Present and Future Relations between ENSO and Winter Synoptic Temperature Variability over the Asian–Pacific–American Region Simulated by CMIP5/6

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ABSTRACT: In this study, the relationship between ENSO and winter synoptic temperature variability (STV) over the Asian–Pacific–American region is examined in 26 CMIP5/6 model outputs. Compared to observations, most models fail to simulate the correct ENSO-STV relationship in historical simulations. To investigate the possible bias in the ENSO-STV simulations, two possible processes for the connection between ENSO and winter STV are examined in high pattern score (HPS) models and low pattern score (LPS) models, respectively. On the one hand, both HPS and LPS models can overall reproduce a reasonable relationship between STV and the mean-flow conditions supporting extratropical eddy development. On the other hand, only HPS models can well capture the relationship between ENSO and the development of extratropical eddies, while LPS models fail to simulate this feature, indicating that the bias in the simulated ENSO-STV relationship among CMIP5/6 models can be traced back to ENSO simulation. Furthermore, the bias of the ENSO simulation is characterized by an unreasonable SST pattern bias, with an excessive westward extension of warm SST anomalies over the western Pacific and weak warm SST anomalies over the equatorial central-eastern Pacific, resulting in the underestimation of the zonal SST anomaly gradient among models. Therefore, the ENSO pattern bias induces an unrealistic circulation and temperature gradient over the Asian–Pacific–American region, affecting the simulations of the ENSO-STV connection. In addition, the ENSO-STV relationship over the Asian–Pacific–American region is still robust in future projections based on HPS models, providing implications for the selection of future climate predictors.

KEYWORDS: Climate change; Climate variability; ENSO

1. Introduction

El Niño–Southern Oscillation (ENSO), which is the dominant mode in the tropical Pacific with interannual variation, is characterized by warm sea surface temperature (SST) anomalies in the central-eastern tropical Pacific and horseshoe-shaped cold SST anomalies in the western Pacific (Trenberth 1997; McPhaden et al. 2006). Many studies have revealed that ENSO events can exert tremendous impact on climate around the world, especially in the Asian–Pacific–American region, which has the largest population, highly developed economies, and huge agricultural production, suggesting that ENSO is a vital influence to consider in climate prediction due to its socioeconomic impact over this region (Ropelewski and Halpert 1986; Webster and Yang 1992; Wang et al. 2000; Alexander et al. 2002; McPhaden et al. 2006; Zhou et al. 2007; Geng et al. 2017; Martineau et al. 2021; Taschetto et al. 2020). In general, ENSO events reach their peak during boreal winter, influencing winter temperature variation significantly by remote forcing, suggesting potential predictability for the winter climate over the Asian–Pacific–American region. For example, during an El Niño year, ENSO-related SST anomalies can induce a low-level anomalous anticyclone, which weakens the East Asian winter monsoon (EAWM), resulting in a warmer winter over East Asia (Zhang et al. 1996, 1999; Chen et al. 2000; Wang et al. 2000). Meanwhile, ENSO-related SST anomalies also influence the North American winter temperature via a Rossby wave train (Rasmusson and Wallace 1983; Trenberth et al. 1998; Straus and Shukla 2002; Bulić and Branković 2007; Leung and Zhou 2016).

Apart from seasonal or monthly mean temperature anomalies, temperature fluctuation during boreal winter also needs to be considered because it is important to agriculture and human disease transmission (Yin et al. 1996; Ikram et al. 2015; Xu et al. 2020). Some studies have found that ENSO events are also related to Asian–Pacific–American temperature variability on a subseasonal time scale (Geng et al. 2017; Martineau et al. 2021). Moreover, Leung and Zhou (2016) indicated that ENSO can modulate Asian–Pacific–American winter synoptic temperature variability (STV) by influencing the temperature gradient in the midlatitudes via a Rossby wave train. For example, during El Niño (La Niña) years, ENSO-related SST forcing causes a stronger (weaker) meridional temperature gradient and atmospheric baroclinicity in the midlatitudes.

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over East Asia, resulting in larger (smaller) winter STV due to stronger (weaker) intensification of extratropical eddies. Meanwhile, the opposite ENSO–STV relationship exists in North America compared to East Asia, which is consistent with Higgins et al. (2002). They discovered a relationship between ENSO, the number of extreme temperature cases, and winter daily mean temperature variance over the United States, showing that less extreme temperature cases and smaller temperature variance occur during El Niño years, while the opposite occurs in La Niña years. Based on 58 years of meteorological station data, Ren et al. (2020) further examined the relationship between ENSO and winter STV over China. They noted that winter STV becomes larger (smaller) during El Niño (La Niña) years. One possible reason they suggested is that El Niño events enhance the meridional temperature gradient in the mid- to high latitudes over Eurasia, inducing stronger storm activity and larger STV over China downstream. All these results suggest that the influence of ENSO on the midlatitude temperature gradient over the Asian–Pacific–American region via a Rossby wave train is an important modulation of winter STV over this region.

