing

To estimate the SST and atmospheric circulation responses to the external radiative forcing, we use the fully coupled models from the CMIP5 historical experiment, of which a total of 59 ensemble members from 27 CMIP5 models are selected. The external forcing and the forced signal in all ensemble members are common. The number of selected ensemble members is large enough, and the internal variability in different runs are uncorrelated and cancel out in the multimodel ensemble means (MMEM). Thus, the externally forced component of multidecadal climate variability in response to the time-varying radiative forcing in the models can be reasonably represented by the MMEMs of the CMIP5 fully coupled models, consistent with the method used by previous studies (Dong and McPhaden 2017; Kravtsov et al. 2018). A combination of all-forcing historical (1850–2005) and Representative Concentration Pathway 4.5 (RCP4.5) future (2006–2100) simulations are used in this study.

To evaluate the role of external forcing in the SST footprint of AMO outside the North Atlantic, we use a regression method. In the observation, the footprint of AMO is estimated by using the regression of variables onto the observed AMO index (referred to as R_o). The role of external forcing in the AMO footprint can be estimated by regression of the variables simulated in the CMIP5 MMEM onto the observed AMO index (R_f). The closer R_f resembles R_o, the more important the role external forcing plays in the AMO footprint outside the North Atlantic.

2.3 Partially coupled experiment and evaluation of the role of internal dynamics

Previous studies have also suggested an important role of the internal dynamics of atmosphere–ocean interactions in the inter-basin teleconnection between Atlantic and Pacific SST multidecadal variability (Kucharski et al. 2016; Li et al. 2016; Sun et al. 2017). Atlantic Pacemaker experiments (integrated with the observed SST prescribed only over the Atlantic Ocean) are designed to capture the internal atmosphere–ocean dynamics generated by Atlantic multidecadal SST variations. This study focuses on the interactions between the SST and atmospheric teleconnection, and the Atlantic Pacemaker experiment here refers to the partially coupled model simulations (AGCM forced with the observed Atlantic SST and an Indo-Pacific mixed layer without prescribing time-varying external forcings). This simple partially coupled model allows us to focus on the atmospheric teleconnection induced by the AMO SST forcing and its role in the multidecadal SST connection between the AMO and tropical western Pacific. Previous studies have also shown that the partially coupled model has a reasonable capability in reproducing the observed SST inter-basin teleconnection associated with the AMO (Kucharski et al. 2016; Sun et al. 2017).

In this study, we employ the International Centre for Theoretical Physics AGCM (ICTPAGCM, version 41) coupled to a slab ocean thermodynamic mixed-layer model (SOM). Detailed descriptions about the intermediate ICTPAGCM and the coupled SOM including the resolution, physical parameterization, and spatially varying mixed layer depth were provided in previous studies (Kucharski et al. 2016; Sun et al. 2017). A suite of Atlantic Pacemaker experiment (partially coupled experiment) is carried out by applying atmosphere–ocean coupling everywhere except in the Atlantic (20° S–70° N), where SSTs are the observational monthly-varying SSTs from ERSST version 5 data (Gong et al. 2020; Sun et al. 2017). In the other basins outside the Atlantic, the SOM is used and run coupled to the ICTPAGCM, integrating the atmospheric heat fluxes and providing feedback to the atmosphere. The Atlantic Pacemaker experiment considers the effects of not only the North Atlantic SST forcing of atmospheric teleconnection patterns but also the atmosphere–ocean coupling over the Indo-Pacific basin. Meanwhile, as the external radiative forcing in the Atlantic Pacemaker experiment remains constant, the simulation results from the Atlantic Pacemaker experiment largely represent the internal atmosphere–ocean dynamics induced by the North Atlantic SST variations.

The simulations of the Atlantic Pacemaker experiment are integrated from 1871 to 2013 and a set of five ensemble simulations are conducted by restarting the model with small initial perturbations. The first 29 years of all simulations are taken as spin-up, and the results from the rest of the period during 1900–2013 are analyzed and compared with the results from the observation/reanalysis and CMIP5 simulations for the same period.

3 Results

The AMO index based on the ERSST observational data depicts the multidecadal variability of the North Atlantic SST for the period 1900–2013. The AMO is in its cold phase before 1930 and turns into a warm phase afterward until the late 1960s. There is a transient cold period during the 1970s but then the AMO has experienced consistent warming since 1980 (Fig. 1a). However, the externally forced AMO (simulated AMO in the CMIP5 MMEM, referred to as AMO_CMIP hereafter) does not exhibit such a clear decadal variability. For instance, the AMO_CMIP remains stable before 1980 and shows little fluctuation, whereas a warming trend can be found after the late 1970s. The two time series of AMO index exhibit a generally consistent warming trend during the analyzed period, which may contain the persistent global warming signal (Fig. 1a). Therefore, we remove the long-term linear trend to better highlight the multidecadal variations. In Fig. 1b, the multidecadal variability in observed AMO is still significant, with alternating warm and cold phases from 1900 to 2013. As for the AMO_CMIP, the multidecadal fluctuation is less prominent. The discrepancies are nonnegligible, since the phases of AMO_CMIP and observed AMO are inconsistent with each other before the 1970s, and they are out of phase particularly before the late 1930s. Furthermore, the amplitude of AMO_CMIP is clearly weaker than the observed AMO before the 1970s. Albeit the similarity between the observed and externally forced AMO index during the recent decades, it is not sufficient to determine that the AMO_CMIP comprehensively represents the observed AMO multidecadal fluctuations. It

