

Underestimated changes of the satellite epoch Amundsen Sea Low associated with unrealistic interdecadal Pacific-Atlantic variability in CMIP6 models*

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Received Apr. 1, 2025; accepted in principle Aug. 11, 2025 accepted for publication Nov. 10, 2025

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Abstract The Amundsen Sea Low (ASL) is a connection between the tropical variabilities and climate changes in the Antarctic. The combination of the negative trend of the Interdecadal Pacific Oscillation (IPO) and the positive trend of the Atlantic Multidecadal Oscillation (AMO) results in the strengthening of the ASL as well as the dipole Sea Ice Concentration (SIC) trend of the Ross Sea (RS) and Amundsen and Bellingshausen Sea (ABS) since the satellite era. In this study, we demonstrate that models in the Coupled Model Intercomparison Project phase 6 (CMIP6) largely underestimate this congruent ASL trend that is related to the IPO and AMO. The unrealistic relationship between the IPO and AMO among coupled models, which potentially cancels out their effects on the ASL each other, is one potential factor for the underestimated ASL variability. Another factor is the large inconsistent AMO-related teleconnection patterns among models. Further analysis is carried out to explore the origin of the large intermodel spread, and the mean SST biases over the tropical Atlantic, tropical Pacific and southeast Pacific are found to be the dominant sources for the underestimated ASL change. These results emphasize the collaborative effect of the IPO and AMO on the Southern Ocean region. Thus, reducing related mean state SST bias may lead to improved coupled simulations of tropical variabilities as well as the climate of the Antarctic.

Keyword: Amundsen Sea Low (ASL); model evaluation/performance; Coupled Model Intercomparison Project Phase 6 (CMIP6); interdecadal variability

1 INTRODUCTION

Since the 1970s, the Antarctic has experienced substantial and complex climate changes. Antarctic sea ice generally expanded during recent decades (Chung et al., 2022), which contrasts with the rapidly declining trend of Arctic sea ice (Parkinson, 2019). For the Antarctic continent, an asymmetric change is observed, in which West Antarctica displayed a warming trend, whereas East Antarctica experienced slight cooling, and this dipole-like trend subsequently reversed from the beginning of the 21st century (Nicolas and Bromwich, 2014; Xin et al., 2023).

Many studies have consensus on the crucial role of the Amundsen Sea Low (ASL) in causing recent

climate changes in the Antarctic (Li et al., 2014; Hobbs et al., 2016; Raphael et al., 2019). Since 1979, the ASL has deepened by at least 1.4 hPa (Turner et al., 2013). This trend causes northward wind anomalies in the Ross Sea and southward wind anomalies in the Amundsen Sea and the Bellingshausen Sea, leading to regional sea ice expansion and retreatment, respectively (Turner et al., 2013). This explains the change in Antarctic sea ice over recent decades (Turner et al., 2016; Raphael et al., 2019; Li et al., 2021). For the factors

* Supported by the National Key Research and Development Program of China (Nos. 2023YFF0805100, 2018YFA0605704) and the National Natural Science Foundation of China (Nos. 42230405, 42475026)

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contributing to the deepening trend of the ASL, in addition to the external forcing (e.g., anthropogenically forced positive trend in the SAM; Thompson and Solomon, 2002), the internal climate variability is also important, especially for the tropical interdecadal climate variability such as the Interdecadal Pacific Oscillation (IPO; Kosaka and Xie, 2013; Meehl et al., 2016b) and Atlantic Multidecadal Oscillation (AMO; Knight et al., 2005). The current negative trend of the IPO (Meehl et al., 2016a) and positive trend of the AMO (Li et al., 2014) from 1979–2014 imposed a joint intensification of the ASL (Li et al., 2021). In these processes, tropical anomalies are transmitted to high latitudes through Rossby waves (Li et al., 2014; Meehl et al., 2016a), generating anomalous circulation to modify the regional climate. Moreover, it is also important to highlight the interaction between the Pacific Ocean and Atlantic Ocean. For the recent decades, studies attributed the intensified cross-equatorial winds (Hu and Fedorov, 2018) as well as the strengthening of the Pacific trade winds (McGregor et al., 2014) to the Atlantic warming, which is responsible for modulating the mean state of the Pacific or the decadal variability. Meehl et al. (2021) further unveiled the alternately forcing relationship between the tropical Pacific Ocean and the Atlantic Ocean through the Walker circulation and along with the midlatitude teleconnection at the decadal timescale. Although still being debated, these theoretical evidences implicate that the superimposition of the effect of the IPO and AMO is not a coincidence.

Due to the sparse observational data, the latest studies focused on short periods of climate change in the Antarctic (Wang et al., 2019; Eayrs et al., 2021). These studies also raised the question whether the recent changes are solely random incidents or are parts of a long-term trend (Hobbs et al., 2016). This uncertainty may highlight the importance of simulated data that have much longer time spans. However, the state-of-art coupled general circulation models (CGCMs) fail to reproduce realistic trends in the extent of Antarctic sea ice (Zhang et al., 2021). Moreover, by carrying out nudging experiments, studies revealed that wind bias in atmosphere models is the principal factor that led to underrepresentation of the Antarctic sea ice expansion trend from 1979 to 2014 (Blanchard-Wrigglesworth et al., 2021; Zhang et al., 2021). It can be inferred that there may be biases in these models when simulating the ASL, which is in charge of regulating local circulation in the Antarctic.

Given that the decadal variability of the ASL can be affected by both the IPO and the AMO, there is another reason to doubt the reliability of CGCMs in simulating the ASL: the absence or underestimation of processes dominated by the Atlantic Ocean. With the growing consensus on the vital role of the Atlantic Ocean in tropical and remote climate systems (Li and Xie, 2014), numerous studies have reported that one of the widespread problems among most models is the underestimated climate effects of the Atlantic Ocean (McGregor et al., 2018), especially the ability to affect the Pacific Ocean. For example, Kajtar et al. (2018) emphasized the significant role of the mean state SST in the tropical Atlantic and related SST anomalies in reproducing realistic Pacific trade winds in the Coupled Model Intercomparison Project Phase 5 (CMIP5) models. This related deficiency was further proven to exist in CMIP6 (Deng et al., 2024). The study revealed that coupled models produce a positive correlation between the tropical Pacific decadal variability (TPDV) and the tropical Atlantic variability (TAMV) when TAMV leads, which is opposite to the negative correlation from observational data or idealized pacemaker experiments (Meehl et al., 2021). Deng et al. (2024) emphasized that these biases should be attributed to unrealistic background SSTs in the tropical Atlantic, which subdue local convections and therefore decrease remote responses (i.e., the potential effect of cooling the tropical Pacific region by intensifying the local trade wind). In addition, it should be noted that this deficiency prevails only among coupled models, as the AMIP results agree with those in observations (Kajtar et al., 2018), again suggesting that the SST biases of the tropical Atlantic (both in mean states and anomalies) should be the original problem. Besides, Li et al. (2020) demonstrated that the ability of the tropical Atlantic affecting the tropical Pacific among coupled models can be further dampened due to warm mean SST biases in the southeast Pacific. However, in terms of the simulation ability of numerical models, extratropical climate effects that originate from the Atlantic have not been deeply discussed. Owing to the lack of studies in these aspects, the capability of the up-to-date climate models (CMIP6) in simulating ASL that is congruent with the IPO and AMO changes and whether the mean state SST biases contribute to the coupled models' performance are examined in this study. Our analysis reveals that coupled models appear to underestimate the ASL variability that is

congruent with the IPO and AMO. Furthermore, the unrealistic Pacific-Atlantic relationship and the intermodel spread of the AMO-related teleconnection patterns are the potential factors, which are likely the intermediate results of the underrepresentation of the mean state SST bias in the tropical Atlantic, tropical Pacific and southeast Pacific among coupled models.

