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Key Points:

- Phase 6 of the Coupled Model Intercomparison Project multi-model-mean reproduces the observed Indo-Pacific warm pool size well, but there is a huge inter-model spread in warm pool size
- Model biases in warm pool size have local and remote effects on subtropical winds and precipitation in present-day and future climates
- Emergent constraints reduce projection uncertainty of subtropical winds and precipitation by ruling out models with biased warm pool size

Supporting Information:

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

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Implications of Warm Pool Bias in CMIP6 Models on the Northern Hemisphere Wintertime Subtropical Jet and Precipitation

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Abstract Although the multi-model average compares well with observations, individually most of the latest climate models do not simulate a realistic size of the Indo-Pacific Warm Pool in the present-day climate. This study explores the implications of this warm pool size bias in climate models in Northern Hemisphere winter. The warm pool size bias in phase 6 of the Coupled Model Intercomparison Project models is related to the subtropical jet and precipitation distribution, both in the present-day climate and in response to climate change, through extratropical Rossby wave trains and tropical circulation pathways. Based on these relationships, emergent constraints are developed to observationally constrain the future subtropical jet response over Asia and the Atlantic Ocean and precipitation response over North and Central America, which can help to reduce uncertainty in future projections of these features. Thus, accurate model simulation of the warm pool in the present-day climate is important for future projections of the subtropical jet and precipitation.

Plain Language Summary This study examines the impact of a common problem in the latest climate models where they do not accurately simulate the size of the Indo-Pacific Warm Pool in the present-day climate. The effects of this issue are investigated in the Northern Hemisphere winter. The warm pool size problem in the models affects the subtropical winds and precipitation, both in the current climate and in response to climate change. Based on the relationships between the present-day warm pool size and future projections of the subtropical winds and precipitation across models, we can help to constrain future projections of the subtropical winds over Asia and precipitation over North and Central America by ruling out models with biased warm pool size. The results show that having an accurate simulation of the warm pool in the present-day climate is crucial for more reliable future projections of subtropical winds and precipitation.

1. Introduction

The Indo-Pacific Warm Pool (referred to as the warm pool hereafter) is Earth's largest region of warm sea surface temperatures (SSTs) where SSTs exceed 28°C, serving as a heat engine of the global climate due to deep atmospheric convection and huge latent heat release to the atmosphere (de Deckker, 2016; Yan et al., 1992). The warm pool supports the rising branch of the Walker Circulation, and its size and temperature are important in regulating the global atmospheric circulation and precipitation distribution (Duan et al., 2008; Feng et al., 2013).

Most climate models suffer from errors in simulating tropical SST patterns, which may limit the reliability of their future climate projections. For example, Li and Xie (2014) found an excessive westward extension of the equatorial Pacific cold tongue in CMIP5 models, which is closely associated with deficient precipitation and surface easterly wind biases. Furthermore, G. Wang et al. (2021) showed that both CMIP5 and CMIP6 models simulate an overly tilted thermocline, leading to overly high SST variability in the equatorial Indian Ocean. Recently, Park, Yeh, Min, and Son (2022) (hereafter P22) explored the representation of warm pool size in the present-day climate and found a relationship between the warm pool area in the present-day and its changes in the future under various warming scenarios. However, their study did not examine the subsequent impacts of the warm pool bias, especially those remote impacts in the extratropics.

Previous studies have also documented the relationship between tropical convection (which is closely related to the underlying SST pattern) and variability of the subtropical jet (STJ) on the interannual timescale. Gallego et al., 2005 found that ENSO strongly modifies the latitude and especially the strength of the STJ in the Southern Hemisphere (SH). During Northern Hemisphere (NH) winter, Liu et al., 2021 (hereafter L21) showed that, in both observations and CMIP6 models, a La Niña like pattern in anomalous tropical convection

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is associated with a strengthening of the STJ over Eurasia. However, the relationship between the warm pool and tropical convection in the present-day climate and the response of the STJ to climate change has not been examined.

