Atlantic Multidecadal Oscillation Drives Interdecadal Pacific Variability via Tropical Atmospheric Bridge

XIAOHE AN,^{a,b} BO WU,^{a,c} TIANJUN ZHOU,^{a,b,c} AND BO LIU^d

^a State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

^b University of Chinese Academy of Sciences, Beijing, China

^c CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing, China

^d Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, China

(Manuscript received 18 December 2020, in final form 28 March 2021)

ABSTRACT: The interdecadal Pacific oscillation (IPO) and Atlantic multidecadal oscillation (AMO), two leading modes of decadal climate variability, are not independent. It was proposed that ENSO-like sea surface temperature (SST) variations play a central role in the Pacific responses to the AMO forcing. However, observational analyses indicate that the AMO-related SST anomalies in the tropical Pacific are far weaker than those in the extratropical North Pacific. Here, we show that SST in the North Pacific is tied to the AMO forcing by convective heating associated with precipitation over the tropical Pacific, instead of by SST there, based on an ensemble of pacemaker experiments with North Atlantic SST restored to the observation in a coupled general circulation model. The AMO modulates precipitation over the equatorial and tropical southwestern Pacific through exciting an anomalous zonal circulation and an interhemispheric asymmetry of net moist static energy input into the atmosphere. The convective heating associated with the precipitation anomalies drives SST variations in the North Pacific through a teleconnection, but it remarkably weakens the ENSO-like SST anomalies through a thermocline damping effect. This study has implications that the IPO is a combined mode generated by both AMO forcing and local air–sea interactions, but the IPO-related global warming acceleration/slowdown is independent of the AMO.

KEYWORDS: Air–sea interaction; Climate change; Climate models; Decadal variability

1. Introduction

Sea surface temperature (SST) in the North Atlantic shows alternative warming and cooling on multidecadal time scales (~50–70 years), which is referred to as the Atlantic multidecadal oscillation (AMO) (Kerr 2000; Knight et al. 2006) or Atlantic multidecadal variability (AMV) (Ting et al. 2009; Zhang 2017; Sutton et al. 2018). As one of the leading modes of the internal decadal variability, the AMO has great impacts on the circum-Atlantic climate and on the North Hemispheric and global-mean temperature (see review by Zhang et al. 2019). The AMO is one of the major sources of the predictive skill of decadal climate prediction experiments initialized using observational data (Keenlyside et al. 2008; Smith et al. 2010; Doblas-Reyes et al. 2013; Kushnir et al. 2019), including for the prediction of decadal variations in the Pacific (Chikamoto et al. 2015).

In addition to the AMO, the climate system has the other dominant decadal variability mode, the interdecadal Pacific oscillation (Power et al. 1999; Henley et al. 2015) [IPO; also known as Pacific decadal oscillation (Mantua et al. 1997; Newman et al. 2016), with a focus on the North Pacific]. The two modes are not orthogonal, but the IPO is partly contributed to by the AMO in the historical data (Tung et al. 2019). The AMO has lead–lag relationships with the IPO, especially

on interdecadal scales (>20 years) (d’Orgeville and Peltier 2007; Zhang and Delworth 2007; Wu et al. 2011; Chylek et al. 2013; Marini and Frankignoul 2014).

It has been proposed that SST anomalies in the Atlantic can modulate Pacific variability through two pathways: tropical and extratropical atmospheric bridges (Zhang et al. 2019). For the extratropical pathway, the positive AMO weakens atmospheric meridional eddy heat transport, which further leads to the weakening of the storm track and the Aleutian low. This extratropical atmospheric teleconnection drives the positive SST anomalies in the North Pacific (Zhang and Delworth 2007; Sun et al. 2017; Ruprich-Robert et al. 2017). This physical process was also used to explain the linkage of cold biases in the North Atlantic and in the North Pacific in coupled models (Wang et al. 2014). Zhang and Zhao (2015) further noted that cold SST biases in the extratropical North Atlantic make a major contribution to cold SST biases in the North Pacific through the Northern Hemisphere annular mode and the associated strengthening of the Aleutian low.

For the tropical pathway, the warm SST anomalies in the tropical North Atlantic can drive zonal easterly anomalies over the equatorial Pacific through exciting a variation in the Walker circulation, which causes La Niña-like SST cooling in the equatorial central-eastern Pacific, based on idealized simulations of a coupled general circulation model (GCM) (Ruprich-Robert et al. 2017; Yang et al. 2020; Meehl et al. 2021) and a hybrid GCM (Kucharski et al. 2011), in which SST anomalies in the North Atlantic are specified. The SST cooling in the tropical eastern Pacific in past 20–30 years was partly attributed to the SST warming in the tropical North Atlantic (McGregor et al. 2014; Li et al. 2016). The La Niña-like cold SST anomalies further

Denotes content that is immediately available upon publication as open access.

Corresponding author: Bo Wu, wubo@mail.iap.ac.cn

DOI: 10.1175/JCLI-D-20-0983.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

TABLE 1. Numerical experiments used in this study.

Expt ID	Design	Integration
HIST	Forced by the historical external forcing from the CMIP5	1870–2004, eight members
HIST-NA	Simulated SST anomalies in the North Atlantic (0°–70°N, 70°W–0°) are restored to the observations from the HadISST 1.1 dataset (Rayner et al. 2003), while in the other ocean areas, the model is freely integrated; meanwhile, the model is forced by the same external radiative forcing as the HIST runs	1870–2004, eight members
HIST-ENA	As the HIST-NA, but the SST anomalies in the extratropical North Atlantic (23°N–70°N, 70°W–0°) are restored	1870–2004, eight members
HIST-TNA	As the HIST-NA, but the SST anomalies in the tropical North Atlantic (0°–23°N, 70°W–0°) are restored	1870–2004, eight members

modulate North Pacific climate through exciting atmospheric teleconnections, as does the IPO (Ruprich-Robert et al. 2017). On the other hand, numerical experiment by an atmospheric GCM indicates that the tropical component of the AMO can modulate vertical motion anomalies over the tropical central Pacific and further excite atmospheric teleconnections propagating toward the North Pacific directly (Lyu et al. 2017).

However, we will show that the tropical SST anomalies associated with the AMO is far weaker than those in the extratropical North Pacific in the observational SST data over the past century, as noted by Chen and Tung (2018). This raises the question of whether the tropical air–sea interactions are essential for AMO forcing on the Pacific interdecadal variability.