The rest of this paper is structured as follows. The data and methods used in this study are introduced in Section 2. The evaluation of coupled models in reproducing the IPO-AMO relationship and its effect on the ASL trends is shown in Section 3. A summary with discussion is presented in Section 4.

2 DATA AND METHOD

2.1 Observational and model dataset

For the reanalyzed monthly sea surface temperature (SST), we use multiple datasets, including NOAA's Extended Reconstructed Sea Surface Temperature version 5, ERSSTv5 (Huang et al., 2017), Hadley Center Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al., 2003) and European Center for Medium-Range Weather Forecasts twentieth century Reanalysis (ERA-20C; Poli et al., 2016). The indices of ASL and the regressions of surface level pressure (SLP) anomalies are calculated based on NOAA's Extended Reconstructed Surface Pressure (ERSLP; Smith and Reynolds, 2004), Hadley Center's surface level pressure dataset (HadSLP2; Allan and Ansell, 2006), and ERA-20C.

The satellite-observed sea ice data used in this study is produced by National Snow and Ice Data Center (NSIDC). Based on the bootstrap sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 4 (NSIDC-0079v4; Comiso, 2023), the sea ice concentration (SIC) trend from 1983–2009 in the Antarctic are computed. Details

for the abovementioned datasets can be found in Table 1.

In terms of the model evaluation, we use model output data from historical experiments of 26 members of the CMIP6. Only the first ensemble (identified by the label r1i1p1f1 that specifies Realization index, Initialization index, Physics index, and Forcing index) of each model member was used (Table 2). Additionally, all datasets were interpolated into $2.5^{\circ} \times 2.5^{\circ}$ grids.

2.2 Method

First, we obtain anomalous signals by removing the monthly climatology. To obtain the decadal signals, we apply the 11-year moving average to all the time series except the SIC data. We conduct only 37-month moving average to the SIC data due to limited time length.

2.2.1 Isolating the internal climate variability

In this study, we considered the IPO and AMO as internal climate variabilities (Knight et al., 2005; Kosaka and Xie, 2013; Meehl et al., 2016b). Yet, the contribution of recent warming signals of the SSTs are not neglectable, especially for the AMO (Ting et al., 2009; Wu et al., 2011; Zanchettin et al., 2014). Moreover, the forcing of aerosols is revealed to exist in both Pacific and the North Atlantic basin in the recent study (Qin et al., 2020). Thus, it is necessary to isolate the internal climate variability from external forcing signals (i.e., greenhouse warming and aerosol forcing). Here, assuming that the total variability is linearly summed by internal climate variability and external forcing, we first estimated the response to external forcing in the models by calculating the multi-model mean (MMM) for all the historical runs (Knight, 2009; Wang and Zheng, 2023). Next, time series of climate variables were regressed onto the MMM to estimate the external

Table 1 Summarized information of observed/reanalyzed data

Dataset	Variable	Spatial resolution	Period of analysis	Reference
ERSSTv5	SST	$2^{\circ} \times 2^{\circ}$	1870–2014	Huang et al., 2017
HadISST	SST	$1^{\circ} \times 1^{\circ}$	1870–2014	Rayner et al., 2003
ERA-20C	SST, SLP	$1^{\circ} \times 1^{\circ}$	1910–2010	Poli et al., 2016
ERSLP	SLP	$2^{\circ} \times 2^{\circ}$	1870–1997	Smith and Reynolds, 2004
HadSLP2	SLP	$5^{\circ} \times 5^{\circ}$	1870–2012	Allan and Ansell, 2006
ERA5	Ua, Va	$1^{\circ} \times 1^{\circ}$	1940–2014	Hersbach et al., 2020
NSIDC-0079v4	SIC	25 km $\times$ 25 km	1979–2014	Comiso, 2023

Table 2 Summarized information of 26 CMIP6 models with historical simulations applied to this study

Model number	Model name	Country
M1	ACCESS-CM2	Australia
M2	ACCESS-ESM1-5	Australia
M3	BCC-CSM2-MR	China
M4	CESM2-FV2	USA
M5	CESM2-WACCM	USA
M6	E3SM-1-1	USA
M7	EC-Earth3-Veg	European countries
M8	FGOALS-f3-L	China
M9	FGOALS-g3	China
M10	GFDL-CM4	USA
M11	GFDL-ESM4	USA
M12	GISS-E2-1-G-CC	USA
M13	GISS-E2-1-G	USA
M14	GISS-E2-1-H	USA
M15	HadGEM3-GC31-MM	UK
M16	IPSL-CM6A-LR	France
M17	KACE-1-0-G	Republic of Korea
M18	MCM-UA-1-0	USA
M19	MIROC-ES2L	Japan
M20	MIROC6	Japan
M21	MPI-ESM-1-2-HAM	German
M22	MPI-ESM1-2-LR	German
M23	MRI-ESM2-0	Japan
M24	NorCPM1	Norway
M25	NorESM2-LM	Norway
M26	SAM0-UNICON	Republic of Korea

forcing component of every grid in each model, and these components are then removed.

2.2.2 Calculating the congruent trend

A simple multivariable linear regression is applied to calculate the SLP variability that is congruent with the IPO and AMO, as in Chung et al. (2022). In this approximation, the variability of any other variables y related to the IPO/AMO is assumed as:

$$y = a \times \text{Index}_{\text{IPO}} + b \times \text{Index}_{\text{AMO}} + \text{nonlinear} + \text{const.} \quad (1)$$

In this approximation, a and b denote the regression coefficients. The residual includes nonlinear interaction term and the constant term, representing the baseline value of y . Note that the filtered indices

are used here to produce decadal results. In that case, for a given trend of the IPO and AMO, the corresponding trend of y (Trend_y) can be represented in the equation below:

$$\text{Trend}_y = \text{Trend}_{\text{IPO}} \times a + \text{Trend}_{\text{AMO}} \times b. \quad (2)$$

2.3 Definition of indices of the IPO, AMO, and ASL

According to previous studies, indices of the large-scale climate variability can be obtained by averaging the SST anomalies of specific regions. The tripole index is commonly used to represent the decadal variability of the Pacific Ocean (Henley et al., 2015; Chung et al., 2022), which is defined as SST anomalies averaged in the tropical Pacific region (10°S – 10°N , 170°E – 90°W) subtracted by the mean average of the SST anomalies over the northwest Pacific (25°N – 45°N , 140°E – 145°W) and the southwest Pacific (50°S – 15°S , 150°E – 160°W).