Following these studies, it is natural to ask: (a) what are the potential impacts of models' warm pool size bias on their representation of the NH wintertime STJ both in the present-day climate and in response to climate change?, (b) are these biases linked with models' representation of precipitation?, and (c) can the inter-model spread in the representation of the warm pool size in CMIP6 models be used to reduce uncertainty in their future projections of the STJ and precipitation? To fill this gap, the purpose of this paper is to understand the potential impacts of models' warm pool size bias on the NH wintertime STJ and precipitation both in the present-day climate and in response to climate change.

The study is organized as follows. Section 2 describes the data and methods. Sections 3.1 and 3.2 examine the warm pool bias in CMIP6 models and its implications for their representation of the STJ and precipitation in the present-day climate. Section 3.3 explores emergent constraints between the models' present-day warm pool size and their projected changes in the STJ and precipitation in the future. Section 4 concludes with a summary and discussion.

2. Data and Methods

2.1. Data

We use three observational monthly-mean data products in this study: (a) SST from the HadISST v1.1 data set (Rayner et al., 2003) to compute the warm pool area, (b) zonal wind from the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) (Hersbach et al., 2020) for analysis of the STJ, and (c) precipitation from the Global Precipitation Climatology Project (GPCP; Adler et al., 2003) for analysis of precipitation.

For the modeling part of this study, we use two sets of model runs from global climate models from phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016), the historical runs and the Shared Socioeconomic Pathway (SSP) 5–8.5 scenario runs. The SSP5-8.5 scenario (Kriegler et al., 2014) uses a forcing scenario in each CMIP6 model that reaches ~8.5 W m^{-2} radiative forcing by 2100 and is similar to the RCP8.5 scenario in CMIP5. Specifically, we use monthly Outgoing Longwave Radiation (OLR), zonal wind, precipitation, and SST from both the historical and SSP5-8.5 runs in 40 CMIP6 models, which are listed in Table S1 in Supporting Information S1. We only examine the first ensemble member per model.

All variables are interpolated to a common spatial resolution (2.5° latitude × 2.5° longitude) before analysis. When talking about the future response of a specific variable, we refer to the difference between the field of this variable averaged over the last 30 years (2070–2099) at the end of the 21st century in the SSP5-8.5 run and the field of this variable averaged over the 1979–2014 period in the historical run. As in L21, we consider only the December–February (DJF) season when tropical-extratropical teleconnections are large in the NH.

2.2. Methods

The warm pool area is defined using the ocean area enclosed by the 28°C isotherm for the Indian Ocean and West Pacific Ocean domain (30°S to 30°N and 40°E to 180°E). The unit of the warm pool area is a percent as it is defined as the proportion of the warm pool area to the Indian and West Pacific Ocean domain. Our key findings are insensitive to the use of a larger warm pool domain (the whole tropical Indian and Pacific Oceans). To examine the future expansion of the warm pool, we linearly regress out the impact of climate sensitivity on the warm pool expansion to isolate the component of the future warm pool expansion that is uncorrelated with the concurrent trend in global-mean surface temperature, following the same technique in Equation 1 of Schmidt and Grise (2021). The warm pool expansion with and without the global-mean surface temperature removal is qualitatively similar ($r = 0.87$).

To distinguish the STJ from the polar front jet, following L21, we define the STJ as maximum of the difference field between the upper tropospheric (250 hPa) and lower tropospheric zonal wind (850 hPa) averaged over a given longitude band between 10°N and 40°N.