In this study, we propose a new mechanism of tropical atmospheric bridge through which AMO drives SST variations in the extratropical North Pacific but suppresses growth of SST anomalies in the tropical Pacific. The remainder of this paper is organized as follows. Section 2 describes model experiments and analysis methods used in this study. Section 3 investigates the AMO-related interdecadal variability in the Pacific and related physical processes in the numerical experiments. Finally, the key findings are summarized in section 4.

2. Materials and methods

a. Coupled GCM experiments

A coupled global climate model, the Community Earth System Model (CESM), version 1.2.0 (Hurrell et al. 2013), developed by the National Center for Atmospheric Research (NCAR), was used in this study. Its atmospheric component is the Community Atmosphere Model, version 4 (CAM4), with horizontal resolution of 1.25° longitude × 0.94° latitude. The oceanic component is an extension of the Parallel Ocean Program, version 2 (POP2), with horizontal resolution of approximately 1°.

We conducted four sets of numerical experiments using the CESM (Table 1). The first is standard historical simulations of the CMIP5 (HIST; 1870–2004). The second is the North Atlantic pacemaker experiment (Zhou et al. 2016), in which the SST in the North Atlantic (0°–70°N, 70°W–0°, Fig. 1a) was restored to the observational SST anomalies (T'_o) plus the model climatological SST ($\overline{T_m}$), and atmospheric and oceanic component are freely coupled in other ocean areas,

$$\frac{\partial T}{\partial t} = \text{original } T \text{ tendency terms} + \alpha \frac{(T'_o + \overline{T_m}) - T}{\tau}, \quad (1)$$

where $\tau = 10$ days denotes restoring time scale, and α denotes restoring coefficient, a function of horizontal position. This experiment is forced by the external forcing identical to the HIST and is referred to as HIST-NA.

Another two pacemaker experiments similar to the HIST-NA were conducted, except that the restoring areas are the extratropical North Atlantic (HIST-ENA; 23°–70°N, 70°W–0°, Fig. 1c), and tropical North Atlantic (HIST-TNA; 0°–23°N, 70°W–0°, Fig. 1e), respectively. All these experiments have eight members and cover the period of 1870–2004. The first 30-yr integrations for the “spin up” are not used in the analysis.

The HIST-NA runs are stable and have no obvious model drift. The SST bias of the ensemble mean of the HIST-NA runs in the North Atlantic relative to the ensemble mean of the HIST runs is less than 0.8 K for the period of 1900–2004. The HIST-NA runs reproduce the observed AMO time evolutions accurately. The temporal correlation coefficient of the unfiltered (8-yr low-pass-filtered) AMO index between the ensemble average of the HIST-NA and the observational reference reaches 0.83 (0.92) (Fig. 1b). The definitions of the AMO index will be described in section 2b(3). Though only SST anomalies in the North Atlantic are restored, the pattern of AMO-related upper-ocean heat content anomalies (0–700 m) in the North Atlantic derived from the HIST-NA runs are consistent with those from the HIST runs (Fig. 2).

b. Analysis methods

1) CLIMATE VARIABILITY DUE TO EXTERNAL RADIATIVE FORCING

Model-based forced signals due to external radiative forcing are estimated by using the ensemble mean of the HIST runs. A variable Φ of year m in the HIST of member n can be decomposed as

$$\Phi_{mn} = \Phi^C + \Phi_m^{\text{Ex}} + \Phi_{mn}^I, \quad (2)$$

where superscripts C , Ex , and I denote climatology, externally forced variability, and internal variability, respectively. The first term on the right-hand side, Φ^C , is

$$\Phi^C = \overline{\Phi_{mn}}^{m,n}, \quad (3)$$

where the overbar denotes the average over time and the ensemble members. The externally forced component is calculated as

$$\Phi_m^{\text{Ex}} = \overline{\Phi_{mn}} - \Phi^C. \quad (4)$$

FIG. 1. SST anomalies associated with the AMO simulated by the HIST-NA runs. (a) 8-yr low-pass-filtered SST anomalies (units: K) regressed onto the normalized AMO index from the NA-forced components of the HIST-NA runs (ϕ_m^{NA}). Gray shading represents the area where the SST anomalies were restored to the observation. (b) AMO indices in the observation (black, HadISST1.1) and HIST-NA runs (red). The AMO index is defined as the 8-yr low-pass-filtered area-averaged SST anomalies in the North Atlantic (0° – 60° N, 80° W– 0°) with the global warming signals removed. For the observation, the global warming signal is obtained through regression on the global-mean SST. (c),(d) As in (a) and (b), but for the extratropical component of the AMO from the HIST-ENA runs. (e),(f) As in (a) and (b), but for tropical component of the AMO from the HIST-TNA runs.

2) CLIMATE VARIABILITY DUE TO REMOTE FORCING FROM THE NORTH ATLANTIC

Climate variability associated with the North Atlantic SST anomalies are estimated based on the HIST-NA runs. A

variable ϕ of year m in the HIST-NA of member n can be decomposed as

$$\phi_{mn} = \phi^C + \phi_m^{\text{Ex}} + \phi_m^{\text{NA}} + \phi_{mn}^{\text{RI}}, \quad (5)$$

FIG. 2. Simulated upper-ocean heat content anomalies (0–700 m) in the North Atlantic associated with the AMO. (a) 8-yr low-pass-filtered ocean heat content anomalies (units: $\times 10^9 \text{ J m}^{-2}$) from the NA-forced component (ϕ_m^{NA}) of the HIST-NA runs regressed onto the corresponding AMO index. (b) Ensemble mean of the AMO-related ocean heat content anomalies from the eight HIST runs. The 8-yr low-pass-filtered heat content anomalies are regressed onto corresponding AMO index for each HIST runs and then ensemble mean is calculated.

where ϕ_m^{NA} and ϕ_{mn}^{RI} are the NA-forced component and remaining internal component not associated with the NA forcing. Similarly, ϕ^C is equal to $\overline{\phi_{mn}^{m,n}}$. Supposing that the externally forced component in the HIST-NA is equal to that in the HIST ($\phi_m^{\text{Ex}} = \Phi_m^{\text{Ex}}$), the NA-related climate variability can be estimated through the ensemble average of the anomalous field with the externally forced signals removed, that is,

$$\phi_m^{\text{NA}} = \overline{\phi_{mn}^C} - \Phi_m^{\text{Ex}}. \quad (6)$$

The internal component not associated with the NA forcing is

$$\phi_{mn}^{\text{RI}} = \phi_{mn} - \phi^C - \Phi_m^{\text{Ex}} - \phi_m^{\text{NA}}. \quad (7)$$

3) ATMOSPHERIC RESPONSES TO THE AMO FORCING

Simultaneous regressions onto the AMO index are used to obtain AMO-related atmospheric anomalies for fast atmospheric responses to SST forcing. In this study, the AMO index is defined as the 8-yr low-pass-filtered, annual-mean area-averaged SST anomalies in the North Atlantic (0°–60°N, 80°W–0°) with the global warming signals removed. For the HIST-NA runs, the global warming signal is estimated by using the ensemble mean of the corresponding HIST runs. For the observation, the global warming signal is obtained through regression on the global-mean SST series. Here the annual mean is from June to May in the next year for the central role of winter variability. The significances of regression analyses are tested through a non-parameter “random phase” method (Ebisuzaki 1997).