Recently, Jian et al. (2021) discovered that an interdecadal shift in the relationship between ENSO and winter STV over the Asian–Pacific–American region occurred in the 1980s, suggesting that the ENSO–STV relationship may change under global warming. However, due to the limited length of observational data at present, we need to use climate models to examine possible changes in the ENSO–STV connection over the Asian–Pacific–American region in a warmer climate. Currently, outputs from state-of-the-art climate models in phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) are widely used to examine robust relationships in observations and project possible changes in climate systems. Although the relationship between ENSO and winter mean temperature over the Asian–Pacific–American region has been examined with climate models in previous studies (Weare 2013; Gong et al. 2014; Zou et al. 2014; Gong et al. 2015), few studies have focused on the relationship between ENSO and winter STV based on a multimodel ensemble. Moreover, Gong et al. (2015) and Zou et al. (2014) further investigated the uncertainty in ENSO’s impact on winter surface temperature over East Asia and North America, respectively. The results of both studies indicated that the bias of the ENSO-related SST pattern with the unreasonable zonal extension affects simulations of ENSO’s impact over these two regions, which suggests that a more realistic ENSO pattern is essential to reproducing accurate atmospheric wave train propagation. As mentioned above, whether the possible bias of the simulated ENSO–STV relationship may be related to ENSO pattern simulation is also worth considering. Furthermore, future change in the ENSO–STV relationship over the Asian–Pacific–American region is still unclear. In addition, phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016) has recently been released. Whether the models of the new version can produce a more realistic ENSO–STV simulation than the last generation (CMIP5) also needs to be evaluated. In this study, we first aim to examine the relationship between ENSO and STV over the Asian–Pacific–American region with CMIP5/6 models in a historical simulation and analyze the possible cause of model bias. Then we try to project the ENSO–STV relationship by using the models with good performance in the historical simulation, discussing the influence of ENSO on winter STV over the Asian–Pacific–American region in the future climate, which will provide implications for our selection of climate predictors. The rest of this paper is organized as follows. Section 2 describes the model output, data, and methodologies used in this study. Section 3 examines the relationship between ENSO and winter STV over the Asian–Pacific–American region in the historical simulation. Section 4 investigates the possible cause of the model bias in the ENSO–STV relationship in the historical simulation. Section 5 projects the ENSO–STV relationship in the future climate. Finally, a summary and discussion are provided in section 6.

2. Models, datasets, and methodologies
a. Models and datasets
To examine the relationship between ENSO and winter STV in the present and future climate, we use daily and monthly outputs of 15 CMIP5 models and 11 CMIP6 models in both a historical run from 1950 to 2005 and a future projection from 2016 to 2100 under a high-level greenhouse gas emission scenario representative concentration pathway (RCP) 8.5 experiment in CMIP5, and a shared socioeconomic pathway (SSP) 5–8.5 experiment in CMIP6 (hereafter the SSP5–8.5 scenario, which uses the same greenhouse gas emission level as RCP8.5 but updates some of the boundary conditions), including the variables of air temperature, sea surface temperature, geopotential height, and horizontal winds (Taylor et al. 2012; Eyring et al. 2016). Details of the models are shown in Table 1. For comparison, we use the daily mean and monthly output datasets from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 1 with a horizontal resolution of 2.5° latitude × 2.5° longitude (Kalnay et al. 1996), including near-surface air temperature, geopotential height, and horizontal winds. Sea surface temperature is obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature (version 5) with a horizontal resolution of 2° latitude × 2° longitude (Huang et al. 2017), and HadISST1 from the Met Office Hadley Centre (Rayner et al. 2003). For comparison between the models and observations, all model outputs and observational datasets are interpolated to a uniform 2.5° × 2.5° horizontal grid. To calculate the multimodel ensemble (MME) mean, we first obtain the result from each model and then calculate the composite average of model results. In addition, we use the oceanic Niño index (ONI), which represents the intensity of ENSO events and can be downloaded from the Climate Prediction Center (CPC) website (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). The research period for the reanalysis data is from December 1950 to February 2018. Here we define the winter of 1951 as the period from December 1950 to February 1951, and so on.
b. Methodologies

For investigation of STV, we first apply a Lanczos filter to the daily mean near-surface temperature to remove low-frequency variation of longer than 10 days from December to the following February (Duchon 1979; Leung et al. 2019). Then we calculate the standard deviation for synaptic temperature from December to the following February, representing winter STV. All data used in this study have been detrended. The Student’s t test is applied to examine the significance of the correlation coefficients, regression coefficients, and composite analysis.