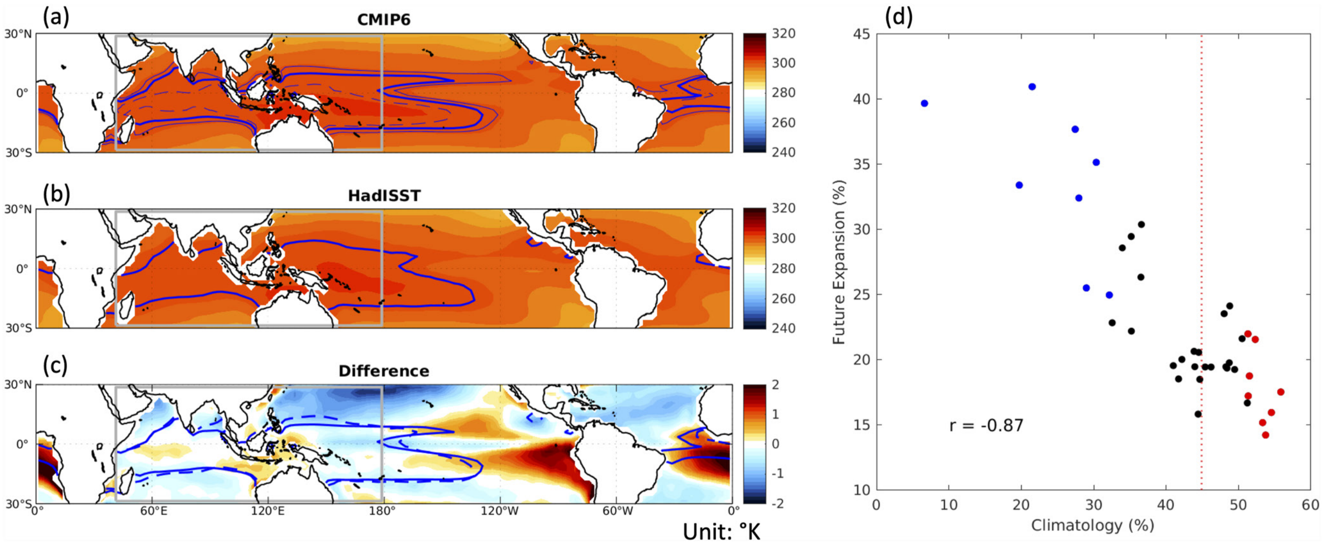

Figure 1. (a) Phase 6 of the Coupled Model Intercomparison Project (CMIP6) model-mean sea surface temperature (SST) climatology with the 28°C SST isotherm (bold: model-mean; dashed: small group; thin solid: large group). (b) Observed SST climatology with the 28°C SST isotherm. (c) Difference between (a) and (b) with the 28°C SST isotherm (solid: CMIP6 model mean; dashed: HadISST). The gray-boxed region in (a)–(c) is the domain used to define the warm pool area. (d) Scatter plot between climatological percent area of warm pool and its future expansion (red dashed line: HadISST warm pool area). Each dot represents a CMIP6 model (red: large warm pool group; blue: small warm pool group).

3. Results

3.1. Warm Pool Area in the Present-Day Climate and Its Future Response

We begin by reviewing the climatological warm pool in observations and CMIP6 models in the present-day climate during DJF. Figures 1a and 1b show the CMIP6 model-mean and observed SST climatology in the tropics from 1979 to 2014. Figure 1c shows the CMIP6 multi-model mean SST bias compared to the observations. The CMIP6 model-mean reproduces the warm pool reasonably well compared to the observations, but there is huge inter-model spread in the warm pool size as indicated in Figure 1d. As in P22, we find a strong relationship ($r = -0.87$) between a model's climatological warm pool area and its future change across 40 CMIP6 models (Figure 1d), which means models with currently small warm pools tend to expand more in the future. Note, however, that we use 10 more CMIP6 models and slightly different definitions of the present-day climate and the warm pool area than in P22. Hereafter, for further analysis, we select 8 CMIP6 models with the largest warm pool area in the present-day climate as the "large warm pool group" (Figure 1a, thin solid contour; models labeled in red in Figure 1d and Table S1 in Supporting Information S1) and 8 CMIP6 models with the smallest warm pool area in the present-day climate as the "small warm pool group" (Figure 1a, dashed contour; models labeled in blue in Figure 1d and Table S1 in Supporting Information S1).

The response of tropical convection over the warm pool to climate change is closely associated with the future responses of the Asian and Atlantic STJ strength (Figure S1 in Supporting Information S1), qualitatively similar to the relationships found on interannual and month-to-month timescales by L21 (see their Figure 7), especially for the Asian STJ. This implies that a model's climatological warm pool bias should have impacts on its future projections of NH winter STJ strength in these regions, considering the tight relationship between the present-day warm pool size and its future change (Figure 1d; P22). This motivates the need to examine the downstream impacts of the warm pool biases in CMIP6 models, which will be the focus of the remainder of this study.