4) DIVERGENT ATMOSPHERIC MSE TRANSPORT

In this study, we try to understand tropical precipitation responses to remote forcing from the perspective of the atmospheric moist static energy (MSE) transport. For atmospheric columns, divergence of atmospheric MSE flux ($\mathbf{F} = \int_0^{P_s} \mathbf{v} h dp/g$) is balanced by net energy input to the atmosphere (F_{net}) (Neelin and Held 1987):

$$\nabla \cdot \int_0^{P_s} \mathbf{v} h \frac{dp}{g} = F_{\text{net}}, \quad (8)$$

where h is MSE, $\mathbf{v}$ is horizontal wind vector, g is gravitational acceleration, and P_s is surface pressure. Following previous studies (Trenberth et al. 2002; Adam et al. 2016; Boos and Korty 2016), energy flux potential χ is introduced:

$$\nabla^2 \chi = \nabla \cdot \mathbf{F}. \quad (9)$$

The gradient of χ is divergent component of the atmospheric MSE flux. Then the atmospheric MSE transport is linked to the distribution of net energy input to the atmosphere (F_{net}). We can decompose F_{net} into net shortwave radiative flux, net long-wave radiative flux, and sensible and latent heat flux. It is worth noting that χ and its gradient shown below are inverted from F_{net} based on Eqs. (8) and (9), rather than be calculated directly using horizontal wind and MSE. The direct calculation of vertically integrated energy transport needs to be done on high-temporal-resolution data (e.g., 6 hourly; Trenberth 1997), which cannot be archived here for the model outputs are monthly.

3. Results

a. AMO-related interdecadal Pacific variability and internal IPO

We first extract AMO-related interdecadal Pacific variability (IPV) in the observation and compare it with the conventional IPO. Considering of the multidecadal time scale of the AMO, which is much longer than one of IPO periods at about 20 years (Minobe 1999; Liu 2012), we try to use a 20-yr low-pass filtering to highlight signature associated with the AMO forcing. We apply the maximum covariance analysis (MCA) to 20-yr low-pass-filtered SST anomalies in the Pacific and in the North Atlantic to extract their coupled interdecadal variability. Global warming signals have been removed prior to the MCA based on regression onto the global-mean SST (Fig. 3a). The spatial pattern of the AMO-related IPV has strong SST anomalies in the extratropical North Pacific, but weak, opposite SST anomalies in the tropical Pacific (Fig. 3a). The SST anomalies in the North Pacific are about twice the magnitude of the SST anomalies in the tropical central-eastern Pacific. The AMO leads the AMO-related IPV by 5 years, with their lagged correlation reaching 0.82.

In contrast to the AMO-related IPV mode, the IPO derived from the second empirical orthogonal function (EOF) of 8-yr low-pass-filtered SST anomalies in the Pacific has close magnitudes of tropical and extratropical components (Fig. 3b). This implies that the relative role of tropical component in the AMO-related IPV mode is far lower than in the IPO. What causes the difference between the AMO-related IPV and the IPO is a key to understand the AMO forcing mechanism on the Pacific variability. However, for the observational analysis, it is difficult to entirely distinguish the AMO-related signal from the IPO generated by local air–sea interactions in the Pacific for the limitation of the data length and their resemblance in spatial pattern. Below, we separate them explicitly based on idealized numerical experiments.

We use the eight-member North Atlantic pacemaker experiment (HIST-NA runs) to investigate the AMO-related IPV with temporal evolution. After removing signals generated by the external radiative forcing, we separate internal variability in the HIST-NA runs into two components, North Atlantic–forced (NA-forced) variability and internal variability not associated with the North Atlantic forcing (non-NA internal variability), which are derived from the ensemble mean and ensemble member spread of the HIST-NA runs, respectively (see section 2 for details).

For the whole spectrum of decadal variability (>8 years) of SST outside of the North Atlantic, the ratio of globally averaged NA-forced variance and total internal variance is about 23.9% (Fig. 4a). For interdecadal variability (>20 years), the ratio rises to 27.3% (Fig. 4b). The most prominent variance contribution of the NA-forced component is in the North Pacific (20°–60°N), where about 30.1% (39.8%) of the internal decadal (interdecadal) variance is accounted for by the NA-forced variance. In contrast, for the tropical Pacific (20°S–20°N), the variance ratio is only 22.6% (24.1%), even lower than the global-mean values (Fig. 4), indicating that the SST in

FIG. 3. AMO-related IPV and IPO. (a) AMO-related IPV and (b) IPO (units: K) in the observation derived from the HadISST1.1 over the period of 1900–2014. The AMO-related IPV is a homogeneous map of the annual-mean SST in the Pacific for the first MCA mode, which is obtained by performing singular-value decomposition (SVD) of the covariance matrix of the 20-yr low-pass-filtered SST anomalies between the Pacific (40°S – 60°N , 120°E – 100°W) and the North Atlantic (0° – 60°N , 80°W – 0°). The global warming signals have been removed prior to the SVD through regression on the global-mean (60°S – 60°N) SST. The IPO is the second EOF of the 8-yr low-pass-filtered SST anomalies in the Pacific (40°S – 60°N , 120°E – 100°W). (c),(d) Simulated AMO-related IPV and the internal IPO (units: K) derived from the HIST-NA runs, respectively. The AMO-related IPV is the first EOF of the 8-yr low-pass-filtered SST anomalies in the Pacific from the NA-forced components of the HIST-NA runs (ϕ_m^{NA}). The internal IPO is the first EOF mode of SST anomalies in the Pacific from the internal component of the HIST-NA runs not associated with the NA forcing ($\phi_{\text{int}}^{\text{RI}}$). All these patterns correspond to normalized time series.

the tropical Pacific is less modulated by the remote forcing from the North Atlantic.