To estimate the intensification of extratropical eddies, we employ the maximum Eady growth rate to measure atmospheric baroclinicity instability (Eady 1949; Lindzen and Farrell 1980; Simmonds and Lim 2009; Leung and Zhou 2016). Similar to Simmonds and Lim (2009), we calculate the maximum Eady growth rate ($\sigma_E$) by the following formula:

$$\sigma_E = 0.3098 \frac{\left| f \right| \frac{\partial u(z)}{\partial z}}{N},$$

where $N$ is the Brunt–Väisälä frequency [$N^2 = (g/\theta)\left(\partial \theta/\partial z\right)$], $g$ is the gravitational acceleration, $\theta$ is potential temperature, $f$ is the Coriolis parameter, and $u(z)$ is the vertical profile of the zonal wind component.

3. The relationship between ENSO and winter STV over the Asian–Pacific–American region in the historical simulation

Figure 1 shows the distribution of correlation coefficients between winter STV and ONI over the Northern Hemisphere in observations and 15 CMIP5 models. As in previous studies (Leung and Zhou 2016; Ren et al. 2020), ENSO events are well related to the winter STV over Eastern China and North America, showing that the winter STV over Eastern China tends to become larger (smaller) during El Niño (La Niña) years, while the opposite occurs over North America (Fig. 1a). Meanwhile, ENSO events also exert stronger influence over Eastern China and North America, with larger regression coefficients between ONI and winter STV than other land areas, suggesting that Eastern China and North America are the two key regions of ENSO–STV connection over Asian–Pacific–American region. To quantify model performance in simulating the ENSO–STV relationship over the Asian–Pacific–American region, we designed a pattern score ($P_{\text{SEN_SO-STV}}$). First, we calculated ONI-STV correlation maps for the models and observations. Then we obtained the spatial correlation coefficients of the two correlation maps between the models and observations over the whole Asian–Pacific–American region, representing $P_{\text{SEN_SO-STV}}$.

Most CMIP5 models (Figs. 1b–p) do not simulate the pattern of the ENSO–STV relationship correctly, and only a few [e.g., MIROC5, CMCC-CMS, BCC_CSM1.1(m)] can well capture the pattern of this relationship with high pattern scores. On the other hand, CMIP6 models overall produce better simulations of the ENSO–STV relationship (Figs. 2b–i) than the CMIP5 models, with a higher average pattern score of 0.51 compared to 0.43 for the CMIP5 models. In addition, the results of some CMIP6 models (e.g., GFDL_CM4, $P_{\text{SEN_SO-STV}}$: 0.8; MPI-ESM1.2-LR, $P_{\text{SEN_SO-STV}}$: 0.74) are significantly improved compared to the last generation of CMIP5 (GFDL_CM3, $P_{\text{SEN_SO-STV}}$: 0.4; MPI-ESM-LR, $P_{\text{SEN_SO-STV}}$: 0.13), which shows excellent performance in reproducing the ENSO–STV relationship. However, nearly half of the CMIP6 models still do not well capture the overall pattern of the ENSO–STV relationship. Although some models can capture this pattern well, most fail to correctly simulate it. This lowers the predictability of winter STV over the Asian–Pacific–American region based on ENSO by using a
CMIP5/6 multimodel ensemble, suggesting that the cause of the bias is worth investigating.