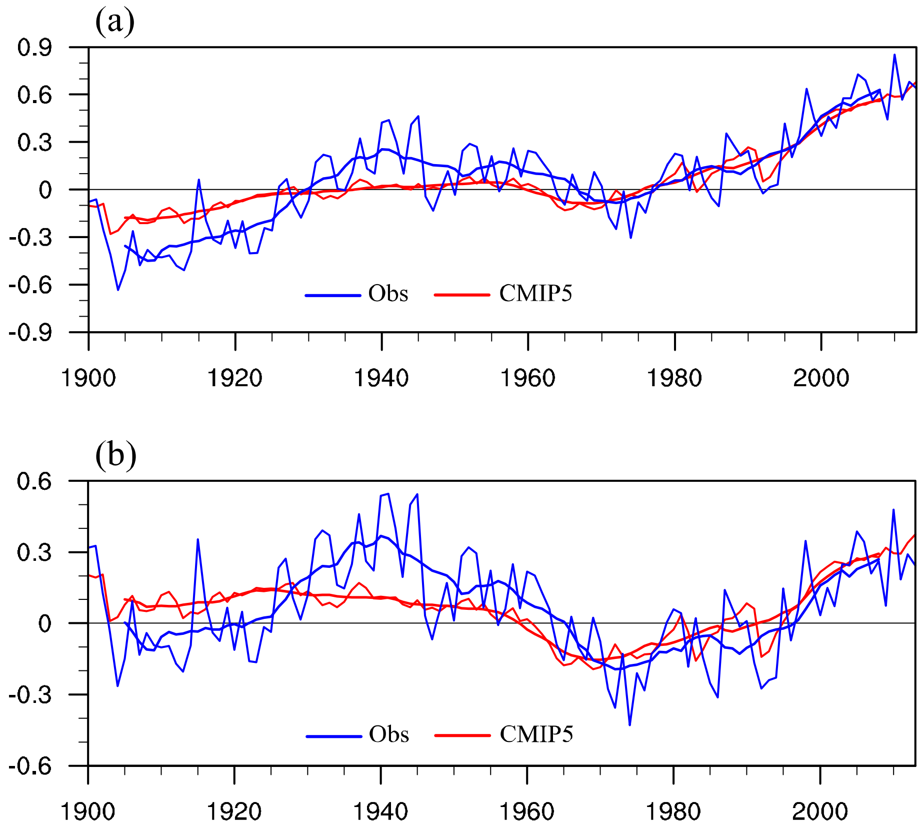


Fig. 1 **a** Time series of AMO indices (units: K) in both observation and CMIP5 multimodel ensemble mean simulations for the period 1900–2013 and their 11-year running means. **b** As in **a**, but for the time series after removing the long-term linear trend

also implies that the external radiative forcing alone may not stand for the origin of AMO. The AMO_CMIP indicates an externally forced component in the AMO, as also suggested in previous studies (Bellucci et al. 2017; Booth et al. 2012; Qin et al. 2020), but the external forcing alone cannot explain the observed phase shifts and amplitude of AMO. This indicates an important role of the dynamic processes associated with internal variations like the AMOC and NAO (Zhang et al. 2019b).

Zhang et al. (2019a, b) have provided a comprehensive review of the relative roles of external forcing and internal dynamics in the origin of AMO. In this study, we focus on their relative roles in the SST footprint of AMO outside the North Atlantic basin. To investigate the spatial coherence between the AMO and SSTs and the distinct roles of external forcing and internal variability, we analyze the regression map of global SSTs in the observation, CMIP5 MMEM, and Atlantic Pacemaker experiment onto the normalized observed AMO index (the long-term trend has been removed) between 30° S and 60° N. In the 20CR reanalysis (Fig. 2a), the North Atlantic exhibits coherent SST warming, corresponding to the AMO spatial pattern. Besides the North Atlantic, the North Pacific and western tropical Pacific SSTs are consistently warming as well. The multidecadal connections between AMO and SSTs outside the North Atlantic are also significant in other observational data sets, as suggested in previous studies (Gong et al. 2020; Sun et al. 2017). Another feature is that the eastern tropical Pacific SST exhibits cooling in response to the AMO, which is contrary to the western tropical Pacific. As a result, the SST zonal gradients along the tropics in the Pacific are further increased associated with the AMO forcing. However, the externally forced components of AMO and the associated SST footprints (Fig. 2b) are not as significant as those observed in neither the North Atlantic nor the western Pacific. The externally forced SST pattern is less agreed with the AMO spatial features over the North Atlantic, indicating that the external radiative forcing is unlikely to drive the changes in the AMO predominantly, consistent with the above analyses and previous findings (Zhang et al. 2019a, b). More importantly, the externally forced component of AMO-related changes in the western Pacific SST is weak and the SST responses across the tropical Pacific only slightly vary with latitude. The tropical SSTs are uniformly influenced by the radiative forcing, leading to an approximately horizontally homogeneous pattern. Therefore, the externally forced component of the AMO-related tropical Pacific SSTs may have limited impacts, since the zonal gradient is too weak to modulate large-scale changes in atmospheric circulation over the tropics.

Different from the CMIP5-MMEM-simulated regression pattern, the Atlantic pacemaker experiment (Fig. 2c)