For the AMO, time series were simply obtained from the mean SST anomalies for the North Atlantic region (0° – 60°N , 80°W – 15°E (Enfield et al., 2001)). For the time series of the IPO and AMO, an 11-year moving average is calculated.

We used the ASL SLP index calculated by averaging the mean SLP over the ASL domain (60°S – 75°S , 170°E – 70°W) (Hosking et al., 2013).

According to Li et al. (2021), the decadal variability of the ASL is associated with IPO and AMO related teleconnection for all seasons except austral summer (DJF). Thus, when calculating the IPO/AMO-related linear coefficients a and b (Section 2.2) (Eq.1), we shall average the monthly values of ASL from March to November to obtain the yearly ASL indices to better illustrate this relationship.

2.4 Rossby wave source and TN wave flux

The Rossby wave source (RWS) and TN wave flux (Takaya and Nakamura, 2001) are further calculated to analyze the physical process behind the intermodel inconsistency of teleconnection patterns.

As a common diagnostic method for the Rossby wave-related process, the RWS describes the nature of Rossby waves, which is the result of nonzero absolute vorticity and the divergent flow (Li et al., 2015) and can be given by the equation below:

$$\text{RWS} = -\nabla \cdot \zeta \mathbf{v}_\chi = -\zeta' \nabla \cdot \bar{\mathbf{v}}_\chi - \bar{\zeta} \nabla \cdot \mathbf{v}'_\chi - \mathbf{v}'_\chi \cdot \nabla \bar{\zeta} - \bar{\mathbf{v}}_\chi \cdot \nabla \zeta', \quad (3)$$

where the ζ is the absolute vorticity, and the v_x represents the divergent components of the horizontal wind.

On the basis of the physical features in this study, the TN wave flux is computed to diagnose the propagation of Rossby waves, which is more applicable to large-amplitude Rossby waves and those propagating through the subtropical jet than to the Plumb and local E-P wave fluxes (Shi et al., 2017). The TN wave flux can be given by:

$$W = \frac{1}{2|\bar{U}|} \left(\bar{u}(\psi_x'^2 - \psi'\psi_{xx}') + \bar{v}(\psi_x'\psi_y' - \psi'\psi_{xy}'^2) \right), \quad (4)$$

where $\bar{U} = (\bar{u}, \bar{v})$ represents the mean state wind velocity and ψ' stands for the streamfunction anomalies derived from the geopotential height data based on the quasigeostrophic approximation. Note that the regressed components are used as perturbation terms in this study.

3 RESULT

3.1 Trend in observations

First, we reproduce the time series of the IPO and AMO from 1920–2009 and the trend of the congruent ASL and the sea ice changes from 1983–2009 (Fig.1). For the aspect of the IPO and AMO, we calculate the indices based on ERSSTv5, HadISST and ERA-20C as it is shown in Fig.1a, with the solid line denoting the mean value of the

three datasets. The figure shows that these results basically agree with each other, suggesting that these reanalysis data are reliable for our study. Except that the AMO based on ERSSTv5 partially detaches from the other two series during 1947–1950. This inconsistency may be attributed to the decreased sampling size due to the WWII (Zhao et al., 2022). In this study, because this data flaw imposes minor effect on our final result, ERSSTv5 is used for the following analyses.

Apart from the effect of the ozone depletion (England et al., 2016), the deepening of the ASL is also a result of the superimposed teleconnection of the IPO and AMO. Since the middle of the 1970s, the AMO transformed its phase from negative to positive (Fig.1a). In addition, the IPO tended to shift toward a negative phase in the 1980s. According to Li et al. (2021), during the period of 1983–2009, the trends of the IPO and AMO were opposite (also shown in Fig.1a, pink shading). Consequently, there should be a considerable deepening trend in the ASL (Fig.1b & c). For the sea ice change during this period, a dipole-like trend can be observed in Fig.1c, where increasing SICs are found in the Ross Sea, and a decreasing trend is found in the Amundsen and Bellingshausen seas. Consistent with previous studies (Turner et al., 2016; Wang et al., 2023), the dipole-like trend of sea ice is the result of the deepening of the ASL, which can be explained by the congruent sea ice flow promoted by the ASL-induced anomalous circulation. Specifically, for the

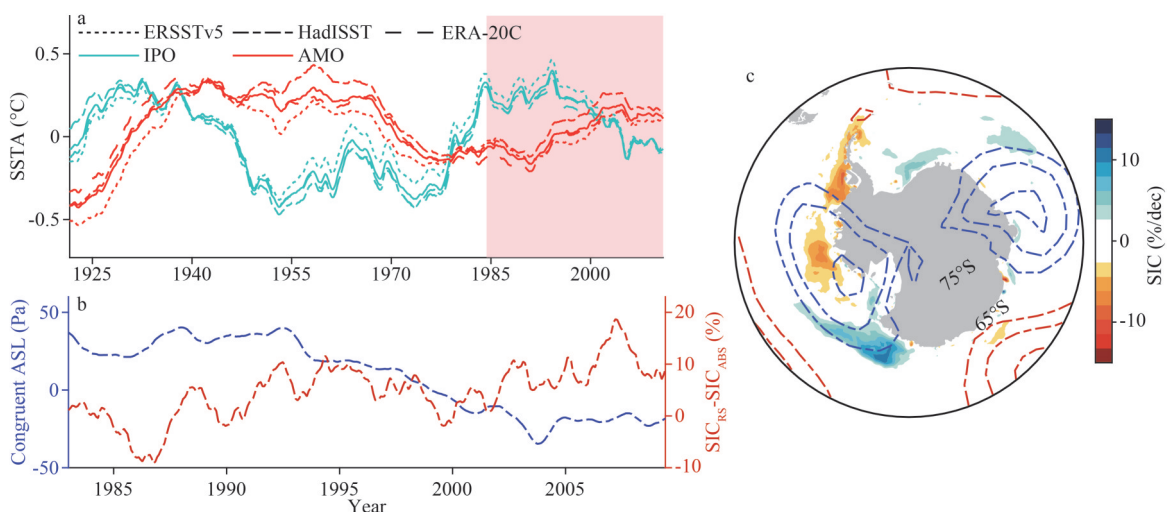


Fig.1 Time series of the IPO and AMO in observational data (a); time series of congruent ASL and the SIC dipole of the Ross Sea and the Amundsen and Bellingshausen seas from 1983–2009 (b); the SLP (contour, unit: Pa/dec, interval: 10 Pa/dec) and SIC (shading, unit: %/dec) trend from 1983–2009 (c)

The pink shading in (a) highlights the period of 1979–2014. The red and dark blue dotted lines in (b & c) denote the positive and negative SLP trends, respectively.

western branch of the circulation, an offshore (northward) sea ice flow can be generated, favoring the expansion of sea ice and vice versa for the eastern branch. This dipole-like trend is demonstrated in Fig.1b, and the indices is defined as the contrast between the mean SIC anomalies in the Ross Sea (75°S–60°S, 160°E–170°W) and the mean SIC anomalies in the Amundsen Sea and Bellingshausen Sea (75°S–60°S, 170°W–55°W).