4. Bias analysis for the ENSO–STV relationship in the historical simulation

As many previous studies have shown, ENSO can influence the winter STV over the Asian–Pacific–American region by modulating the temperature gradient in the midlatitudes, which is directly associated with the intensification of extratropical eddies, resulting in temperature fluctuation along the path of the extratropical eddies (Leung and Zhou 2016; Ren et al. 2020; Jian et al. 2021). Similarly, here we try to examine the performance of the CMIP5/6 models based on the mechanism mentioned above. The CMIP5/6 models in Figs. 1 and 2 are sorted according to $P_{\text{SENSO-STV}}$. To explore the source of the bias in the ENSO–STV relationship simulation, we choose seven high pattern score (HPS) models [GFDL CM4, MPI-ESM1.2-LR, MIROC6, MPI-ESM1.2-HR, MIROC5, CMCC-CMS, BCC_CSM1.1(m)] with $P_{\text{SENSO-STV}}$ above 0.6, and seven low pattern score (LPS) models (IPSL-CM5A-MR, INM-CM4.0, INM-CM4.8, GFDL-ESM2G, MRI-CGCM3, MPI-ESM-LR, INM-CM5.0) with $P_{\text{SENSO-STV}}$ below 0.3. Figures 3a and 3b show the performance of the HPS models and LPS models, respectively, in simulating the ENSO–STV relationship. With HPS models, a significant ENSO–STV connection can be found in both Eastern China and North America (Fig. 3a). But with LPS models (Fig. 3b), the simulated ENSO–STV relationship over the Asian–Pacific–American region is much weaker than with HPS models, while the main differences on land between these two groups appear in Eastern China and North America (Fig. 3c). In addition, since the ENSO–STV relationship over Eastern China and North America is opposite in the observations (Fig. 1a), those results will be discussed separately in the following.

As Fig. 4 shows, the winter STV over Eastern China (ECSTV, averaged STV over 110°–130°E, 20°–40°N) is well related to the Eady growth rate in the midlatitudes over East Asia in both HPS and LPS models (Figs. 4a,c), which is also physically consistent with low-level meridional wind synoptic variability over Eastern China (Figs. 4b,d). For example, when an extratropical cyclone propagates along the midlatitudes, it strengthens more with a high Eady growth rate, which brings southerly wind and raises the temperature over Eastern China.
when it approaches Eastern China, and then it leads to a temperature drop with northerly wind when it leaves, resulting in a larger temperature fluctuation. All these results, which are quite similar to observations (figures not shown), suggest that the robust relationship between the intensity of ECSTV and the development of extratropical eddies can be found in the models, indicating that the direct physical process associated with extratropical eddies does not account for the bias in the ENSO–STV relationship simulation over Eastern China. Therefore, we turn our attention to the relationship between ENSO and the development of extratropical eddies in HPS and LPS models. As shown in Figs. 5a and 5b, ENSO is related to the Eady growth rate near Japan and the low-level meridional wind synoptic variability over Eastern China in HPS models, which overlap the ECSTV-related regions (Figs. 4a,b). But with LPS models, the relationship between ENSO and extratropical eddy development is weaker than that with HPS models (Fig. 5c) while ENSO is also poorly related to low-level circulation synoptic variability (Fig. 5d), suggesting that the main difference in the ENSO–STV relationship simulations between HPS models and LPS models is the connection between ENSO and the development of extratropical eddies (Figs. 5e,f). On the other hand, similar results can also be found over North America. Both HPS and LPS models can overall reproduce the relationship between winter STV over North America (NASTV; averaged STV over 30°–60°N, 130°–80°W) and the development of extratropical eddies (Figs. 6a,c). Meanwhile, both HPS and LPS models show that when high (low) synoptic variability of 850-hPa meridional wind occurs over North America (Figs. 6b,d), associated with strong (weak) extratropical eddies passing through this region, NASTV tends to become larger (smaller). We then examine model performance in simulating the relationship between ENSO and extratropical eddy development over North America. Figures 7a–d show composited correlation maps of the ENSO-related Eady growth rate and meridional wind variability at 850 hPa over North America with HPS and LPS models, respectively. Compared to the results with HPS models (Figs. 7a,b), LPS models do not well capture the relationship between ENSO and the Eady growth rate and 850-hPa meridional
wind synoptic variability in either spatial distribution or magnitude (Figs. 7c,d), which seems to contribute to the poorly simulated ENSO–STV relationship over North America. All these results suggest that the uncertainty of the ENSO-related bias is larger, which is also supported by the differences shown in previous figures (Figs. 4e,f, 5e,f, 6e,f, and 7e,f), highlighting that the bias of the ENSO–STV relationship simulation is related to ENSO rather than to the direct influence of extratropical eddies.