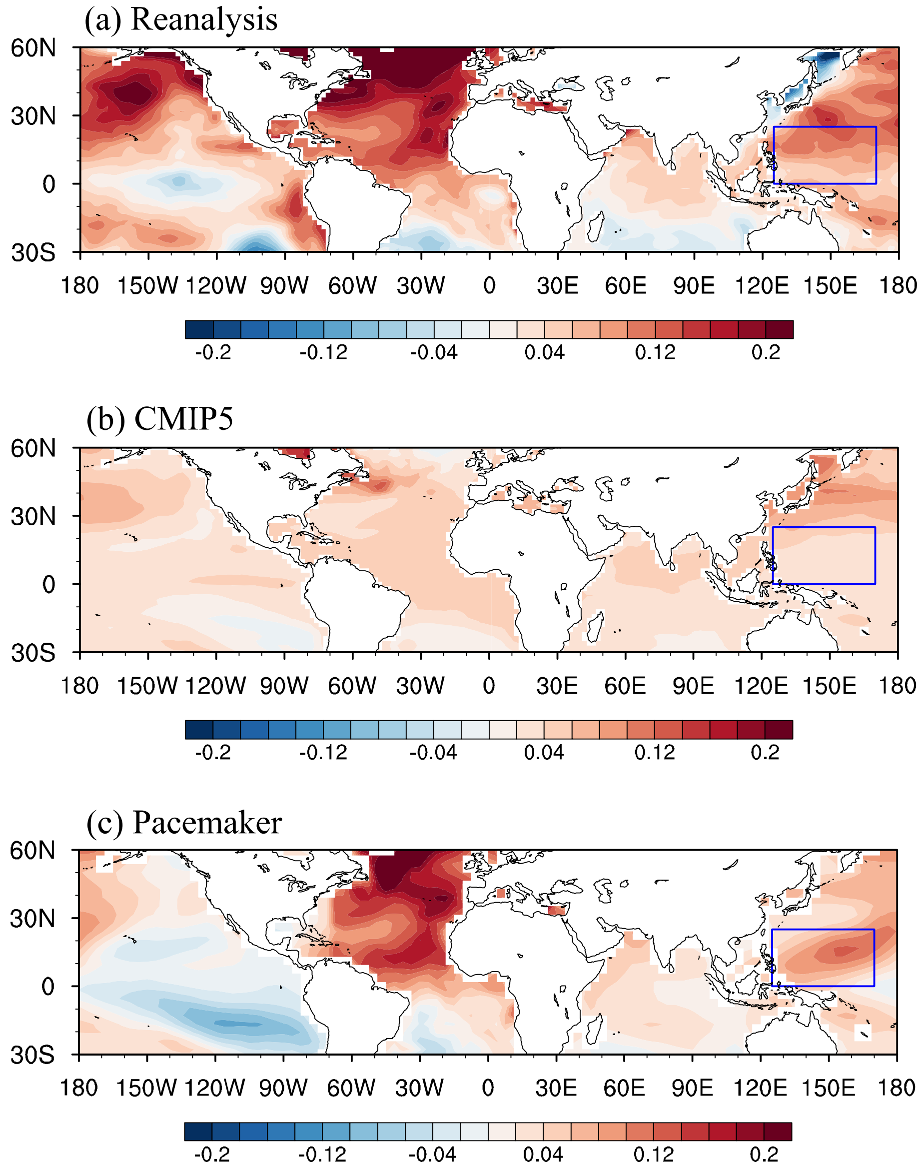
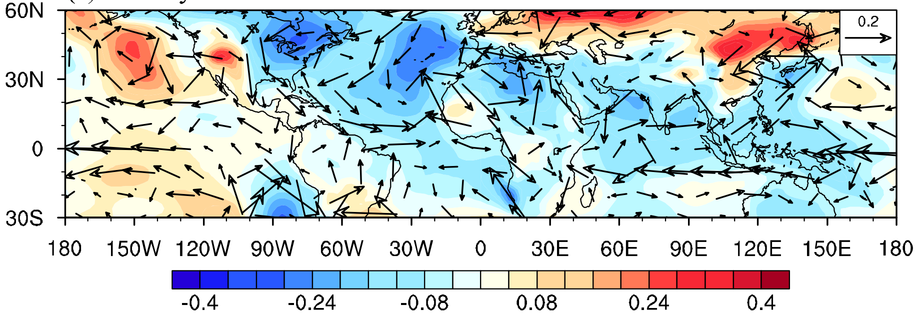


Fig. 2 **a** The regression map of SST (units: K) on the normalized AMO index over decadal timescales for the period 1900–2013 in the 20CR reanalysis data. The blue box indicates the western tropical Pacific region (0°–25° N, 125°–170° E). **b**, **c** As in **a**, but for **b** CMIP5 simulations and **c** the Atlantic pacemaker experiment

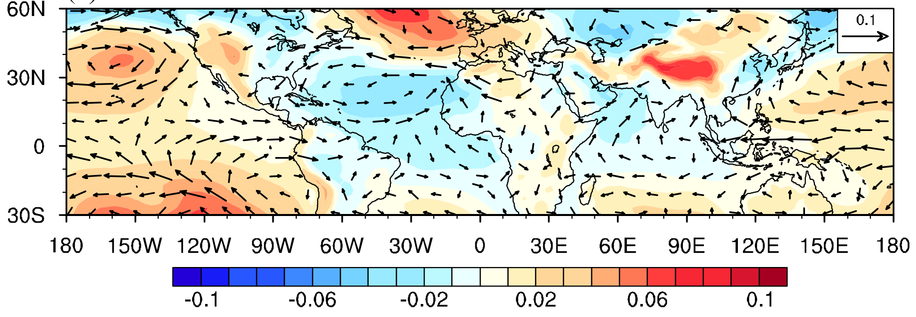
successfully reproduces the overall observed features. Especially in the western Pacific, it exhibits prominent SST warming in response to the remote AMO forcing consistent with the reanalysis data. Also, over the eastern tropical Pacific, SST cooling can be partially reproduced, suggesting the intensified zonal SST gradients found in the observation, are physically connected with the AMO. Note that the regression maps of the Pacific SST anomalies onto the AMO index in the reanalysis and Atlantic pacemaker experiment resemble the SST pattern in a previous modeling study based on preindustrial control simulations with a much longer period (1100 model years) (Lee et al. 2020), which provides further modeling evidence for the multidecadal inter-basin teleconnection. Albeit the model underestimates the warming over the northern North Pacific and eastern Pacific, the inhomogeneous SST footprint of the AMO shows some agreement with the observation over the tropical and subtropical Pacific Ocean. However, in the CMIP5 experiment (external forcing component), the warming response over the western Pacific is rather weak and the eastern Pacific cooling is missing, resulting in an insignificant zonal difference. The above analyzes indicate that the external radiative forcing can induce global temperature synchronization and generate a somewhat similar SST pattern to the observation in association with the AMO, but it may only play a minor role. However, the observation and Atlantic pacemaker experiment consistently indicate the importance of Atlantic SST variation (AMO) in modulating the western Pacific SST, which can be regarded as the AMO footprint. Previous studies (Sun et al. 2017, 2019) have addressed this issue based on observation and model simulations. The hypothesis is that the North Atlantic warming, corresponding to the positive AMO, induces anomalous ascending motion and upper-level divergence. Consequently, changing atmospheric circulation aloft leads to strengthened subsidence over the North Pacific, further weakening the Aleutian Low and the corresponded westerlies. Through wind-evaporation-SST (WES) mechanism, the subtropical North Pacific SST continues to warm and reduces the SLP in this region, accompanied by anomalous convergence flows. The SST warming signal spreads to the western tropical Pacific and can be maintained via SST-longwave radiation feedback (local air–sea interaction). Thus, the external forcing may not be solely responsible for the western Pacific SST warming, but the remote AMO forcing and associated inter-basin atmospheric teleconnection may play a more dominant role.