An EOF analysis is applied to 8-yr low-pass-filtered, NA-forced annual-mean SST anomalies in the Pacific (40°S – 60°N , 120°E – 100°W) (Fig. 3c). The first EOF mode accounts for 49.2% of the NA-forced variance. Its PC time series has a similar fluctuation period to the AMO index, but lags about 2 years behind, with their 2-yr lagged correlation reaching 0.79 (Fig. 7b). This mode represents AMO-related IPV in the HIST-NA runs.

An EOF analysis is applied to the non-NA internal variability derived from the ensemble member spread of the HIST-NA runs (see in section 2). The first EOF mode accounts for 29.4% of the non-NA internal variance. This mode represents the IPO internally generated in Pacific (Fig. 3d). Both the AMO-related IPV and internal IPO have opposite SST anomalies in the North Pacific and the tropical central-eastern Pacific. Their intensities in the North Pacific are close, but the tropical component of the internal IPO is about 3 times as strong as that

of the AMO-related IPV (Figs. 3c,d). This indicates the response of the SST in the tropical Pacific to the remote forcing from the North Atlantic is far weaker than the SST response in the extratropical North Pacific, consistent with the observational analysis (Fig. 3) and other simulations by coupled GCMs, such as Dong et al. (2006) and Okumura et al. (2009).

b. AMO-driven precipitation anomalies over the tropical Pacific

Although SST anomalies in the tropical Pacific associated with the AMO are extremely weak (Fig. 1a), precipitation anomalies over the tropical Pacific regressed onto the normalized AMO index reach more than half the intensity of those associated with the internal IPO mode (Fig. 5). The AMO-driven precipitation anomalies over the tropical Pacific show a pattern antisymmetric about the equator. The intertropical convergence zone (ITCZ) in the Northern Hemisphere is strengthened and shifted northward, while the South Pacific convergence zone (SPCZ) in the Southern Hemisphere is

FIG. 4. Simulated ratios of NA-forced variance and total internal variance for the (a) 8- and (b) 20-yr low-pass-filtered annual-mean SST (units: %). The NA-forced variance and the total internal variance are calculated using the NA-forced component (ϕ_m^{NA}) and the internal component (sum of ϕ_m^{NA} and ϕ_{mn}^{RI}) derived from the HIST-NA runs, respectively. The regions where the SST anomalies were restored to the observations are masked.

weakened. The equatorial Pacific is dominated by negative precipitation anomalies. The AMO-driven tropical precipitation anomalies have a similar spatial pattern to that associated with the internal IPO (Figs. 5a,b), and thus excite similar atmospheric teleconnections, which modulate SST anomalies in the North Pacific, as shown in following section.

The AMO has two centers in the North Atlantic, with one in the tropics and the other in the subpolar gyre (Fig. 1a), which have different forcing mechanisms for the precipitation over the tropical Pacific. The tropical Atlantic warm SST anomalies enhance local convection and thus drive an anomalous zonal circulation (Kucharski et al. 2011), with an anomalous ascending motion over the equatorial Atlantic and a descending motion over the tropical Pacific corresponding to a westward transport of the vertically integrated MSE from the tropical North Atlantic to the tropical Pacific (Fig. 6c). Meanwhile, the extratropical Atlantic warm SST anomalies in the subpolar gyre increase local upward latent heat flux (Fig. 6b), and thus lead to interhemispheric asymmetry in the anomalous net MSE flux inputting into the atmosphere (Fig. 6a). The interhemispheric asymmetry in the net MSE flux further drives a southward cross-equatorial MSE transport to maintain the atmospheric energy balance (Fig. 6c) (Kang et al. 2009; Schneider et al. 2014; Levine et al. 2018), corresponding to the precipitation anomalies antisymmetric about the equator (positive in the north and negative in the south; Fig. 5a) (Zhao and Fedorov 2020).

FIG. 5. Simulated precipitation and atmospheric circulation anomalies associated with the AMO and the internal IPO. (a) 8-yr low-pass-filtered annual-mean precipitation (shading, units: mm day^{-1}) and 300 hPa streamfunction anomalies (contoured at $2 \times 10^5 \text{ m}^2 \text{ s}^{-1}$ intervals) from the NA-forced components of the HIST-NA runs (ϕ_m^{NA}) are regressed onto the corresponding normalized AMO index. (b) As in (a), but for the internal IPO derived from the internal component of the HIST-NA runs not associated with the NA forcing (ϕ_m^{RI}). Green dashed lines denote the climatological ITCZ and SPCZ (mean precipitation $> 4 \text{ mm day}^{-1}$). Vectors are wave activity fluxes (Takaya and Nakamura 2001) (units: $\text{m}^2 \text{ s}^{-2}$) corresponding to the 300 hPa streamfunction anomalies. Dots represent values reaching the 10% significance level.

c. Difference in the responses between North Pacific and tropical Pacific

The AMO-driven precipitation anomalies over the tropical Pacific have a similar spatial pattern to IPO-related precipitation anomalies, and thus excite a similar Pacific–North American–like (PNA-like) atmospheric teleconnection (Fig. 5). The suppressed convective heating over the equatorial Pacific and the associated PNA-like teleconnection lead to the weakening of the Aleutian low (Fig. 5a) (Trenberth et al. 1998; Alexander et al. 2002; Lyu et al. 2017).

Two centers of the warm SST anomalies in the central North Pacific and the Oyashio Frontal zone associated with the AMO-related IPV (Fig. 3c) are driven by the weakening of the Aleutian low (Fig. 7a). The anomalous anticyclone over the eastern North Pacific stimulates oceanic Rossby waves propagating westward at the speed of about 2 cm s^{-1} (Fig. 7b), close to the phase speed of baroclinic Rossby wave at the latitude of 40°N in Qiu (2003). The Rossby waves cause the meridional

FIG. 6. Simulated responses of atmospheric energy flux to the AMO forcing. (left) 8-yr low-pass-filtered annual-mean (a) net energy input to the atmosphere (F_{net}) (units: W m^{-2}) and (b) latent heat flux (LH) derived from the ϕ_m^{NA} in the HIST-NA runs regressed onto the corresponding normalized AMO index. Dots represent values reaching the 10% significance level. (right) The zonal mean values. (c) As in (a), but for energy flux potential (χ , shading, units: 0.001 PW) and divergent component of the vertically integrated atmospheric energy flux (vectors, units: 10^6 W m^{-1}).

shift of the Oyashio Front and the SST warming to the east of Japan (Miller et al. 1998; Newman et al. 2016). The easterly anomalies to the southern flank of the anticyclone lead to the SST warming in the central North Pacific through driving northward oceanic Ekman transport and weakening mean westerly wind and upward latent heat flux (figures not shown) (Alexander and Scott 2008).