3.2 Model performance in simulating IPO- and AMO-related ASL trends

Next, we evaluate the extent to which the model can reproduce the reliable ASL trend. For each model, the linear coefficients a and b are computed based on yearly ASL indices and IPO/AMO time series. The congruent ASL trend is linearly summed up by the IPO-related component and the AMO-related component (see the regression method described in Eq.1, as introduced in Section 2.2). Thus, all possible linear trends of annual-mean SLP associated with the IPO and AMO for any consecutive 27-year period during 1870–2014 are calculated (Fig.2). The possible trends are calculated by separating the common period of the model and reanalysis dataset (HadISST/HadSLP2, 1870–2014) into consecutive running 27-year windows (for instance, 1900–1926, 1901–1927, 1902–1928, and so on) and thus we can obtain the range of ASL congruent trends for each model as well as the reanalysis dataset. The congruent ASL trend from 1983–2009 based on HadISST/HadSLP2 is highlighted as a black tick line in Fig.2. Apparently, 2/3 of the models fail to capture the observed negative trend from 1983–2009. There are seven models able to reproduce the observed trend (GISS-E2-1-G, E3SM-1-1, FGOALS-f3-L, ACCESS-CM2, MPI-ESM-1-2-HAM, GISS-E2-1-G-CC, and KACE-1-0-G), but three of them only cover the observed trend at their 90%–100% percentile interval, which is not significant. The other coupled models tend to largely underestimate the observed range of the IPO/AMO congruent ASL trend.

With the implications of the case introduced in Section 3.1, the ASL trend congruent with the IPO and AMO is composed of four possible combined trends of the IPO and AMO. The procedure to obtain this result is the same as that for Fig.2, except that samples are categorized into 4 assemblies (IPO+AMO+, IPO-AMO+, IPO-AMO-, and IPO+AMO-) and are then composited. It is suggested that significant ASL trends are usually related to

opposite trends of the IPO and AMO since the response of the ASL of the two variabilities has different signs (Fig.3). The composited results are based on HadISST and HadSLP2 because their time spans are similar to those of the coupled models. Because of the negative IPO-AMO relationship (Fig.3i), the probability of robust congruent ASL trends is amplified. Also, the negative relationship is consistent among the reanalysis datasets used in this study (HadISST, ERSSTv5, and ERA-20C). The negative relationship is determined by the intrinsic connection of the tropical sectors of two basins. According to Meehl et al. (2021), the SST in the tropical Pacific (TP) and North tropical Atlantic (NTA) interact with each other at the decadal timescale. Specifically, the NTA tends to be warmed by the TP when the TPDV leads, and the TP tends to be cooled by the NTA when the TAMV leads (Deng et al., 2024). However, this lead-lag relationship is largely underestimated in coupled models. In the present study, although the definitions of the two variabilities in the two basins are different, we also show a similar underestimation of the relationship between the IPO and AMO in the CMIP6 models (Fig.3i), which may cause a decreased probability for the scenarios with strong ASL trends (i.e., IPO-AMO+ in the Fig.3b & f; IPO+AMO- in Fig.3d & h) and therefore underestimate the possible congruent ASL range. These results suggest that the coupled models potentially underestimate the

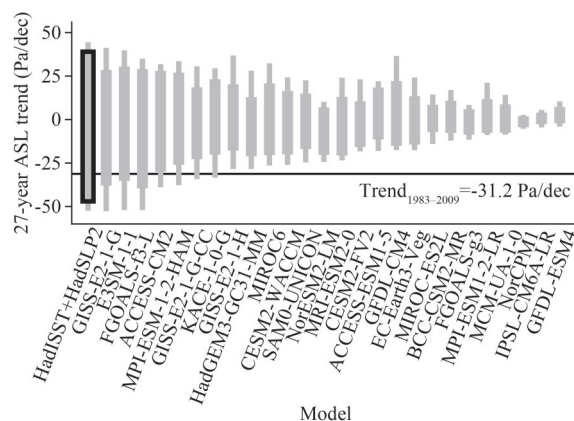


Fig.2 Ranges in the 27-year-trend of the IPO/AMO congruent ASL in CMIP6 and observational data

The observed range based on the HadISST and HadSLP2 is shown at the most left bar which is highlighted by the black edging. The rest of bars represent the performance of 26 CMIP6 model members. The widths of the bars denote the 10%–90% intervals and the whiskers denote the full range. The black line indicates the observed trend during 1983–2009.

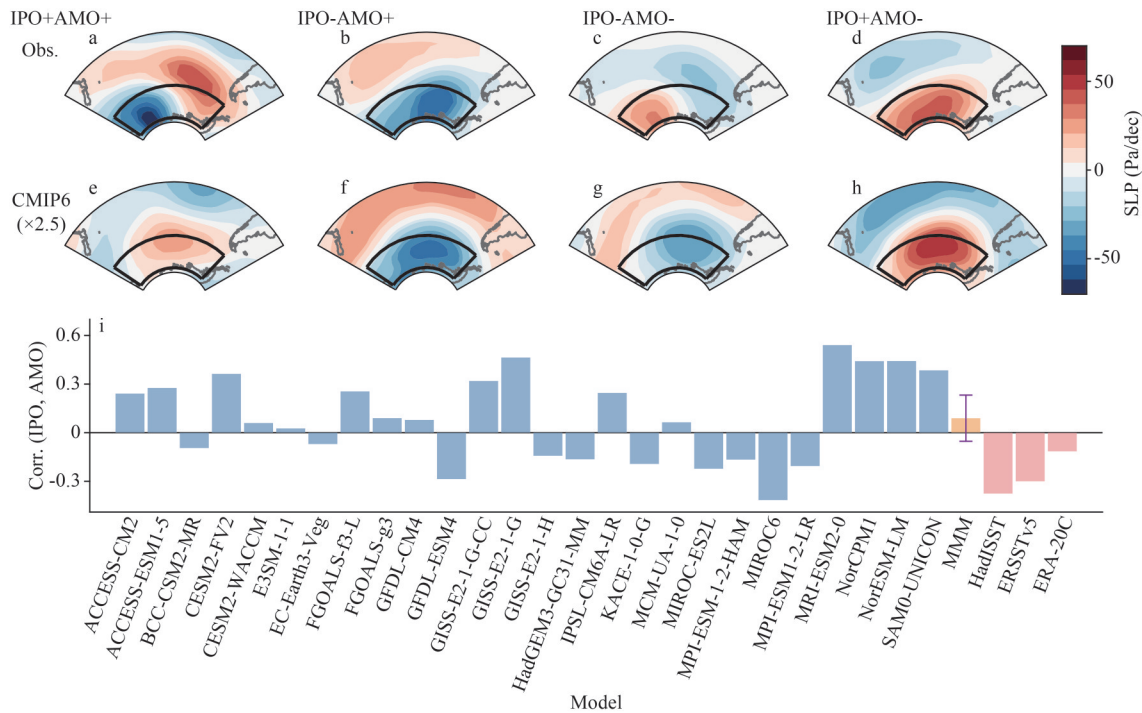


Fig.3 Composite congruent 27-year trends under 4 possible combinations of IPO/AMO trends and the correlation between the IPO and AMO in the observational data (HadISST/HadSLP2) and the CMIP6 multimodel ensemble

a. the composite of 27-year trend that is congruent with the positive IPO trend and positive AMO trend in observations; b-d. other three situations of the composite in observations. The sign of the IPO/AMO is determined by the linear trend of IPO/AMO in a certain 27-year events; e-h. similar to (a-d) but for the MMM result of CMIP6 models; i. the correlation between the IPO and AMO.