We calculate the anomalies of atmospheric variables regressed on the observed ERSST AMO index in the reanalysis, CMIP5 and Atlantic pacemaker experiment, respectively, to better evaluate the relative roles of external forcing and the AMO dynamically induced changes in the tropical Pacific atmosphere. In the reanalysis data (Fig. 3a), the North Atlantic exhibits a uniform SLP decline in association with the AMO-related SST warming, accompanied by the corresponding cyclonic flow. Meanwhile, an anomalous high-pressure center locates in the northern North Pacific, which further weakens the Aleutian Low. By contrast, the western Pacific, however, shows a relatively notable SLP decline coupled with the underlying SST warming, consequently strengthening the zonal pressure gradients over the entire tropical Pacific Ocean. Therefore, anomalous easterlies are observed over the tropical and subtropical Pacific. In addition, the Atlantic pacemaker experiment (Fig. 3c) reproduces the regression map, exhibiting a relatively consistent pattern. For example, the inter-basin SLP contrast between the North Atlantic and North Pacific is well depicted. Moreover, the western Pacific SLP decline is also evident and somewhat agrees with the observation. The anomalous easterlies over the tropics are simulated in the model since the zonal SLP gradients are as significant as those in the

(a) Reanalysis



(b) CMIP5



(c) Pacemaker

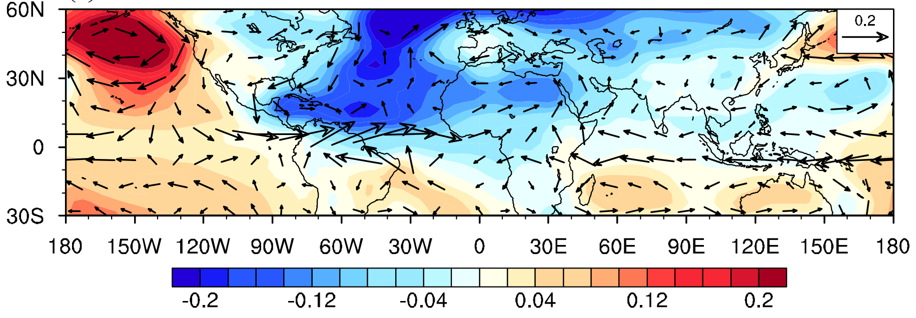


Fig. 3 **a** The regression map of SLP (shading, units: hPa) and surface winds (vectors, units: m s^{-1}) on the normalized AMO index (based on the ERSST) over decadal timescales for the period 1900–2013 in the 20CR reanalysis data. **b**, **c** As in **a**, but for **b** CMIP5 simulations and **c** the Atlantic pacemaker experiment

reanalysis data. Note that there're some discrepancies over East Asia, eastern Siberia and southeastern Pacific, but the North Pacific responses are generally consistent, indicating that the AMO is largely responsible for most of the observed SLP and corresponding horizontal circulation changes over western tropical Pacific. And, the results from the partially coupled model suggest the aforementioned inter-basin teleconnection mechanism may be the key process, dynamically connecting the AMO and its footprint over the North Pacific. However, the externally forced CMIP5 experiment (Fig. 3b) simulates rather minor changes of the Pacific lower level circulation related to the AMO and the disagreements over the North Atlantic are also nonnegligible. The externally forced SLP responses to the AMO is about two to four times weaker than the observation and Atlantic pacemaker experiment. The CMIP5 poorly reproduces the consistent SLP decline over the North Atlantic, with an anomalously high-pressure center located in the subpolar Atlantic. Despite the fact that the CMIP5 model somewhat reproduces the weakened Aleutian low, the response is too weak to induce the subtropical North Pacific SST warming and low-pressure anomalies via the changes in atmospheric circulation. Thus, it is unlikely to initiate the local air–sea interaction that strongly contributes to the western Pacific SST warming as is suggested in the observation and pacemaker experiment. Another disagreement is that due to the uniform SST warming over the tropical Pacific, the regressed SLP field exhibits consistent high-pressure anomalies across the tropical Pacific and the anomalous easterlies are rather too weak resultant from the small gradients in zonal pressure. Based on the above analyses, we may conclude that the dynamical processes associated with the AMO may play a more important role in modulating the related horizontal atmospheric changes over the tropical Pacific, whereas the CMIP5-simulated externally forced component of the AMO-related changes are weak and inconsistent with the observation.

Corresponding to the horizontal circulation in response to the AMO-related SST changes outside the North Atlantic, the vertical motions represented by the 200-hPa velocity potential and divergent winds are also examined. In the reanalysis (Fig. 4a), the African and Eurasian continents exhibit uniform upward motion, whereas the American continent and Australia generally show intensified descending motion in response to the AMO forcing. More importantly, the North Atlantic and the western Pacific Ocean are observed with notable upward motion, while the eastern Pacific is governed by the most intense air descent. Accordingly, strong upper-level divergent winds mainly distribute over the Atlantic and East Asia where the upward motions are prominent. On the other hand, notable convergence locates in the eastern tropical Pacific, corresponding to the descending zone. We may find two featured pathways by which these vertical motion centers are connected. One bridges the North Atlantic and eastern Pacific across the American continent and can be further divided into the northern (North America) and southern (South America) branches. The other connects the western Pacific to the eastern counterpart, exhibiting strong zonal advection over the tropics. However, the simulated responses of vertical motion and divergent winds are rather too weak in the CMIP5 MMEM (Fig. 4b). The externally forced component of the AMO-related changes over the North Atlantic is incapable of inducing significant changes over the upper-level atmospheric circulation. Over the Pacific, the AMO related descending motion extends far west to the western tropical Pacific, where there is a prominently observed ascent (Fig. 4a, c). The descending motions correspond to the high-pressure anomalies over the western Pacific in the CMIP5 MMEM (Fig. 3b). The corresponding divergent wind field is insensitive to the external forcing and the inter-basin connection is not significant either. Nevertheless, it must note that the 200 hPa velocity potential response shows a zonal dipole teleconnection pattern and that the upward and downward motions over the Atlantic and eastern Pacific share a slight similarity with that observed, indicating that the external forcing may induce a weak inter-basin atmospheric teleconnection, apart from the aerosol radiative forcing, but the teleconnection response is too weak to create any substantial SST structures in the Pacific.