In contrast to the strong responses in the North Pacific, the SST anomalies in the tropical Pacific associated with the AMO-related IPV are far weaker than the tropical component of the internal IPO (Figs. 3c,d). The AMO-driven negative precipitation anomalies over the equatorial Pacific stimulate equatorial easterly anomalies to the west (Fig. 8a). However, the easterly anomalies do not generate strong La Niña-like cold SST anomalies in the equatorial central-eastern Pacific (Fig. 3c) as suggested by the theory of the Bjerknes feedback, implying that some negative feedbacks may come into the play.

The negative precipitation anomalies over the off-equatorial tropical southwestern Pacific stimulate low-level anticyclonic

FIG. 7. Simulated ocean responses in the North Pacific to the AMO forcing. (a) 8-yr low-pass-filtered surface wind stress anomalies (vectors, units: N m^{-2}) derived from the ϕ_m^{NA} in the HIST-NA runs regressed onto the corresponding normalized AMO index. (b), (left) AMO-related IPV index (the PC time series of the first EOF mode, blue line) and the low-pass-filtered, annual-mean AMO index from the ϕ_m^{NA} (red line). The 2-yr lagged correlation between the AMO index and the PC time series (PC time series lags AMO index) is noted above (b). (b), (right) Time-longitude diagram of the 8-yr low-pass-filtered SSH anomalies (units: cm) zonally averaged over the $38^{\circ}\text{--}42^{\circ}\text{N}$ from the ϕ_m^{NA} . The dashed line represents a phase speed of 2 cm s^{-1} .

anomalies to the west in terms of the Gill model (Gill 1980) (Figs. 5a, 8a). The related anticyclonic wind stress anomalies drive underlying ocean subsurface warm anomalies through downward anomalous Ekman pumping velocity (Fig. 8a). The subsurface warm anomalies propagate northward to the equatorial western Pacific (Figs. 8b,c). This subsurface warming process deepens the zonal mean thermocline depth of the equatorial Pacific (Figs. 8b,c), which greatly offsets shallowing of the thermocline in the eastern Pacific due to the east–west tilting of the thermocline driven by the equatorial easterly wind anomalies, and thus suppresses the growth of the La Niña-like cold SST anomalies.

This damping effect originated in the off-equatorial South Pacific was proposed by Luo et al. (Luo and Yamagata 2001; Luo et al. 2003) to explain the formation of the ENSO-like decadal variation. There, it was taken as a delayed negative feedback for the slow off-equatorial oceanic Rossby wave propagation. In this study, the subsurface oceanic temperature anomalies at the depth of climatological 20°C isotherm (Z20)

FIG. 8. Simulated ocean responses in the tropical Pacific to the AMO forcing. (a) 8-yr low-pass-filtered wind stress (vectors, units: N m^{-2}) and wind stress curl (shading, units: 10^{-9} N m^{-3}) anomalies derived from the ϕ_m^{NA} in the HIST-NA runs regressed onto the corresponding normalized AMO index. (b) 3-yr lagged regression of low-pass-filtered 20°C isotherm (Z20) anomalies (units: m) from the ϕ_m^{NA} onto the normalized AMO index. (c) Latitude–depth diagram of 3-yr lagged regression of low-pass-filtered oceanic temperature anomalies (units: K) zonally averaged over the Pacific derived from the ϕ_m^{NA} onto the normalized AMO index.

in the tropical southwestern Pacific ($5^\circ\text{--}18^\circ\text{S}$, $150^\circ\text{E}\text{--}170^\circ\text{W}$) lag the AMO index by about 3 years ($r = 0.69$). For the time lag is shorter than the period of the AMO with one order of magnitude, the processes caused by the AMO-driven off-equatorial negative precipitation anomalies can be considered as a synchronous damping factor with the positive Bjerknes (thermocline) feedback, rather than a delayed oscillator. Hence, the much longer time scale of the AMO than the internal IPO is essential for the former SST anomalies in the tropical Pacific being much weaker than the latter.

d. Relative roles of forcing from tropical and extratropical North Atlantic

Above, we proposed that both the tropical and extratropical components of the AMO modulate the precipitation over the tropical Pacific through distinct forcing mechanisms. To identify their relative roles, we conducted pacemaker experiments separately for the tropical and extratropical North Atlantic and refer them to as HIST-TNA and HIST-ENA runs, respectively (Fig. 1; see also section 2).

FIG. 9. Simulated precipitation and atmospheric circulation anomalies associated with the tropical and extratropical components of the AMO. (a),(b) As in Fig. 5a, but for the HIST-ENA and HIST-TNA runs, respectively (contoured at $10^5 \text{ m}^2 \text{s}^{-1}$ intervals).

The two pacemaker experiments indicate that both the tropical and extratropical components of the AMO have contributions to the precipitation anomalies over the tropical Pacific and the excited PNA-like teleconnection (Figs. 9 and 5). The antisymmetry in the precipitation anomalies about the equator is stronger in the HIST-ENA, for the cross-equatorial MSE transport is mainly driven by the interhemispheric asymmetry in the MSE flux associated with the extratropical component of the AMO (Fig. 9a). In contrast, the equatorial negative precipitation anomalies are stronger in the HIST-TNA (Fig. 9b). As a result, the PNA-like teleconnection in the HIST-TNA is stronger than the HIST-ENA. Correspondingly, the AMO-related IPV in the North Pacific in the HIST-TNA is stronger than that in the HIST-ENA (Fig. 10). Here, the AMO-related IPV in the HIST-ENA and the HIST-TNA runs are obtained through the EOF analysis on their NA-forced components of the SST anomalies in the Pacific identical to that performed on the HIST-NA runs shown in Fig. 3c. These results indicate that the tropical component of the AMO has somewhat larger contributions to the IPV than the extratropical component in the model.

4. Conclusions and discussion

a. Conclusions

In this study, we conducted three sets of pacemaker experiments for the North Atlantic, tropical North Atlantic and

FIG. 10. Simulated IPV associated with the remote forcing from the extratropical North Atlantic and tropical North Atlantic. (a),(b) As in Fig. 3c, but from the NA-forced components of the HIST-ENA and the HIST-TNA runs, respectively. The variance fractions accounted for by the EOF modes are noted on the upper-right corner of each panel.

extratropical North Atlantic, respectively. Based on the pacemaker experiments, we link the interdecadal variability in the Pacific (IPV) to the AMO via the direct precipitation responses over the tropical Pacific, rather than via air–sea interactions there. The major conclusions are summarized as follows.