decadal variability that is related to the tropical teleconnection.

3.3 Evaluation of the teleconnection process

We also evaluated the extent to which the coupled model members can reproduce the

teleconnection of the IPO and AMO, since the inconsistency may also dampen the multi-model mean and therefore underscore the model performance. Therefore, SLP anomalies as a binary function were regressed on the IPO and AMO time series (see Eq.1 in Section 2.2 (Fig.4)). For the

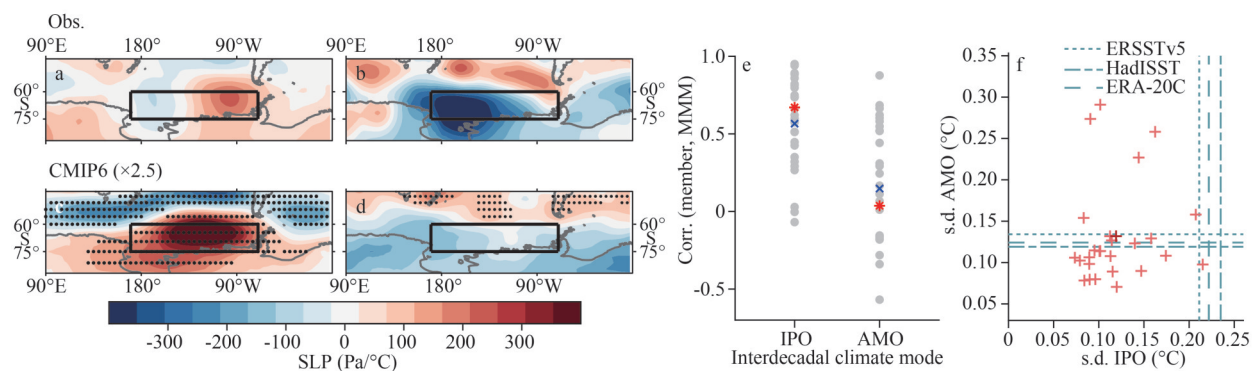


Fig.4 The SLPA regressed on the IPO and AMO in CMIP6 and observational data and the intermodel spread in CMIP6

a-b. the results produced with the observed data, where (a) refers to the component that is related to the IPO and (b) refers to the component related to the AMO; c-d. the same as (a-b) except that the data source is the multimodel mean (MMM) of CMIP6. The dots represent the averaged value are significant at the 90% confidence level based on Student's *t*-test. The observed results are based on the mean values of HadISST/HadSLP2 and ERSSTv5/ERSLP; e. the intermodel spread in the regression of CMIP6, where grey dots in the left column denote the spatial correlation between the IPO-related teleconnection pattern of individual model member and the pattern of the observed result, and dots in the right column are the case of AMO. The blue crosses denote the median values and the red stars denote the correlation in the MMM and observed results; f. the standard deviation of the IPO and AMO in observed data and CMIP6 members, where the red cross denotes the results of individual model member and the MMM are highlighted with the dark red cross. Blue lines represent the observed values based on ERSSTv5, HadISST, and ERA-20C.

observations, a pattern like Pacific-South-America (PSA) (Mo and Higgins, 1998) is clearly produced during the positive phase of the IPO, resulting in positive pressure anomalies over the regions of the Bellingshausen and Amundsen Seas (Fig.4a). Correspondingly, a wavenumber 3-like pattern associated with the AMO results in a negative anomaly center in the ASL domain (Fig.4b), consistent with Li et al. (2015).

Apart from the underestimated magnitude of regression which probably because the underrepresented amplitudes of both the IPO and AMO (Fig.4f), for the simulated responses of the IPO, the MMM results of CMIP6 (Fig.4c–d) show patterns that are basically consistent with the observed results (Fig.4a–b), with a spatial correlation of 0.67 between the observed pattern and the MMM (red stars in Fig.4e, left column), and strong intermodel agreement (blue cross in Fig.4e, left column). However, the MMM of the AMO-related pattern failed to capture the negative anomaly located in the ASL region (the spatial correlation between the observed pattern and the MMM for the IPO is 0.01, red stars in Fig.4e, right column), with only less significant negative signals scattering along the Southern Ocean. This is attributed to the large intermodel spread of the AMO-related patterns (blue cross in Fig.4e, right column). This nonequivalent strength of the remote signal of the IPO and AMO can be regarded as a manifestation of the model deficiency in reproducing the Atlantic Ocean related-process, which is also reported in previous studies. For example, in coupled models, the tropical Pacific can influence the tropical Atlantic, yet the influence of the tropical Atlantic is quite limited (Deng et al., 2024). Our results suggest that it is also underestimated for the extratropical climate effects that originated from the North and tropical Atlantic.

According to previous studies, the marginal role of the tropical Atlantic Ocean in the TP-NTA interaction in coupled models is largely attributed to unreliable background tropical Atlantic SSTs (Kajtar et al., 2018; McGregor et al., 2018), which is a common bias in coupled models (Richter and Xie, 2008). Further study revealed that the warm background SST biases in the southeast Pacific (also known as the double ITCZ bias; Li et al., 2020) may also dampen the relationship between the tropical sectors of the two basins. Given these close ties between the tropical Atlantic and the tropical Pacific Ocean, we further investigate whether the large

spread of the teleconnection of the AMO is related to the mean SST bias in the tropical Atlantic or Pacific among the coupled models.