Since ENSO’s impact is closely associated with the ENSO-related SST pattern simulation, we here examine model performance in simulating ENSO by using the dominant EOF mode of winter SST anomalies. Similar results can also be obtained from the ONI-related SST pattern (figure not shown). What is more, in order to examine the asymmetrical nature of ENSO, we also checked composited SST in different ENSO phases (El Niño and La Niña), with very similar results (figure not shown). Therefore, we show only the results based on the EOF mode of winter SST anomalies in the following discussion. Figures 8a, 8c, 8e, and 8g show the first EOF mode of winter SST anomalies over the tropical Pacific (25°S–25°N, 120°E–80°W) in observations, HPSMME, LPSMME, and the difference between LPSMME and HPSMME, respectively. As

Fig. 4. Composited correlation map between ECSTV (20°–40°N, 110°–130°E) and the (a) Eady growth rate (EGR) at 850 hPa and (b) synoptic meridional wind variability at 850 hPa for HPS models. (c),(d) As in (a) and (b), but for LPS models. (e),(f) The difference between (c) and (a) and (d) and (b), respectively. Stippling in (a)–(d) indicates the MME of correlation coefficients exceeding the 0.05 significance level based on one sample t test. Stippling in (e) and (f) indicates values exceeding the 0.05 significance level.
similar results can be obtained from the two SST datasets, we here show only the results from ERSST (version 5). Compared to observations (Fig. 8a), both HPS and LPS models can well simulate the overall ENSO pattern, with warming SST over the equatorial central-eastern Pacific and horseshoe-shaped cooling SST over the tropical western Pacific (Figs. 8c,e). However, we note that warming SST in LPS models extends more westward and has a smaller magnitude over the equatorial central-eastern Pacific than in observations and HPS models, presenting a significant SST zonal gradient bias along the equatorial Pacific (Fig. 8g). In addition, since recent studies pointed out that the unreasonable ENSO-related SST pattern bias is associated with the mean-state bias (Li et al. 2019; Jiang et al. 2021), we also examine the mean-state condition of SST among HPS and LPS models in Figs. 8d and 8f, respectively. Compared to observations (Fig. 8b), the mean state of SST in LPS models (Fig. 8f) is colder than in HPS models (Fig. 8d), with excessive westward extension of the cold tongue in the mean state (Fig. 8h), suggesting that the ENSO-related SST pattern bias may also be related to the mean-state bias of SST. However, since we focus here on the impact of ENSO pattern bias on simulations of the ENSO–STV connection among models, the relationship between the ENSO pattern bias and mean-state bias is beyond our current study. Therefore, we will discuss the relationship between the ENSO–STV connection and mean-state condition of SST in a later section. Furthermore, the intermodel relationship between the ENSO pattern simulation and $P_{\text{ENSO-STV}}$ is examined in
Fig. 9a. Similar to $P_{\text{SENSO-STV}}$, we define $P_{\text{SST}}$ as the pattern correlation between the EOF1 mode of winter tropical Pacific SST anomalies in the models and observations. Consistent with previous results (Fig. 8), the model $P_{\text{SENSO-STV}}$ is well related to $P_{\text{SST}}$, with an intermodel correlation of 0.63 exceeding the 0.01 significance level based on the Student’s $t$ test, indicating that the ENSO–STV relationship is associated with the ENSO simulation. Moreover, as Fig. 9b shows, most models have a weaker zonal SST anomaly gradient along the equatorial Pacific (east–west gradient, difference between averaged SST anomalies over 2.5°S–2.5°N, 170°–120°W and 2.5°S–2.5°N, 140°–160°E) compared to observations. Meanwhile, models with a weaker zonal SST anomaly gradient tend to have low $P_{\text{SST}}$, with a significant intermodel correlation of 0.6 (Fig. 9b). Therefore, the bias of the ENSO–STV relationship simulation can be traced back to the SST zonal gradient bias in the ENSO pattern simulations, with a high intermodel correlation of 0.77 (Fig. 9c). This suggests that the pattern bias of ENSO-related SST anomalies plays an important role in the poorly simulated ENSO–STV relationship over the Asian–Pacific–American region among CMIP5/6 models. To further investigate the influence of the ENSO pattern bias, we compare ENSO-related temperature and circulation patterns between observations, HPS models, and LPS models in Fig. 10. As Fig. 10a shows, in observations, ENSO-related SST anomalies induce a pair of anomalous cyclonic and anticyclonic circulations in the lower troposphere over East Asia and North America via a Rossby wave train. The anomalous northerly (southerly) wind in the Siberian region brings cold (warm) air from higher latitudes (tropics) to northeast Asia, resulting in cold (warm) temperature anomalies near Japan, which leads to a temperature anomaly gradient over this region. As mentioned before, the temperature gradient over northeast Asia is directly associated with the development of extratropical eddies in the midlatitudes due to atmospheric baroclinicity, which affects the winter STV over Eastern China. On the other hand, as in Eastern China, ENSO-related circulations also tend to produce a temperature gradient in the midlatitudes over North America, associated with the development of extratropical eddies over North America (Fig. 10a). Consistent with the good simulations of the ENSO pattern, the ENSO-related temperature and circulation patterns in HPS models (Fig. 10b) are quite similar to observations (Fig. 10a). However, due to the bias of the SST zonal gradient, LPS models fail to simulate the ENSO-related circulation pattern and temperature gradient in both East Asia and North America.
America compared to observations, which produces a relatively weak ENSO-related temperature gradient in the midlatitudes over the Asian–Pacific–American region, suggesting that ENSO-related SST anomalies in LPS models cause the atmospheric response to be more focused on the Pacific region rather than over the wider Asian–Pacific–American region (Fig. 10c). To further examine the atmospheric responses to different ENSO-related SST anomaly patterns over the tropical Pacific in HPS and LPS models, we employ a model named Simplified Parameterizations, Primitive Equation Dynamics (SPEEDY; Molteni 2003; Kucharski et al. 2006, 2013) to perform numerical simulations. SPEEDY is an atmospheric general circulation model (AGCM) developed by the International Centre for Theoretical Physics (ITCP), with eight vertical levels and T30 horizontal resolution. (More detailed information about the SPEEDY model can be found online at http://users.ictp.it/~kucharski/speedy-net.html). As many previous studies have shown (Bracco et al. 2005; Kucharski et al. 2007; King et al. 2010; Dogar et al. 2017; Sun et al. 2017; King et al. 2018; Leung et al. 2020; Jian et al. 2020, 2021), this model is widely used to examine atmospheric circulation responses to SST forcing, suggesting that it can appropriately be used to investigate the influence of different ENSO-related SST anomaly patterns in HPS and LPS models. In this study, we use three types of SST fields as forcing: SST0, SST1, and SST2. SST0 is the climatological SST with an annual cycle during 1979–2018 from observations (Kennedy et al. 2011). SST1 is the composited first EOF mode of winter SST anomalies over the tropical Pacific (25°S–25°N, 120°E–80°W; Fig. 8c) in HPS models. SST2 is also the composited first EOF mode of winter SST anomalies over the tropical Pacific, but for LPS models (Fig. 8e). We design three experiments in this study: Exp_CTRL, which is a control run forced by SST0 with a running period of 145 years; Exp_HPSMME, a sensitivity run forced by (SST0 + SST1), which restarts each December based on Exp_CTRL and runs for three months; and Exp_LPSMME, which is the same as Exp_HPSMME but forced by (SST0 + SST2). To avoid the effect of model spinup and make sure the same initial conditions apply in each experiment, here we use the last 115 years of Exp_CTRL to restart Exp_HPSMME and Exp_LPSMME and then calculate the average of 115 members for analysis. The differences between Exp_HPSMME, Exp_LPSMME, and Exp_CTRL represent the atmospheric response to ENSO-related SST anomalies over the tropical Pacific in HPS and LPS models, separately.