In contrast to the CMIP5-simulated pattern, the key features of the regression map in the Atlantic pacemaker experiment (Fig. 4c) largely resemble the observation. The AMO-related SST warming induces strong upward motions over the Atlantic, accompanied by notable divergent flows aloft. By contrast, the eastern Pacific and northern North Pacific exhibit strong convergence and associated descent, resulting in the increased SLP over this region. Johnson et al. (2020) have suggested that SST warming in the North Atlantic associated with the positive phase of the AMO causes local lower SLP, an increase in precipitation, and upper-level easterly wind anomalies over the Caribbean Sea. The upper-level easterly anomalies are consistent with our study that shows strong upper-level divergent easterlies towards the Pacific basin in both reanalysis and pacemaker experiment. The upper-level divergent easterlies lead to the upper-level convergence and surface pressure increase in eastern Pacific and North Pacific, and the modulated North Pacific SLP further leads to western Pacific SST warming through the WES mechanism. Accordingly, the western Pacific shows intense ascending motion that maintains the SST warming through SST-longwave radiation feedback (Sun et al. 2017). Moreover, the western Pacific ascent corresponds with the eastern counterpart descent, inducing anomalous zonal circulation in response to the AMO. It must note that there are still some biases in comparison with the reanalysis. For instance, the observed vertical motion centers are along the equator, whereas they are generally off the equator in the

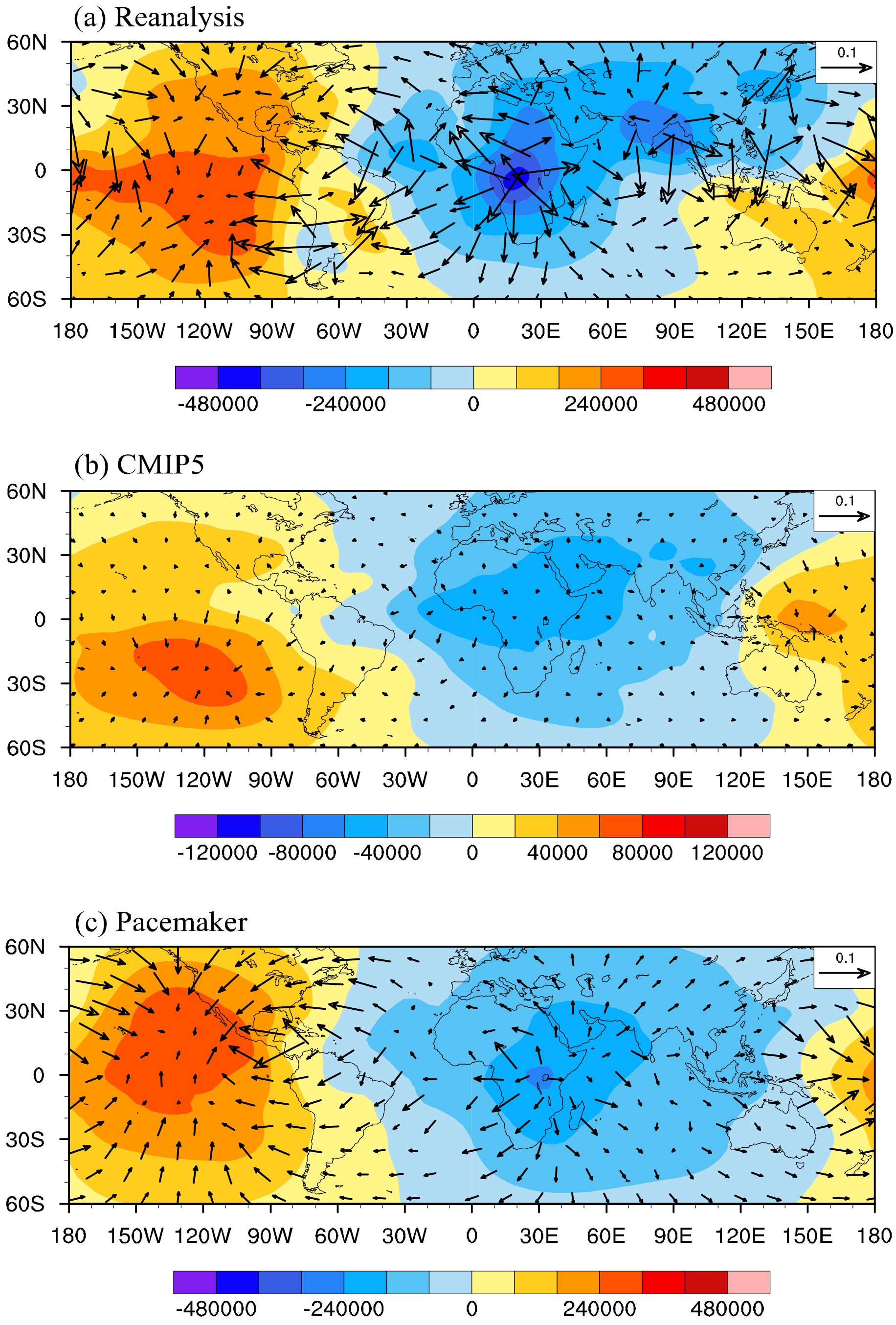
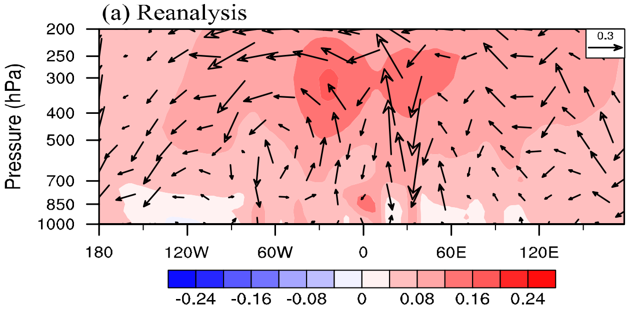


Fig. 4 **a** The regression map of 200-hPa velocity potential (shading, units: $m^2 s^{-1}$) and divergent winds (vectors, units: $m s^{-1}$) on the normalized AMO index over decadal timescales for the period 1900–2013 in the 20CR reanalysis data. **b**, **c** As in **a**, but for **b** CMIP5 simulations and **c** the Atlantic pacemaker experiment