3.2. Implications for the Subtropical Jet and Precipitation in the Present-Day Climate

The global atmospheric circulation responds to convective heating over the warm pool in the Indo-Pacific through two pathways (Bladé & Hartmann, 1995; Jin & Hoskins, 1995; C. Wang, 2005). One pathway is through the Rossby wave train excited by the tropical convective heating that extends poleward and around the globe (Jin & Hoskins, 1995). The other pathway is through the overturning circulations in the tropics (Hong et al., 2022).

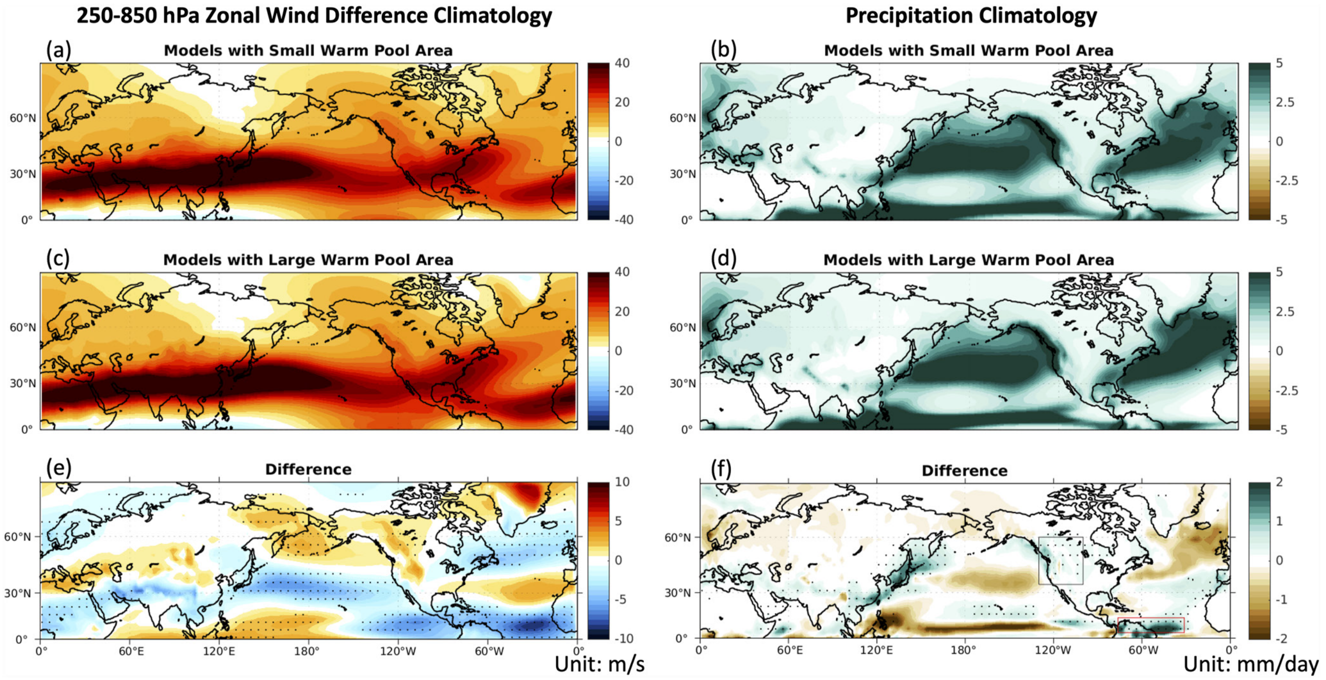

Figure 2. (Left column) Climatology of zonal wind difference field for small warm pool group (a), large warm pool group (c), and their difference (e) in phase 6 of the Coupled Model Intercomparison Project models. (Right column) Same as the left column, but for the precipitation field. Stippling indicates that correlations between the climatological warm pool area and zonal wind difference/precipitation climatology fields across all 40 models are statistically significant at the 95% level according to a two-tailed Student's *t* test.