We regress the intermodel mean SST onto the AMO-ASL relation (Fig.5), and define the indices of region that is likely to impose effect on the simulated AMO-ASL relationship. Previous studies reported that the CMIP5 models simulate relatively warmer mean SSTs in the southeastern Pacific (Li et al., 2021). Thus, we define the indices of the southeastern Pacific (150°W – 70°W , 25°S – 10°S , referred to as the SP indices hereafter) and examine the intermodel correlation between the AMO-ASL relationship and the SP indices. For the CMIP6 models, it is apparent that most members still have a warm bias in the southeastern tropical Pacific SST compared with the observations (Fig.6). There is a positive intermodel correlation between SP indices and the corresponding AMO-ASL relationship (Fig.6), suggesting that smaller (i.e., realistic) SP indices mean more negative AMO-ASL relationships. In addition, there is also a significantly positive intermodel correlation between the tropical Pacific (180° – 120°W , 10°S – 10°N , referred as the TP indices hereafter) and the Tropical Atlantic (50°W – 0° , 10°S – 10°N , referred as the TA indices hereafter) SSTs and the AMO-ASL relationship, indicating that a more negative AMO-ASL relationship is related to a less warm mean SST in the these two regions.

To better understand the intermodel connection between these variables, we first consider the teleconnection process induced by the warming of the tropical Atlantic. When the AMO is in the positive phase, deep convection is generated over the tropical Atlantic region (Li et al., 2015; Ren et al., 2022), intensifying the local Hadley Cell, and a convergence is successively formed in the subtropical south Atlantic (Simpkins et al., 2016; Fig.7, solid contours), thereby exciting the negative RWS (Fig.7, scattered green shadings in the

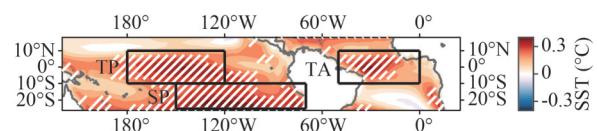


Fig.5 The intermodel regression of the mean SST onto the AMO-ASL correlation

The boxes highlight the definitions of the indices of the tropical Pacific (TP), the tropical Atlantic (TA), and the southeast Pacific (SP). The white slashes indicate that the regressions are significant at the 90% confidence level, based on the Student's *t*-test.

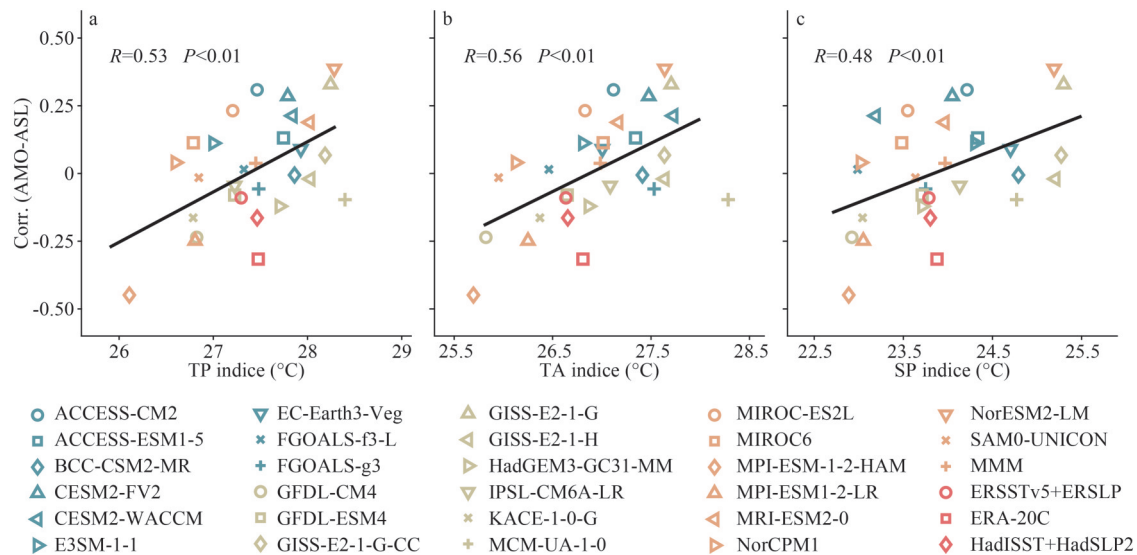


Fig.6 The intermodel correlation between the indices of the tropical Pacific (TP) (a), the tropical Atlantic (TA) (b), and the southeast Pacific (SP) (c) mean SST and the AMO-ASL relationship

subtropical Atlantic) and Rossby wave train to propagate poleward. Thus, we further diagnose the AMO-related Rossby wave activity source (RWS) and the TN wave flux (Eqs.3–4 in Section 2.4). According to the AMO-ASL correlation coefficient, the models are divided into two groups: one group contains five models with the most negative AMO-ASL relationships and the other group contains five models with the most positive AMO-ASL relationships.

For the negative AMO-ASL relationship group, there is a negative RWS at $\sim 35^\circ\text{S}$ over the south America (Fig.8a), referring to the convergent anomalies resulted from the intensified local Hadley Cell (Simpkins et al., 2016). In addition, this Rossby wave train tends to be reflected when encountering the East Antarctic continent and Australia (vectors in Fig.8a). This is consistent with the Rossby wave trajectory induced by the tropical Atlantic perturbation described in Li et al. (2015). Eventually, the

wave train resulted in negative geopotential height anomalies in the ASL domain. Despite the relatively weak magnitude, this branch of the Rossby wave train is considered to play a major role in transmitting negative anomalies to the ASL region, as the Rossby wave train is strengthened along the

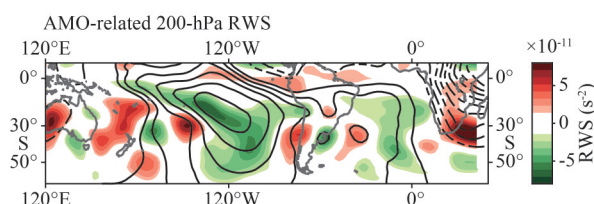


Fig.7 AMO-related 200-hPa Rossby wave source (RWS, shadings, s^2) and velocity potentials (contours, unit: m^2/s) based on ERA5 and HadISST

The solid and dash lines denote the positive and negative velocity potentials respectively. The intervals are $0.5 \times 10^6 \text{ m}^2/\text{s}$.

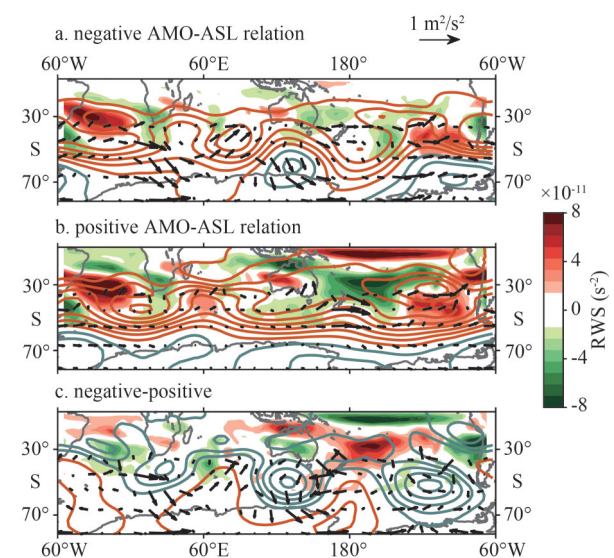


Fig.8 AMO-related 200-hPa Rossby wave source (RWS, shadings, s^2), the corresponding geopotential height anomalies (contours, m) and the TN wave fluxes (vectors, m^2/s) in the negative AMO-ASL relation group (a) and the positive AMO-ASL group (b) and (c) their differences (a-b)

The interval of the contour is 5 m. Red and green solid contours denote positive and negative geopotential height anomalies, respectively.

subtropical jet (Li et al., 2015; Simpkins et al., 2016). For the positive AMO-ASL relation group, there is also a negative RWS at the tip of the South America, but the composite shows a less significant circumpolar Rossby wave train (vectors in Fig.8b). Noticeably, the positive RWS at the south subtropical Atlantic is stronger than those in the negative group (Fig.8c), which seemingly hampers the propagation of the negative RWS.