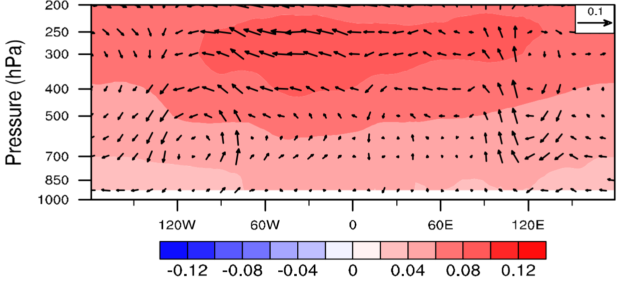
Atlantic pacemaker experiment. This is probable due to the off-equatorial cold SST biases over the eastern Pacific in the simulation. Despite that, the pacemaker experiment still captures the large-scale features of zonal atmospheric circulation responses to the AMO in the reanalysis. The above analyses comprehensively depict an inter-basin teleconnection diagram, emphasizing the AMO dynamically induced SST footprint is responsible for the changes over the western Pacific.

As mentioned above, the AMO-related western Pacific SST warming increases horizontal temperature gradients and induces contrasting vertical motions. Here, we examine the changes in Walker circulation in association with the AMO. As shown in Fig. 5a, the AMO increases the temperature gradients aloft and strengthens the zonal circulation in the reanalysis data. More specifically, the upper-level air is significantly heated resultant from the underlying SST warming and the center locates right above the North Atlantic. The most intense ascending motions locate in tropical Africa accompanied by the adjacent subsidence with the same magnitude. Seemingly, there're two closed circulations. One connects the Atlantic and the tropical eastern Pacific

(a) Reanalysis



(b) CMIP5



(c) Pacemaker

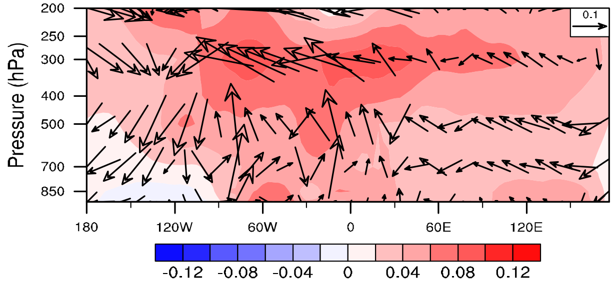


Fig. 5 **a** The regression map of air temperature (shading, units: K) and Walker circulation (vectors: u and – 100 omega, units: m s^{-1} and 100 Pa s^{-1}) on the normalized AMO index over decadal timescales for the period 1900–2013 in the 20CR reanalysis data. **b**, **c** As in **a**, but for **b** CMIP5 simulations and **c** the Atlantic pacemaker experiment. The meridional averages of air temperature and circulation are taken between 10° S and 10° N

across the Intra-American continent. The other locates over the tropical Pacific, with the ascending branch in the western Pacific (135°E–170° E) and the corresponding descending branch in the eastern Pacific (170°E–120° W). As a result, the PWC is strengthened. The former anomalous circulation is a direct response to the AMO-related SST warming, while the latter is mainly induced by the footprint of the AMO over the western Pacific.

Sun et al. (2017) have shown that the changes in subtropical North Pacific SST and atmospheric circulation play a mediating role in the association between the AMO and western Pacific. In fact, the tropical and subtropical responses to the AMO are interrelated, since the warm AMO phase can induce upper-level convergence and surface pressure increase in both tropical eastern Pacific and North Pacific (Fig. 3a). The SLP increase in the tropical eastern Pacific is consistent with intensified descending motion and strengthening of the PWC (Fig. 5a), while the SLP increase in the subtropical North Pacific corresponds to a weakening of the Aleutian low and subtropical surface westerlies (Fig. 3a). The changes in the tropical eastern Pacific may also favor the SLP high anomaly center over extratropical North Pacific; that is the upper-level convergence in the tropical central-eastern Pacific can generate a Rossby wave train propagating to the extratropics (Trenberth et al. 1998). The anomalous high pressure over the North Pacific leads to the weakening of subtropical westerlies and consequently the subtropical Pacific SST warming via the WES mechanism. The SST warming over subtropical North Pacific and western Pacific associated with the surface westerlies weakening (Figs. 2a, 3a) could increase the zonal temperature gradient and further enhance the PWC. The enhanced Walker circulation is also favorable for the SLP decrease and ascending motion over the western tropical Pacific, where the SST warming could be further maintained and amplified through the SLP-SST-cloud-longwave radiation positive feedback. Therefore, the atmospheric responses over subtropical and tropical Pacific due to the Atlantic AMO forcing are interrelated, and both contribute to the multidecadal inter-basin teleconnection.

For the CIMP5-simulated externally forced circulation (Fig. 5b), the responses are much weaker than the observation. It's reasonable since the forced SST (Fig. 2b) and SLP (Fig. 3b) gradients are small and the related vertical motions (Fig. 4b) are not significant. In addition, the external radiative forcing induces an approximately horizontally homogeneous response of the atmospheric temperature (Fig. 4b) and negligible changes in the zonal gradient of atmospheric temperature aloft as a direct thermal response to the external radiative forcing are unlikely to strongly affect the large-scale zonal circulation. Only small circulations can be found over South America and Indonesia, but these are so weak that barely influence the Walker circulation. However, the Atlantic pacemaker experiment reproduces the anomalous temperature gradients and strengthened Walker circulation, consistent with the observation. As shown in Fig. 5c, the upper-level air is unevenly heated in response to the AMO forcing, where this feature is clearly missing in the externally forced experiment (Fig. 5b). The temperature gradients are quite significant from the lower to the upper atmosphere, especially over the Pacific Ocean, consequently inducing strong circulation adjustments. The western Pacific exhibits notable upward motion (90°E–150° E) accompanied by the eastern Pacific descent (170° E–120° W), composing an anomalous Walker circulation. Based on the above analysis, it is suggested that the AMO dynamically induced SST footprint over the western Pacific plays an important role in strengthening the Walker circulation, while the externally forced component of the AMO only has limited influence.