To understand the downstream impacts of CMIP6 models' warm pool area bias on their representation of the NH wintertime STJ and precipitation in the present-day climate, Figure 2 shows the 250–850 hPa zonal wind difference field climatology (which is used to define the STJ), and the precipitation climatology for both the small warm pool group and the large warm pool group of models. For the zonal wind difference field, those models with a smaller climatological warm pool have a weaker STJ in the West Pacific and Atlantic in the present-day climate (Figures 2a, 2c, and 2e; see also Figures S2a and S2b in Supporting Information S1 for scatter plots of all 40 models). Models with a smaller warm pool excite a weaker downstream Rossby wave train, which is associated with a weaker region of lower geopotential heights over the northwest Pacific Ocean (Figure S3 in Supporting Information S1, left column). As a result, the West Pacific STJ, which is on the south side of this region of lower geopotential heights, is stronger in the large warm pool group of models. The impact of the models' warm pool area bias on the Atlantic STJ cannot be explained by the Rossby wave train pathway, but rather through a Walker Circulation mechanism. Models with a smaller warm pool have a weaker ascent in the tropical West Pacific and consequently a weaker descent area in the tropical East Pacific, which supports a stronger Atlantic Walker Circulation (Figure S4a in Supporting Information S1). The stronger Atlantic Walker Circulation in the small warm pool group leads to an anomalously weaker Atlantic Hadley cell in these models (see Figures 6–12 in C. Wang, 2005) and thus a weaker STJ over the Atlantic.

For the precipitation field, while there are many local impacts of the warm pool area bias in the Pacific (Park, Yeh, Min, Ham, & Kirtman, 2022), we will focus here on remote teleconnections into the extratropics and Atlantic. Models with a smaller warm pool tend to simulate more precipitation in the northwestern United States and southwestern Canada (gray box in Figure 2f) and more precipitation in northeastern South America and the tropical West Atlantic (red box in Figure 2f) (see also Figures S2c and S2d for scatter plots of all 40 models). For reference, a zoomed-in version of Figure 2f is also shown in the supplementary material (Figure S5a in Supporting Information S1). The impact of the warm pool area on the precipitation in the northwestern United States can be explained by the Rossby wave train mechanism. Those models with a smaller warm pool have a weaker ridge over northwestern North America, promoting anomalous onshore flow into this region and thus greater precipitation (Figures S3a, S3d, and S3g in Supporting Information S1). The impact of the warm pool area on the precipitation in northeastern South America and the tropical West Atlantic is consistent with the anomalously stronger Atlantic Walker circulation in the small warm pool group of models (Barichivich et al., 2018).