- 1) We extract AMO-related IPV mode and internal IPO mode from the ensemble mean and the ensemble spread of the North Atlantic pacemaker experiments, respectively. The most striking feature of the AMO-related IPV is strong SST anomalies in the North Pacific close to those in the internal IPO. In contrast, the AMO-related SST signal in the tropical Pacific is far weaker than that in the internal IPO. The difference in the intensity of response to AMO forcing between the extratropical North Pacific and tropical Pacific is consistent with that in the observation.
- 2) In contrast to the weak tropical SST response, precipitation response over the tropical Pacific to the AMO forcing is strong. In the positive phase of AMO, precipitation over the equatorial and southwestern Pacific is greatly weakened by two mechanisms. First, the warm SST anomalies in the tropical North Atlantic enhance local convection and thus

drive the variation of the Walker circulation, which suppresses convection over the tropical Pacific, consistent with simulations by an atmospheric CGM (Lyu et al. 2017). Second, the warm SST anomalies over the extratropical North Atlantic enhance local upward latent heat flux and thus cause the interhemispheric asymmetry of net MSE input into atmosphere columns. The interhemispheric asymmetric net MSE flux drive the northward shift of the ITCZ and the weakening of the SPCZ.

- 3) The suppressed convective heating associated with the negative precipitation anomalies over the equatorial and tropical southwestern Pacific generate positive SST anomalies in the extratropical North Pacific but suppress growth of ENSO-like SST variability. On the one hand, the tropical negative precipitation anomalies weaken the Aleutian low through exciting the PNA-like teleconnection. The weakening of the Aleutian low drives northward oceanic Ekman transport and westward-propagating oceanic Rossby waves, which cause SST warming in the central North Pacific and Oyashio Frontal zone, respectively. On the other hand, the negative precipitation anomalies over the tropical southwestern Pacific drive a low-level anomalous anticyclone to the west, which causes local oceanic subsurface warming downward anomalous Ekman pumping velocity. The subsurface warm anomalies propagate equatorward first and then eastward along equator as Kelvin waves. The warming signal greatly offsets La Niña-like SST cooling effect induced by equatorial easterlies.
- 4) Both extratropical and tropical components of AMO have contributions to the AMO-related IPV mode, which is confirmed by the two pacemaker experiments for the extratropical and tropical North Atlantic, respectively.

b. Discussion

It has been noted that the La Niña-like SST anomalies (negative phase of IPO) and associated strengthening of the trade wind lead to the slowdown of the global warming in the early twenty-first century through atmospheric teleconnections excited by tropical heating anomalies (Kosaka and Xie 2013; England et al. 2014). The formation of the La Niña-like SST anomalies was proposed to be partly associated with the SST warming in the tropical Atlantic (Li et al. 2016). In this study, we find that the positive AMO forcing leads to the precipitation anomalies over the tropical Pacific and the poleward-propagating wave train similar to those associated with the negative IPO. However, the global-mean surface temperature is positively correlated with the AMO index for the NA-forced component in the HIST-NA runs ($r = 0.90$), indicating that the SST warming in the North Atlantic accelerates the global warming rather than decelerates it, consistent with previous studies based on hybrid coupled model simulations (Zhang et al. 2007) and observational analysis (Chen and Tung 2018). These results suggest that 1) the modulation effect of the IPO on global warming rate is less contributed by the AMO forcing, and 2) the AMO has a forcing mechanism for the global-mean temperature different from the IPO.

Acknowledgments. We thank the two anonymous reviewers for their constructive comments that helped greatly to improve

the original manuscript. This work is jointly supported by National Key Research and Development Program of China (Grant 2018YFA0606300), the NSFC (Grant 42075163), and the NSFC BSCTPES project (Grant 41988101). This work is also supported by the Jiangsu Collaborative Innovation Center for Climate Change.