Apart from the Rossby wave component induced by the intensified local Hadley cell over the subtropical Atlantic, another RWS contrast between the two groups is shown in Fig.8c, which corresponds to the RWS in the eastern-central subtropical Pacific (Fig.7, green shadings at the subtropical eastern-central Pacific). The negative RWS shifts westward in the both two model groups, locating at the central Pacific, which likely diminishes the teleconnection signal as the Rossby wave train tends to be trapped in the subtropical jet instead of propagating through the exit. Additionally, for the positive AMO-ASL relation group, the positive RWS seemingly dominates in the east sector of the subtropical Pacific and further suppresses the negative RWS as well as the negative geopotential signals.

By decomposing RWSs into vortex stretching (R_v) and divergent advection (R_d) terms (Fig.8d), the specific processes related to the generation of the RWSs are analyzed. The decomposition suggests that the RWSs in both groups are mainly contributed by the vortex stretching term, which is the result of vertical atmospheric circulation anomalies (Simpkins et al., 2016; Ren et al., 2022). As it is concluded in the previous line, for the positive group, the

anomalously robust positive RWS situating at the southeast subtropical Pacific and south subtropical Atlantic (highlighted with the black boxes in Fig.9c) presumptively leads to the relatively positive AMO-ASL relationship. To further examine the intermodel causality, we define indices of these two RWSs and analyze the intermodel relationship between the SST indices and the two RWSs. The result shows that all the SST indices are significantly correlated with the RWS in the southern subtropical Pacific (Fig.10a–c), especially for the TP and SP indices (Fig.10a–b). This correlation suggests that warmer tropical and southeast Pacific SSTs likely lead to more robust ascending motion among the east tropical Pacific, which potentially lowers the convection thresholds (Fig.9i) and promotes the generation of positive RWSs by the effect of vortex stretching (Fig.9c). And that results in a severely restrained AMO-related descending motion as well as the generation of negative RWS. The mean state SSTs in the tropical Atlantic Ocean are also important in promoting the generation of the RWS in the southern subtropical Pacific due to the adjacent location, but only in a secondary role (Fig.10c). However, the correlation between the RWS in the southern subtropical Atlantic Ocean and the SST indices are less significant (Fig.10d–f), which means that RWSs in the subtropical Pacific Ocean related to the background SSTs in the key regions are more likely to be the source of the intermodel spread of AMO-ASL relationship. It should be noted that for all the selected models, the descending motion induced by the AMO is quite weak in the subtropical Atlantic (Fig.9g–h, grey shadings) and the patterns of velocity potentials are completely

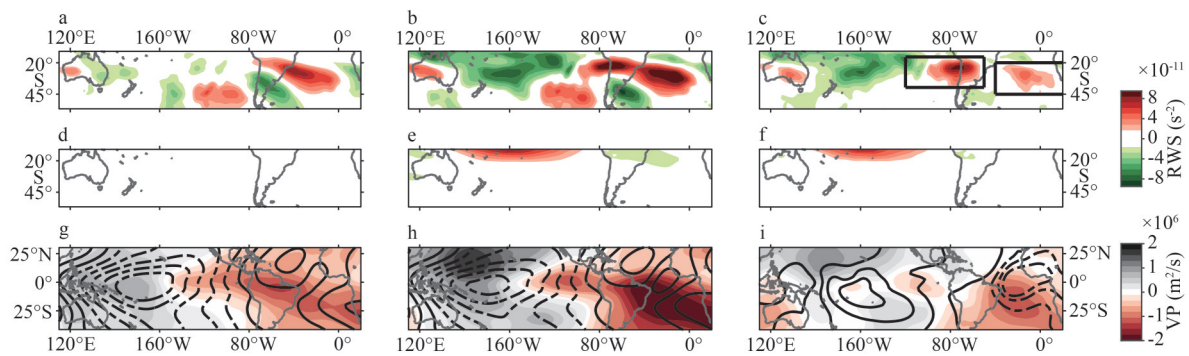


Fig.9 The vortex stretching term ($-\zeta' \nabla \cdot \bar{\mathbf{v}}_{\chi} - \bar{\zeta} \nabla \cdot \mathbf{v}'_{\chi}$, referred as R_v , unit: s^{-2}) of AMO-related RWSs

a–c. the composites of the negative AMO-ASL relation group, the positive AMO-ASL relation group and the contrast (b minus a); d–f. similar to (a–c), but for the divergent advection term ($-\mathbf{v}'_{\chi} \cdot \nabla \bar{\zeta} - \bar{\mathbf{v}}_{\chi} \cdot \nabla \zeta'$ referred as R_d , unit: s^{-2}) of AMO-related RWSs; g–i. similar to (a–c), but for the AMO-related 200-hPa velocity potentials (shadings, unit: m^2/s) and the mean state velocity potentials (contours, unit: m^2/s). The solid and dash lines denote the positive and negative velocity potentials, respectively. The intervals is $2 \times 10^6 m^2/s$ in (g) and (h) and $0.5 \times 10^6 m^2/s$ in (i).