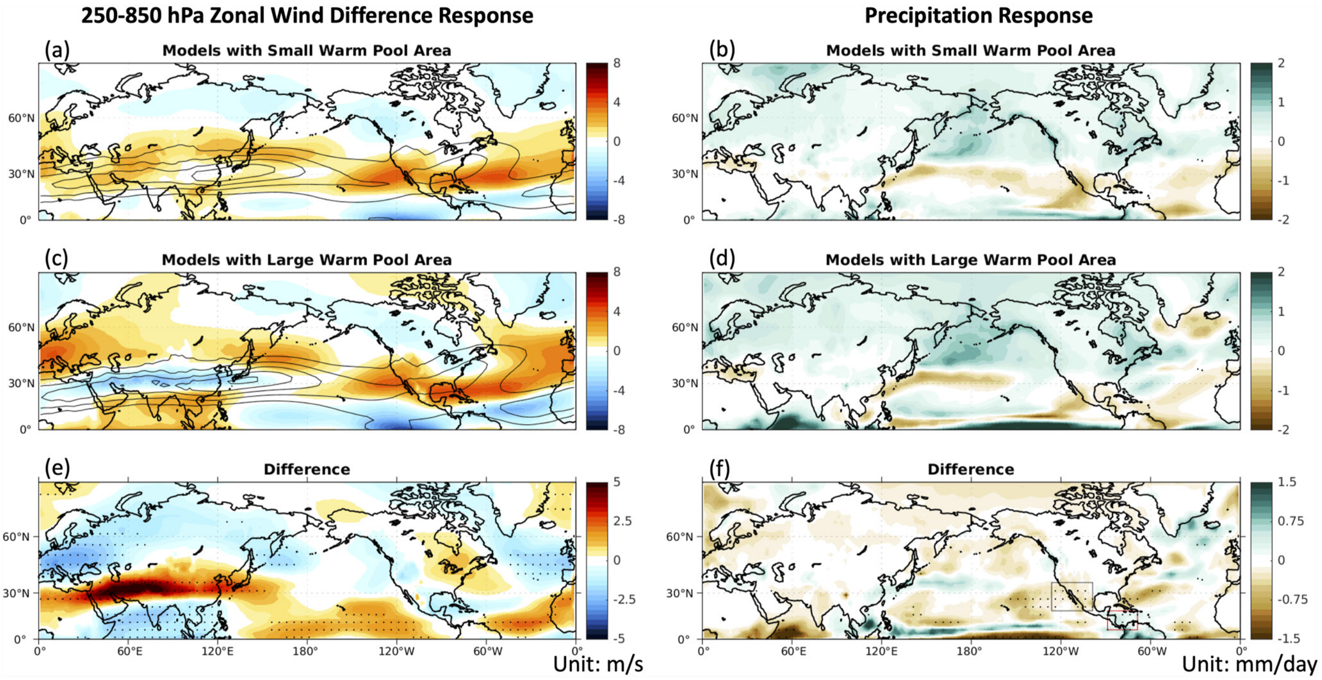

Figure 3. (Left column) Future response (2070–2099 climatology—1979–2014 climatology) of zonal wind difference field for small warm pool group (a), large warm pool group (c), and their difference (e) in phase 6 of the Coupled Model Intercomparison Project models. Black contours in (a) and (c) indicate the present-day climatology of the zonal wind difference field for the corresponding group (contours: 20, 30, 40, 50, and 60 m/s). (Right column) Same as the left column, but for the precipitation field. Stippling indicates that correlations between the climatological warm pool area and zonal wind difference/precipitation response fields across all 40 models are statistically significant at the 95% level according to a two-tailed Student's *t* test.

3.3. Implications for the Subtropical Jet and Precipitation in a Future Climate

We next assess whether CMIP6 models' warm pool area bias in the present-day climate impacts their 21st century projections of the NH wintertime STJ and precipitation under climate change. First, we note that the influence of the models' warm pool size bias on their representation of the NH wintertime STJ and precipitation in the present-day climate (Figure 2) largely persists in the models' climatology of the late 21st century (2070–2099) (Figure S6 in Supporting Information S1). However, while Figure 2 and Figure S6 in Supporting Information S1 are very similar, there are subtle differences between the two figures, suggesting that the climate change signal may be different in the small and large warm pool group of models (see also Figure 1d). To investigate this, Figure 3 shows the 21st century responses of the 250–850 hPa zonal wind difference and precipitation fields for both the small warm pool group and the large warm pool group, highlighting regions where the influence of the models' warm pool size bias changes over the 21st century, not regions where the same climatological biases persist in the presence of climate change (Figure 2 and Figure S6 in Supporting Information S1).

As shown in Figures 3a, 3c, and 3e, models with smaller climatological warm pool areas tend to expand more in the future (Figure 1d), making the Asian and Atlantic STJ weaken less or even strengthen in response to climate change. These relationships are consistent with the regression patterns shown in Figure S1 in Supporting Information S1, which show that a strengthening of the Asian/Atlantic STJ under climate change is associated with enhanced tropical convection (suppressed OLR) over the warm pool region.