The temperature responses to the EOF1 modes of SST anomalies over the tropical Pacific in HPS (Fig. 8c) and LPS
models (Fig. 8e) are shown in Figs. 11a and 11b, respectively. As the figure shows, the temperature gradient in the mid-latitudes over the Asian–Pacific–American region induced by SST anomalies is weaker in Exp_LPSMME than in Exp_HPSMME (Fig. 11c), which is similar to Fig. 10d, suggesting that the bias with the weaker SST zonal anomaly gradient among LPS models contributes to the weaker atmospheric response over the Asian–Pacific–American region. In other words, the weak SST gradient induces a weak air pressure gradient, which directly causes a weak circulation response, thus resulting in a weak ENSO-related temperature gradient in the midlatitudes. With the limited ENSO influence on the midlatitude temperature gradient, which is the key region for extratropical eddy intensification, the connection between ENSO and winter STV in LPS models (Fig. 3b) is weaker than in HPS models (Fig. 3a). Moreover, Jian et al. (2021) recently also discovered that different ENSO-related SST patterns over the tropical Pacific can modulate the ENSO–STV relationship over the Asian–Pacific–American region via a Rossby wave train. All these results highlight that ENSO pattern bias causes unrealistic atmospheric responses, influencing simulations of the ENSO–STV relationship over the Asian–Pacific–American region in CMIP5/6 models.