REFERENCES

- Adam, O., T. Bischoff, and T. Schneider, 2016: Seasonal and interannual variations of the energy flux equator and ITCZ. Part II: Zonally varying shifts of the ITCZ. *J. Climate*, **29**, 7281–7293, <https://doi.org/10.1175/JCLI-D-15-0710.1>.
- Alexander, M. A., and J. D. Scott, 2008: The role of Ekman ocean heat transport in the Northern Hemisphere response to ENSO. *J. Climate*, **21**, 5688–5707, <https://doi.org/10.1175/2008JCLI2382.1>.
- , I. Bladé, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. *J. Climate*, **15**, 2205–2231, [https://doi.org/10.1175/1520-0442\(2002\)015<2205:TABTIO>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<2205:TABTIO>2.0.CO;2).
- Boos, W. R., and R. L. Korty, 2016: Regional energy budget control of the intertropical convergence zone and application to mid-Holocene rainfall. *Nat. Geosci.*, **9**, 892–897, <https://doi.org/10.1038/ngeo2833>.
- Chen, X. Y., and K. K. Tung, 2018: Global-mean surface temperature variability: Space-time perspective from rotated EOFs. *Climate Dyn.*, **51**, 1719–1732, <https://doi.org/10.1007/s00382-017-3979-0>.
- Chikamoto, Y., and Coauthors, 2015: Skilful multi-year predictions of tropical trans-basin climate variability. *Nat. Commun.*, **6**, 6869, <https://doi.org/10.1038/ncomms7869>.
- Chylek, P., M. K. Dubey, G. Lesins, J. Li, and N. Hengartner, 2013: Imprint of the Atlantic multi-decadal oscillation and Pacific decadal oscillation on southwestern US climate: Past, present, and future. *Climate Dyn.*, **43**, 119–129, <https://doi.org/10.1007/s00382-013-1933-3>.
- Doblas-Reyes, F., and Coauthors, 2013: Initialized near-term regional climate change prediction. *Nat. Commun.*, **4**, 1715, <https://doi.org/10.1038/ncomms2704>.
- Dong, B. W., R. T. Sutton, and A. A. Scaife, 2006: Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures. *Geophys. Res. Lett.*, **33**, L08705, <https://doi.org/10.1029/2006GL025766>.
- d'Orgeville, M., and W. R. Peltier, 2007: On the Pacific decadal oscillation and the Atlantic multidecadal oscillation: Might they be related? *Geophys. Res. Lett.*, **34**, L23705, <https://doi.org/10.1029/2007GL031584>.
- Ebisuzaki, W., 1997: A method to estimate the statistical significance of a correlation when the data are serially correlated. *J. Climate*, **10**, 2147–2153, [https://doi.org/10.1175/1520-0442\(1997\)010<2147:AMTETS>2.0.CO;2](https://doi.org/10.1175/1520-0442(1997)010<2147:AMTETS>2.0.CO;2).
- England, M. H., and Coauthors, 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nat. Climate Change*, **4**, 222–227, <https://doi.org/10.1038/nclimate2106>.
- Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447–462, <https://doi.org/10.1002/qj.49710644905>.
- Henley, B. J., J. Gergis, D. J. Karoly, S. Power, J. Kennedy, and C. K. Folland, 2015: A tripole index for the interdecadal Pacific oscillation. *Climate Dyn.*, **45**, 3077–3090, <https://doi.org/10.1007/s00382-015-2525-1>.
- Hurrell, J. W., and Coauthors, 2013: The Community Earth System Model: A framework for collaborative research. *Bull. Amer. Meteor. Soc.*, **94**, 1339–1360, <https://doi.org/10.1175/BAMS-D-12-00121.1>.
- Kang, S. M., D. M. Frierson, and I. M. Held, 2009: The tropical response to extratropical thermal forcing in an idealized GCM: The importance of radiative feedbacks and convective parameterization. *J. Atmos. Sci.*, **66**, 2812–2827, <https://doi.org/10.1175/2009JAS2924.1>.
- Keenlyside, N., M. Latif, J. Jungclauss, L. Kornbluh, and E. Roeckner, 2008: Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, **453**, 84–88, <https://doi.org/10.1038/nature06921>.
- Kerr, R. A., 2000: A north Atlantic climate pacemaker for the centuries. *Science*, **288**, 1984–1985, <https://doi.org/10.1126/science.288.5473.1984>.
- Knight, J. R., C. K. Folland, and A. A. Scaife, 2006: Climate impacts of the Atlantic multidecadal oscillation. *Geophys. Res. Lett.*, **33**, L17706, <https://doi.org/10.1029/2006GL026242>.
- Kosaka, Y., and S.-P. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, **501**, 403–407, <https://doi.org/10.1038/nature12534>.
- Kucharski, F., I. S. Kang, R. Farneti, and L. Feudale, 2011: Tropical Pacific response to 20th century Atlantic warming. *Geophys. Res. Lett.*, **38**, L03702, <https://doi.org/10.1029/2010GL046248>.
- Kushnir, Y., and Coauthors, 2019: Towards operational predictions of the near-term climate. *Nat. Climate Change*, **9**, 94–101, <https://doi.org/10.1038/s41558-018-0359-7>.
- Levine, A. F. Z., D. M. W. Frierson, and M. J. McPhaden, 2018: AMO forcing of multidecadal Pacific ITCZ variability. *J. Climate*, **31**, 5749–5764, <https://doi.org/10.1175/JCLI-D-17-0810.1>.
- Li, X. C., S. P. Xie, S. T. Gille, and C. Yoo, 2016: Atlantic-induced pan-tropical climate change over the past three decades. *Nat. Climate Change*, **6**, 275–279, <https://doi.org/10.1038/nclimate2840>.
- Liu, Z., 2012: Dynamics of interdecadal climate variability: A historical perspective. *J. Climate*, **25**, 1963–1995, <https://doi.org/10.1175/2011JCLI3980.1>.
- Luo, J. J., and T. Yamagata, 2001: Long-term El Niño–Southern Oscillation (ENSO)-like variation with special emphasis on the South Pacific. *J. Geophys. Res.*, **106**, 22 211–22 227, <https://doi.org/10.1029/2000JC000471>.
- , S. Masson, S. Behera, P. Delecluse, S. Gualdi, A. Navarra, and T. Yamagata, 2003: South Pacific origin of the decadal ENSO-like variation as simulated by a coupled GCM. *Geophys. Res. Lett.*, **30**, 2250, <https://doi.org/10.1029/2003GL018649>.
- Lyu, K., J.-Y. Yu, and H. Paek, 2017: The influences of the Atlantic multidecadal oscillation on the mean strength of the North Pacific subtropical high during boreal winter. *J. Climate*, **30**, 411–426, <https://doi.org/10.1175/JCLI-D-16-0525.1>.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.*, **78**, 1069–1079, [https://doi.org/10.1175/1520-0477\(1997\)078<1069:APICOW>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2).
- Marini, C., and C. Frankignoul, 2014: An attempt to deconstruct the Atlantic multidecadal oscillation. *Climate Dyn.*, **43**, 607–625, <https://doi.org/10.1007/s00382-013-1852-3>.
- McGregor, S., A. Timmermann, M. F. Stuecker, M. H. England, M. Merrifield, F. F. Jin, and Y. Chikamoto, 2014: Recent Walker circulation strengthening and Pacific cooling amplified by Atlantic warming. *Nat. Climate Change*, **4**, 888–892, <https://doi.org/10.1038/nclimate2330>.