Scatter plots of these relationships between the present-day warm pool and the future responses of the Asian and Atlantic STJ across all 40 CMIP6 models are shown in Figures 4a and 4b. The results reveal that models with present-day warm pool areas more consistent with observations (filled dots in Figure 4a) are less likely to project future strengthening of the Asian STJ. However, for the Atlantic STJ, although the relationship between the present-day warm pool area and the future response of the Atlantic STJ in CMIP6 models is statistically significant, models with present-day warm pool areas more consistent with observations (filled dots in Figure 4b) are not able to reduce the range of uncertainty in future projections of the Atlantic STJ. Inter-model standard deviations before and after constraining also show that the warm pool size biases in CMIP6 models are useful

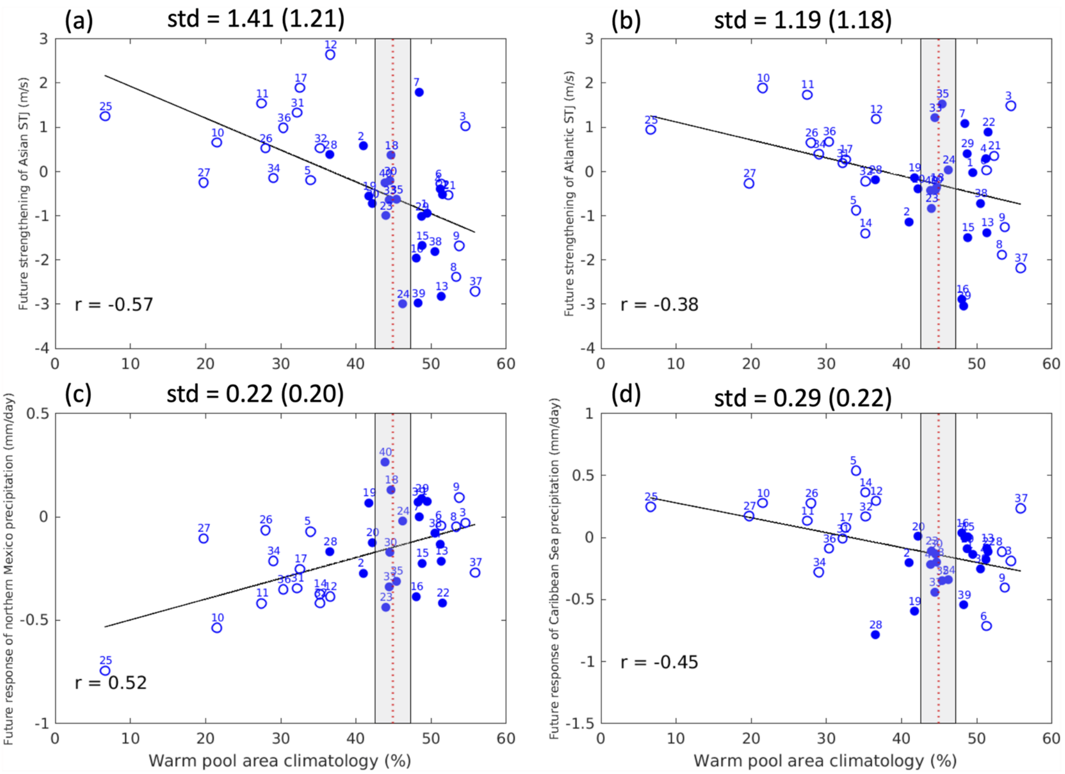

Figure 4. Emergent constraints for future responses of Asian subtropical jet (STJ) strength ((a) STJ strength averaged over 50°E–130°E) and Atlantic STJ strength ((b) STJ strength averaged over 80°W–0°). Emergent constraints for future responses of precipitation near Mexico Coast (c) and Caribbean Sea (d) (gray and red boxed regions in Figure 3, respectively). Red dashed line: HadISST warm pool area. Gray shading: Month-to-month standard deviation in observed warm pool area. Numbers on the scatterplot correspond to models listed in Table S1 in Supporting Information S1. Filled dots denote models whose climatological warm pool area with ±1 standard deviation falls in the gray shading. For each panel, inter-model standard deviations are displayed at top before (after) constraining.

for constraining the future response of the Asian STJ strength (standard deviation decreases by 14%) but not the Atlantic STJ strength (standard deviation decreases by 0.8%).