5. Model-projected ENSO–STV relationship in a warmer climate

As shown by the model performance in section 3, HPS models can well capture the ENSO–STV relationship over the Asian–Pacific–American region in the historical simulation, suggesting that the ability of HPS models to simulate the ENSO–STV relationship is reliable. On the other hand, the
global warming trend of recent decades motivates us to investigate whether ENSO can still influence winter STV over the Asian–Pacific–American region under a warmer climate. Figure 12 shows projected correlation maps between ENSO and winter STV in both HPS and LPS models under the RCP8.5 scenario (CMIP5) and SSP5–8.5 scenario (CMIP6), respectively. As shown in Fig. 12c, HPS models indicate that ENSO is well related to the winter STV over the Asian–Pacific–American region, especially in Eastern China and North America, which is also similar to present-day observations and their historical simulations (Fig. 12a). Furthermore, though the ENSO–STV connection becomes slightly stronger over Eastern China in a warmer climate, the overall pattern over North America is nearly unchanged. On the other hand, for LPS models, both historical simulations and future projections show a poor connection between ENSO and winter STV over the Asian–Pacific–American region, especially in Eastern China and North America, which are the two key regions of ENSO–STV connection. Therefore, based on the consistent results of HPS models, the significant relationship between ENSO and winter STV over the Asian–Pacific–American region tends to exist in a warmer climate, providing implications for our selection of climate predictors in the future.

6. Summary and discussion

a. Summary

In this study, we examine the relationship between ENSO and winter STV over the Asian–Pacific–American region based on 15 CMIP5 and 11 CMIP6 models and investigate the possible source of bias in the ENSO–STV relationship simulations. Compared to observations, although a few models can well capture the pattern of the ENSO–STV relationship, most models fail to simulate it correctly over the Asian–Pacific–American region in the historical output. In addition, the overall performance of the CMIP6 models is better than that of the CMIP5 models, and some CMIP6 models (e.g., GFDL CM4; MPI-ESM1.2-LR) show significant improvement over the last generation in CMIP5 (GFDL CM3; MPI-ESM-LR). To investigate the possible source of bias for the poorly simulated ENSO–STV relationship among the models, we compare two possible processes of the connection between ENSO and winter STV over Eastern China and North America in HPS and LPS models, respectively. On the one hand, both HPS and LPS models can overall reproduce a reasonable relationship between the intensity of ECSTV (NASTV) and the development of extratropical eddies in the midlatitudes over East Asia (North America). On the other hand, only HPS models can well capture the relationship between ENSO and the development of extratropical eddies in both Eastern China and North America, while LPS models fail to simulate this feature, indicating that ENSO-related biases play a role in the bias of the simulated ENSO–STV relationship in CMIP5/6 models. Furthermore, the detailed source of bias for ENSO can be traced back to an ENSO pattern bias with excessive westward extension of warm SST anomalies over the western Pacific and weak warm SST anomalies over the equatorial central-eastern Pacific, resulting in the underestimation of the zonal SST anomaly gradient compared to observations. Therefore, the ENSO pattern bias influences the circulation and temperature gradient pattern over the Asian–Pacific–American region via a Rossby wave train, which induces an unrealistic atmospheric response, affecting the simulations of the ENSO–STV connection over the Asian–Pacific–American region in the CMIP5/6 models. In addition, based on HPS models, a robust ENSO–STV relationship can also be found over the Asian–Pacific–American region in a future projection under a high emission scenario, suggesting that ENSO can still be a vital influence on winter STV over the Asian–Pacific–American region in a warmer climate, providing implications for our selection of climate predictors in the future.
b. Discussion

Many studies have found a possible relationship between the excessive westward extension of ENSO-related SST anomalies and the excessive westward extension of the Pacific cold tongue among CMIP5/6 model simulations, which significantly influences model performance in simulating ENSO-related teleconnections over East Asia (Gong et al. 2015; Jiang et al. 2017; Li et al. 2019; Jiang et al. 2021). Since the excessive Pacific cold tongue is a common bias among climate models and has persisted for several generations (Yu and Mechoso 1999; Lin 2007; De Szoeke and Xie 2008; Zheng et al. 2012; Li et al. 2016; Jiang et al. 2021), characterized by the colder SST over the equatorial eastern Pacific compared to observations, it can potentially limit model skill in simulating ENSO and its impact.