We further calculate the stream function to quantify the AMO-related changes in circulation. The climatological field (Fig. 6 black contours) consists of six cells, as the two prominent clockwise circulations locate in the Atlantic and Pacific (the latter is the well-known Walker circulation), while the Indian Ocean is dominated by the anticlockwise circulation. In the reanalysis data (Fig. 6a), the circulations over the Atlantic and Pacific are significantly strengthened in response to the AMO forcing, but the causes are distinguished. As mentioned in the above analyses, the North Atlantic warming directly induces strong upward motions accompanied by the adjacent descent over the eastern Pacific, resulting in an anomalous anticlockwise circulation shown in Fig. 6a. Through the inter-basin teleconnection and local air–sea interaction processes, the AMO-related SST warming over the western Pacific initiates another anomalous zonal circulation. Such a clockwise circulation over the Pacific corresponds with the climatological Walker circulation and contributes to its intensification and westward extension. Consistent with the observation, the North Atlantic pacemaker experiment (Fig. 6c) finely reproduces the changes in the zonal circulation. Over the Atlantic, an anomalous anticlockwise circulation in response to the underlying SST warming weakens the climatological circulation. Over the western Pacific, the clockwise circulation is significantly intensified, consequently resulting in the strengthened Walker circulation as is observed. By contrast, the CMIP5-simulated externally forced component of the AMO only generates slight changes over the Pacific zonal circulation (Fig. 6b) in accordance with the approximately horizontally homogeneous response in the atmospheric temperature, indicating that the direct thermal response to the radiative forcing is unable to fully explain the observed Walker circulation strengthening associated with the warm AMO phase.

Another evidence for the important role of atmospheric circulation changes in linking the western Pacific multidecadal SST to the AMO is the surface radiation budget. The ascending anomalies over the western Pacific associated with PWC strengthening in response to the warm AMO phase may cause an increase in cloudiness (Sun et al. 2017), and the cloudiness changes have completely opposite effects on the surface longwave and shortwave radiations. Increased cloudiness causes a reduction in the surface shortwave radiation due to reflection, and it traps more longwave radiation inhibiting longwave heat loss from the surface and amplifying the western Pacific multidecadal SST anomalies through SST-cloud-longwave radiation feedback (Sun et al. 2017). As expected, in both the reanalysis and Atlantic Pacemaker experiment, the correlations of surface downward net shortwave and longwave radiations with the observed AMO index are opposite over the western Pacific region (Fig. 7a, c), with negative correlations for shortwave radiation and positive correlations for longwave radiation. This is consistent with the role of Pacific atmospheric circulation changes as shown in the above analyses. By contrast, the external radiative forcing mechanism for the AMO-related synchronization of multidecadal SST variability suggests an important role of aerosol forcing (Qin et al. 2020), which shows strong shortwave radiation modification at the surface. In this mechanism, the simultaneous SST warming (cooling) of the North Atlantic and western Pacific is primarily due to decreased (increased) aerosol loading and the associated increase (reduction) in surface shortwave radiation in both regions (Qin et al. 2020). As expected, the simulated surface downward net shortwave radiation from CMIP5 MMEM shows strong positive correlations with the AMO signal over the western Pacific (Fig. 7b), indicating that the SST warming in

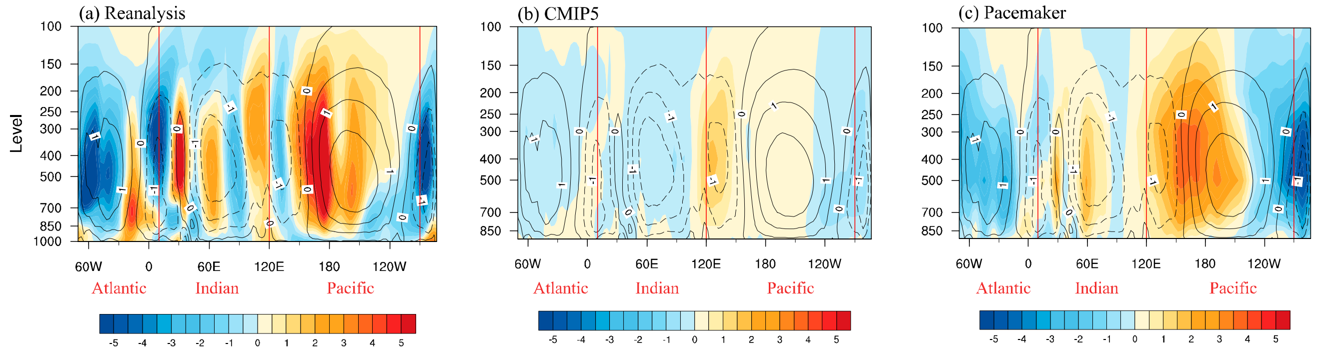


Fig. 6 **a** The regression map of zonal mass stream function (averaged between 10° S and 10° N) (shading, units: 5×10^{9} kg s^{-1}) on the normalized AMO index over decadal timescales for the period 1900–2013. The black contours (interval: 10^{11} kg s^{-1}) indicate the climatological mass stream function in the 20CR reanalysis data. **b**, **c** As in **a**, but for **b** CMIP5 simulations and **c** the Atlantic pacemaker experiment

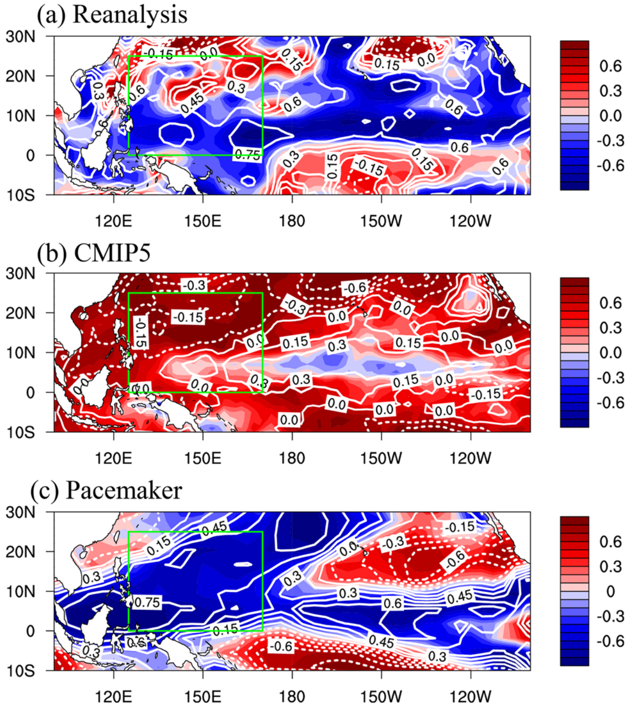


Fig. 7 **a** The correlation map of surface downward net shortwave radiation (shading) and longwave radiation (contours with an interval of 0.1) with the observed AMO index over decadal timescales for the period 1900–2013 in the 20CR reanalysis data. **b**, **c** As in **a**, but for **b** CMIP5 simulations and **c** the Atlantic pacemaker experiment. The green box indicates the western Pacific region