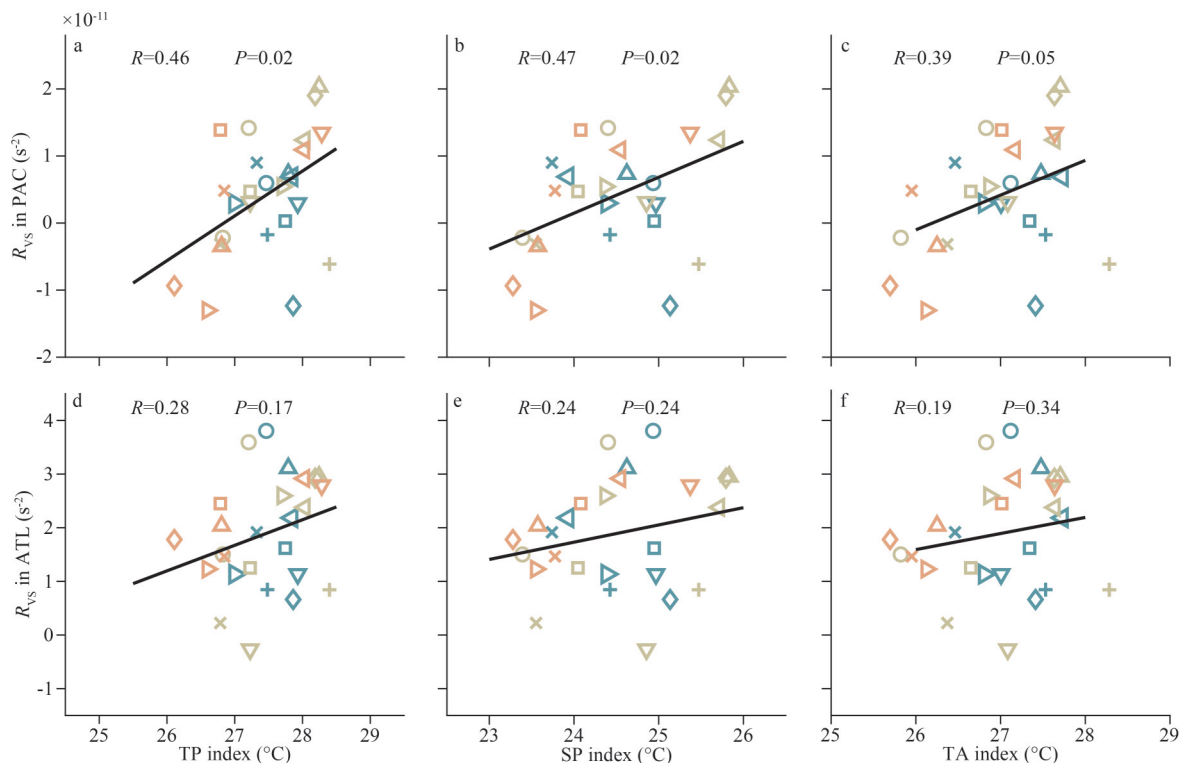


Fig.10 The intermodel correlation between the mean SST indices of and the AMO-related RWS (vortex stretching term) in the subtropical Pacific Ocean (a–c) and in the subtropical Atlantic Ocean (d–f)

TP: the tropical Pacific; SP: the southeast Pacific; TA: the tropical Atlantic. The legends are omitted as the correspondence of the model members, and markers are same to those in the Fig.6.

misaligned. This is probably because of the generally warmer south tropical Atlantic (Kajtar et al., 2018; McGregor et al., 2018) in coupled models, which results in eastward-expanding of the heating sources as well as the eastward shift of the ascending signals induced by the AMO. It also implicates the commonly underrepresented AMO-ASL relationship in coupled models.

4 DISCUSSION AND CONCLUSION

This study evaluates the performance of CMIP6 models in simulating the ASL trend that is congruent with the IPO and AMO. The results show that the recent observed deepening trend of ASL with a positive trend of the AMO and a negative trend of the IPO from 1979–2014, is substantially underestimated in most CMIP6 models. Here, we present two possible explanations for this underrepresentation: (1) the unrealistic relationship between the IPO and AMO in most CMIP6 models; and (2) the large intermodel spread of the AMO-related teleconnection pattern. For the former, based on the consistent ASL responses to four possible combined trends of the IPO and AMO with those in

the observational data, the joint effect of these two climate variabilities is largely underestimated in the coupled models since the relationship between the IPO and AMO in most models is opposite to that in the observations. Another reason is the intermodel spread of the AMO-related teleconnection pattern. Given the commonly overestimated south tropical Atlantic SSTs (Kajtar et al., 2018), the responding pattern of the tropical atmosphere differs from the observed pattern, and the intermodel spread of AMO-related teleconnection patterns are influenced by the mean SSTs in the TP, TA and SP. Due to the warmer Southeast Pacific and tropical Pacific mean SSTs, robust convections are generated in the eastern-central Pacific. The warmer mean SSTs in the tropical Atlantic also heat the east Pacific, further promoting this ascending motion. Eventually, abnormally positive RWSs are generated in the subtropical eastern-central Pacific and the negative geopotential height anomalies are restrained to transmit to the ASL region therefore the intermodel spread increases.

The two possible factors above mentioned are somehow linked with each other, as both of them are

closely related to the mean SST biases over the tropical Atlantic Ocean and southeast Pacific. By determining the reasons behind this model deficiency, we also highlight the importance of simulating the realistic background SST in the tropical regions abovementioned in coupled models, some of which have already been documented as common biases in CMIP models. Such as the warm bias in south tropical Atlantic (partially related to the southern part of the TA indices) as it is introduced in McGregor et al. (2018), the southeast Pacific warm bias, related the double ITCZ bias (Oueslati and Bellon, 2015; Li et al., 2020) and the cold tongue bias (Li and Xie, 2014). For the cold tongue bias, it is similar to the TP region in our study, except that our result suggests warmer TP indices mean positive or unrealistic AMO-ASL relationship. This paradoxical conclusion is probably resulted by the superimposed warm biases of tropical Atlantic and southeast Pacific in the selected models, which potentially alters the anomalous circulation pattern induced by the AMO, and therefore the generation of the RWS is more sensitive to the key convection region (i.e., the TP region). Thus, improving climatological SST, especially for the tropical regions as a whole in the models is urgently needed for long-term climate prediction.

It is also essential to consider the other possible attributors that potentially affect the simulation of ASL or even the variability of Antarctic sea ice. Previous studies pointed out that CMIP5 models tend to simulate warmer SSTs and weakened westerly winds in the Southern Ocean by overestimating the incoming shortwave flux through the cloud feedbacks (Hyder et al., 2018) and these biases still exist in the CMIP6 (Zhang et al., 2023; Gao et al., 2024). The warmer SSTs along with reduced westerlies as well as the cold Ekman transport potentially create the high-pressure condition and therefore hamper the generation of negative SLP signals, which also possibly contributes the underestimation of the ASL.

Nevertheless, the present study is insufficient to fully evaluate the coupled models' ability to reproduce the IPO/AMO congruent ASL trend or diagnose the origin of biases. Based on our results, further questions can be raised, for instance, we may also concern that to what extent the underestimation can be fixed by correcting the mean SSTs in these regions abovementioned. Moreover, although the significant impacts of the tropical Atlantic have been discussed in this paper, these results also

highlight the important role of the northern part of the Atlantic Ocean. Thus, more comprehensive and in-depth work including model sensitivity experiments, is needed in the future.

5 DATA AVAILABILITY STATEMENT

All data analyzed in this study are publicly available. The ERSSTv5 and ERSLP dataset were downloaded from the website of Physical Science Laboratory of NOAA (<http://psl.noaa.gov/data/gridded/index.html>). The HadISST and HadSLP2 dataset were downloaded from the website of Met Office Hadley Centre (<https://www.metoffice.gov.uk/hadobs/index.html>). The ERA-20C dataset were downloaded from the website of ECMWF (<https://www.ecmwf.int/en/forecasts/dataset>). The NSIDC-0079v4 dataset were downloaded from the website of NSIDC (<https://nsidc.org/data/>). CMIP6 data are available at the ESGF website (<https://esgf-node.llnl.gov/projects/cmip6>).

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