Fig. 10. Correlation map between PC1 and winter 700-hPa air temperature and horizontal wind anomalies for (a) observations, (b) HPS models, (c) LPS models, and (d) the difference between LPS and HPS models. The model results are obtained from the composited correlation map for the HPS and LPS model groups, respectively, which are calculated by the multimodel average in each group. The dashed (solid) purple contours indicate the area of negative (positive) correlation coefficients between PC1 and the meridional temperature gradient at 700 hPa exceeding the 0.05 significance level. Wind speed less than 0.2 m s\(^{-1}\) has been masked out. Stippling and contours in (d) indicate the differences between (c) and (b) exceeding the 0.05 significance level.

Fig. 11. Spatial patterns of temperature (°C) and horizontal wind (m s\(^{-1}\)) anomalies at 700 hPa for (a) Exp_HPSMME – Exp_CRTL, (b) Exp_LPSMME – Exp_CRTL; (c) the difference in 700-hPa temperature between Exp_LPSMME and Exp_HPSMME. Wind speed in (a) and (b) less than 0.3 m s\(^{-1}\) has been masked out. The purple contours in (c) indicate the area of the difference in the meridional temperature gradient at 700 hPa between (b) and (a) exceeding the 0.05 significance level. Stippling in (c) indicates the differences between (b) and (a) exceeding the 0.05 significance level.
exceeding the 0.01 significance level based on the Student’s $t$ test. Meanwhile, the equatorial Pacific cold tongue intensity is well related to the east–west gradient, with a high intermodel correlation of 0.65, which is also consistent with the results shown in Jiang et al. (2021), suggesting that the Pacific cold tongue bias may affect ENSO pattern simulation. In addition, some recent studies have discovered that the excessive cold tongue bias can enhance the mean SST zonal gradient in the western Pacific, resulting in the excessive westward extension of ENSO-related SST via unrealistic zonal advection feedback of the ocean current (Graham et al. 2017; Jiang et al. 2021). Therefore, the unreasonable ENSO-related SST pattern causes a limited circulation response over the Asian–Pacific–American region, less affecting the temperature gradient in the midlatitudes, which is the key region for intensification of extratropical eddy development. All of this indicates that the models with a strong cold tongue bias tend to poorly simulate the ENSO–STV relationship over the Asian–Pacific–American region via an unrealistic ENSO-related SST pattern, suggesting that the impact of mean-state bias needs to be considered in climate models. In addition, some studies have also found that the Arctic Oscillation (AO; Thompson and Wallace 1998; Thompson et al. 2000) is related to STV over the Asian–Pacific–American region (Wettstein and Mearns 2002; Gong et al. 2004). Since we focus on the relationship between ENSO and winter STV over the Asian–Pacific–American region in this study, climate model performance in simulating the relationship between other influencing factors (e.g., AO) and winter STV is still unclear and will be investigated in our future research.

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Data availability statement. Datasets analyzed during the current study are available from NCAR/UCAR (https://rda.ucar.edu/) and NOAA/Physical Sciences Laboratory (https://psl.noaa.gov/). These datasets were derived from the following public domain resources: NCEP1 (https://rda.ucar.edu/datasets/ds090.2/), and ERSSTv5 (https://psl.noaa.gov/data/gridded/data.ncep.ersst.v5.html). CMIP5 project data are from the historical and RCP85 experiment, Department of Energy, Lawrence Livermore National Laboratory (https://esgf-node.llnl.gov/search/cmip5/). CMIP6 project data are from the historical and SSP5–8.5 experiment, Department of Energy, Lawrence Livermore National Laboratory (https://esgf-node.llnl.gov/search/cmip6/). Other data are from the National Centers for Environmental Prediction/National Weather Service/NOAA/ U.S. Department of Commerce (1994 data, updated monthly), and NCEP/NCAR Global Reanalysis Products. (1948–continuing), from the Research Data Archive at NOAA/PSL (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html). The oceanic Niño index was obtained from the CPC (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). The Arctic oscillation index was obtained from the CPC (https://psl.noaa.gov/data/correlation/ao.data). Other SST data are obtained from Met Office Hadley Centre (HadISST 1.1—Global sea-ice coverage and SST, 1870–present; https://www.metoffice.gov.uk/hadobs/hadisst/data/HadISST_sst.nc.gz).

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FIG. 12. MME for the spatial pattern of correlation coefficients between ONI and winter STV in (a) historical simulations of HPS models, (b) historical simulations of LPS models, (c) future projections of HPS models, and (d) future projections of LPS models, respectively. The black solid line (dashed) represents the regression coefficient between ONI and winter STV at ±0.07, respectively. Stippling indicates the MME of correlation coefficients exceeding the 0.05 significance level based on one sample $t$ test.