- Meehl, G. A., and Coauthors, 2021: Atlantic and Pacific tropics connected by mutually interactive decadal-timescale processes. *Nat. Geosci.*, **14**, 36–42, <https://doi.org/10.1038/s41561-020-00669-x>.
- Miller, A. J., D. R. Cayan, and W. B. White, 1998: A westward-intensified decadal change in the North Pacific thermocline and gyre-scale circulation. *J. Climate*, **11**, 3112–3127, [https://doi.org/10.1175/1520-0442\(1998\)011<3112:AWIDCI>2.0.CO;2](https://doi.org/10.1175/1520-0442(1998)011<3112:AWIDCI>2.0.CO;2).
- Minobe, S., 1999: Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: Role in climatic regime shifts. *Geophys. Res. Lett.*, **26**, 855–858, <https://doi.org/10.1029/1999GL900119>.
- Neelin, J. D., and I. M. Held, 1987: Modeling tropical convergence based on the moist static energy budget. *Mon. Wea. Rev.*, **115**, 3–12, [https://doi.org/10.1175/1520-0493\(1987\)115<0003:MTCBOT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<0003:MTCBOT>2.0.CO;2).
- Newman, M., and Coauthors, 2016: The Pacific decadal oscillation, revisited. *J. Climate*, **29**, 4399–4427, <https://doi.org/10.1175/JCLI-D-15-0508.1>.
- Okumura, Y. M., C. Deser, A. Hu, A. Timmermann, and S.-P. Xie, 2009: North Pacific climate response to freshwater forcing in the subarctic North Atlantic: Oceanic and atmospheric pathways. *J. Climate*, **22**, 1424–1445, <https://doi.org/10.1175/2008JCLI2511.1>.
- Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta, 1999: Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dyn.*, **15**, 319–324, <https://doi.org/10.1007/s003820050284>.
- Qiu, B., 2003: Kuroshio Extension variability and forcing of the Pacific decadal oscillations: Responses and potential feedback. *J. Phys. Oceanogr.*, **33**, 2465–2482, <https://doi.org/10.1175/2459.1>.
- Rayner, N., and Coauthors, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, 4407, <https://doi.org/10.1029/2002JD002670>.
- Ruprich-Robert, Y., R. Msadek, F. Castruccio, S. Yeager, T. Delworth, and G. Danabasoglu, 2017: Assessing the climate impacts of the observed Atlantic multidecadal variability using the GFDL CM2.1 and NCAR CESM1 global coupled models. *J. Climate*, **30**, 2785–2810, <https://doi.org/10.1175/JCLI-D-16-0127.1>.
- Schneider, T., T. Bischoff, and G. H. Haug, 2014: Migrations and dynamics of the intertropical convergence zone. *Nature*, **513**, 45–53, <https://doi.org/10.1038/nature13636>.
- Smith, D. M., R. Eade, N. J. Dunstone, D. Fereday, J. M. Murphy, H. Pohlmann, and A. A. Scaife, 2010: Skilful multi-year predictions of Atlantic hurricane frequency. *Nat. Geosci.*, **3**, 846–849, <https://doi.org/10.1038/ngeo1004>.
- Sun, C., F. Kucharski, J. Li, F. F. Jin, I. S. Kang, and R. Ding, 2017: Western tropical Pacific multidecadal variability forced by the Atlantic multidecadal oscillation. *Nat. Commun.*, **8**, 15998, <https://doi.org/10.1038/ncomms15998>.
- Sutton, R., G. D. McCarthy, J. Robson, B. Sinha, A. Archibald, and L. Gray, 2018: Atlantic multidecadal variability and the UK ACSIS program. *Bull. Amer. Meteor. Soc.*, **99**, 415–425, <https://doi.org/10.1175/BAMS-D-16-0266.1>.
- Takaya, K., and H. Nakamura, 2001: A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow. *J. Atmos. Sci.*, **58**, 608–627, [https://doi.org/10.1175/1520-0469\(2001\)058<0608:AFOAPI>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<0608:AFOAPI>2.0.CO;2).
- Ting, M. F., Y. Kushnir, R. Seager, and C. H. Li, 2009: Forced and internal twentieth-century SST trends in the North Atlantic. *J. Climate*, **22**, 1469–1481, <https://doi.org/10.1175/2008JCLI2561.1>.
- Trenberth, K. E., 1997: Using atmospheric budgets as a constraint on surface fluxes. *J. Climate*, **10**, 2796–2809, [https://doi.org/10.1175/1520-0442\(1997\)010<2796:UABAAC>2.0.CO;2](https://doi.org/10.1175/1520-0442(1997)010<2796:UABAAC>2.0.CO;2).
- , G. W. Branstator, D. Karoly, A. Kumar, N. C. Lau, and C. Ropelewski, 1998: Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res.*, **103**, 14 291–14 324, <https://doi.org/10.1029/97JC01444>.
- , D. P. Stepaniak, and J. M. Caron, 2002: Interannual variations in the atmospheric heat budget. *J. Geophys. Res.*, **107**, 4066, <https://doi.org/10.1029/2000JD000297>.
- Tung, K. K., X. Chen, J. Zhou, and K. F. Li, 2019: Interdecadal variability in pan-Pacific and global SST, revisited. *Climate Dyn.*, **52**, 2145–2157, <https://doi.org/10.1007/s00382-018-4240-1>.
- Wang, C., L. Zhang, S.-K. Lee, L. Wu, and C. R. Mechoso, 2014: A global perspective on CMIP5 climate model biases. *Nat. Climate Change*, **4**, 201–205, <https://doi.org/10.1038/nclimate2118>.
- Wu, S., Z. Y. Liu, R. Zhang, and T. L. Delworth, 2011: On the observed relationship between the Pacific decadal oscillation and the Atlantic multi-decadal oscillation. *J. Oceanogr.*, **67**, 27–35, <https://doi.org/10.1007/s10872-011-0003-x>.
- Yang, Y.-M., S.-I. An, B. Wang, and J. H. Park, 2020: A global-scale multidecadal variability driven by Atlantic multidecadal oscillation. *Natl. Sci. Rev.*, **7**, 1190–1197, <https://doi.org/10.1093/nsr/nwz216>.
- Zhang, L. P., and C. H. Zhao, 2015: Processes and mechanisms for the model SST biases in the North Atlantic and North Pacific: A link with the Atlantic meridional overturning circulation. *J. Adv. Model. Earth Syst.*, **7**, 739–758, <https://doi.org/10.1002/2014MS000415>.
- Zhang, R., 2017: On the persistence and coherence of subpolar sea surface temperature and salinity anomalies associated with the Atlantic multidecadal variability. *Geophys. Res. Lett.*, **44**, 7865–7875, <https://doi.org/10.1002/2017GL074342>.
- , and T. L. Delworth, 2007: Impact of the Atlantic multidecadal oscillation on North Pacific climate variability. *Geophys. Res. Lett.*, **34**, L23708, <https://doi.org/10.1029/2007GL031601>.
- , —, and I. M. Held, 2007: Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature? *Geophys. Res. Lett.*, **34**, L02709, <https://doi.org/10.1029/2006GL028683>.
- , and Coauthors, 2019: A review of the role of the Atlantic meridional overturning circulation in Atlantic multidecadal variability and associated climate impacts. *Rev. Geophys.*, **57**, 316–375, <https://doi.org/10.1029/2019RG000644>.
- Zhao, B., and A. Fedorov, 2020: The seesaw response of the intertropical and South Pacific convergence zones to hemispherically asymmetric thermal forcing. *Climate Dyn.*, **54**, 1639–1653, <https://doi.org/10.1007/s00382-019-05076-6>.
- Zhou, T., and Coauthors, 2016: GMMIP (v1.0) contribution to CMIP6: Global Monsoons Model Inter-Comparison Project. *Geosci. Model Dev.*, **9**, 3589–3604, <https://doi.org/10.5194/gmd-9-3589-2016>.