North Atlantic is accompanied by more shortwave radiation absorbed by the sea surface due to the low aerosol loading and further warming the SST. This is consistent with the external radiative forcing hypothesis, but contrary to the results from the reanalysis and Atlantic Pacemaker experiment. In addition, the CMIP5 MMEM simulates anomalous descending motion (Figs. 3 and 5) with surface high pressure anomalies located over the western Pacific that is consistent with the increased surface downward short-wave radiation, contributing to the weak SST warming (Figs. 2b and 7b). However, the externally forced atmospheric circulation changes in the CMMIP MMEM are different from the reanalysis and Atlantic pacemaker experiment and unlikely to generate the western Pacific local air–sea feedback (SST-SLP-cloud-long-wave radiation) that amplifies the SST warming and leads to strong multidecadal SST anomalies. Thus, in the observation the SST warming over the western Pacific is strongly coupled with the tropical Pacific atmospheric circulation changes, such as the PWC strengthening and the SLP declining in western Pacific. This indicates that the air–sea coupling plays a more important role than the external forcing in the formations of western Pacific SST warming, as suggested in (Zhang et al. 2019a). Therefore, the difference in the relationship of surface radiation to the AMO between the CMIP5 MMEM and reanalysis/Pacemaker experiment further highlights the important role of atmospheric circulation and the consequent local air–sea feedback in the changes of western Pacific surface heat balance and SST warming associated with the AMO.

4 Discussion and conclusions

In this study, we emphasize the importance of the inter-basin atmospheric teleconnection in the SST footprint of AMO over the western Pacific and compare the dynamically induced and externally forced changes in the atmospheric circulation associated with the AMO. The externally forced AMO shows unnoticeable multidecadal variability but consistent warming trend after 1980, indicating that the external forcing alone can hardly fully explain the evolution of AMO and the internal processes like the AMOC may play an important role. Moreover, the externally forced component of the western Pacific SST variability related to the AMO is weak, while the Atlantic pacemaker experiment reproduces strong SST warming in response to the AMO, consistent with the observation. It is suggested that the inter-basin teleconnection mechanism and local air–sea interaction are the key processes in the formation of the AMO footprint over the western tropical Pacific, rather than the global temperature synchronization as a direct thermal response to the external radiative forcing. The AMO dynamically induced atmospheric teleconnection is strongly coupled with the tropical Pacific SST, resulting in increased zonal temperature gradients. These changes correspond to a strengthening of the PWC since the AMO-related SST warming over the western Pacific induces strong ascending motions and the eastern Pacific exhibits anomalous subsidence. However, the footprint of AMO in atmospheric changes are minor in the CMIP5 MMEM simulations. The approximately horizontally homogeneous response of the atmospheric temperature to the external radiative forcing leads to the negligible zonal temperature gradient and weak responses in the large-scale zonal circulations and consequently vertical motions and surface pressure anomalies. Based on the above analyses, we may conclude that the external radiative forcing alone is unlikely to explain the AMO-related inter-basin synchronization of multidecadal SST variability and its coupling with the atmospheric teleconnection.

Our findings suggest that the tropical Pacific zonal circulation shows a strong response to the SST multidecadal changes in North Atlantic and the external radiative forcing is unlikely to explain the atmospheric circulation changes associated with the AMO. The available reanalysis data have a time period limit for the analyses of multidecadal variability, and the recent modeling study shows that CESM-LES simulations have a reasonable capability to reproduce the observed multidecadal inter-basin teleconnection (Lee et al. 2020). Future study based on large-ensemble simulations is warranted to identify the roles of internal variability and external forcings in the teleconnection. Furthermore, the changes in the zonal circulation are strongly coupled with the ocean beneath. Both atmosphere–ocean coupled GCMs with and without a dynamic ocean have been employed to carry out the Atlantic Pacemaker experiments (Kucharski et al. 2016; Li et al. 2016; McGregor et al. 2014; Ruprich-Robert et al. 2017; Sun et al. 2017). This study uses a slab ocean thermodynamic mixed-layer model to describe the coupling between the atmospheric circulation and Pacific SST (McGregor et al. 2014; Sun et al. 2017), while other previous studies have suggested a dynamical coupling between the tropical Pacific Ocean and the zonal circulation in response to the SST forcing in the North Atlantic (Kucharski et al. 2016; Li et al. 2016; Wu et al. 2020). Moreover, it is also suggested that the inclusion of 3-dimensional ocean temperature and salinity information could improve the simulation of ocean circulation (e.g., AMOC) variability in the pacemaker experiment (Boer et al. 2016; Chikamoto et al. 2019; Polkova et al. 2019). Therefore, it deserves further study to examine the potential role of AMOC variability in the multidecadal inter-basin teleconnection using the fully coupled model with the assimilation of observed 3-dimensional ocean data (Chikamoto et al. 2019).

The time series of observed AMO and the simulated from CMIP5 MMEM show a consistent warming trend since the 1970s, and this raises the question of how to separate the influences of external forcing and internal variability under the circumstances of consistent warming. Recent studies have identified a warming hole over the subpolar North Atlantic (Rahmstorf et al. 2015; Smeed et al. 2017; Hu et al. 2020), despite the basin-wide average SST shows a significant warming trend. This indicates the internal dynamical contribution to the multidecadal changes in North Atlantic SST and the corresponding spatial pattern. Meanwhile, future projection studies have suggested a weakening of PWC due to anthropogenic forced global warming (Vecchi et al. 2006). Investigation of the role of North Atlantic SST changes and internal multidecadal variability in the future projection of Pacific atmospheric circulation warrants further research.

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