To confirm that these relationships can be used as emergent constraints, plausible physical explanations behind them are necessary. In response to climate change, the Rossby wave train downstream of the warm pool generally weakens (Figure S3 in Supporting Information S1), and this weakening is more pronounced in the models with larger present-day warm pool area (i.e., those that had stronger Rossby wave trains in the present-day climate, as discussed in Section 3.2). In models with large present-day warm pool area, the substantial weakening of the climatological region of lower geopotential heights over East Asia and the West Pacific is associated with future weakening of the Asian STJ (Figures 3c and 4a). Similarly, over the Atlantic, the eddy geopotential height weakens with climate change (and more so in the large warm pool group). In the subtropical Atlantic, the response area is more confined to the east and is smaller in the small warm pool group (Figures S3c and S3f in Supporting Information S1), consistent with the Atlantic STJ weakening less on average in these models (Figure 4b).

As for the precipitation response, models with smaller present-day warm pool areas tend to have a larger future drying response in northern Mexico (gray boxes in Figure 3f, and Figure S5b in Supporting Information S1) and less future drying over Central America and the western Caribbean Sea (red boxes in Figure 3f, and Figure S5b in Supporting Information S1). Scatter plots of these relationships are shown in Figures 4c and 4d, revealing that models with present-day warm pool areas more consistent with observations (filled dots in Figure 4) are less likely to project substantial future drying in northern Mexico and wetting over Central America and the western Caribbean Sea. Inter-model standard deviations before and after constraining decrease by 9% (Figure 4c) and 24% (Figure 4d).

The precipitation response in northern Mexico is consistent with the weakening of the climatological Rossby wave train response with climate change (Figure S3 in Supporting Information S1), which is more pronounced in those models with larger present-day warm pool areas. Consequently, geopotential heights over southern North America decrease less in the future climate in the small warm pool group (Figure S3, right column in Supporting Information S1), which contributes to the greater drying response in northern Mexico (gray box in Figure 3f). The precipitation response over Central America and the western Caribbean Sea is consistent with the weakening of the Pacific Walker circulation with climate change (Vecchi & Soden, 2007). Because the Pacific Walker circulation was initially stronger in models with larger present-day warm pool areas (Figure S4a in Supporting Information S1), a weakening of the Walker circulation in these models produces more anomalous ascent in the eastern tropical Pacific and compensating anomalous descent further eastward over Central and tropical South America (Figure S4c in Supporting Information S1). Consequently, the climatological ascent associated with the Atlantic Walker circulation remains stronger in a future climate in the small warm pool group of models (Figure S4b in Supporting Information S1), allowing for future precipitation increases at these longitudes.

4. Summary and Discussion

In this study, we examined the bias in Indo-Pacific warm pool area in CMIP6 models and its implications for the NH wintertime STJ and precipitation in both present-day and future climates. Compared to observations, the CMIP6 multi-model-mean reproduces the warm pool size well (Figure 1c), but there is huge inter-model spread in the warm pool size (Figure 1d). In the present-day climate, models with smaller warm pool areas (more biased models) tend to simulate a weaker West Pacific and Atlantic STJ and more precipitation over the northwestern United States and the tropical West Atlantic (Figure 2). In response to climate change, those biased models with smaller climatological warm pool areas generally tend to simulate strengthening (or less weakening) of the Asian and Atlantic STJ, larger decreases in precipitation over northern Mexico, and increases in precipitation over Central America and the western Caribbean Sea (Figure 3). Based on these relationships, we propose four emergent constraints to constrain the future responses of the Asian/Atlantic STJ strength and the precipitation over northern Mexico and the Caribbean Sea by ruling out those models which do not simulate a reasonable present-day warm pool size (Figure 4). Our results show that warm pool size in the present-day climate can help to constrain the future projections of Asian STJ strength, precipitation over northern Mexico, and precipitation over Central America and the western Caribbean Sea. However, a robust emergent constraint for the Atlantic STJ strength could not be established. If we use a zonal contrast index (difference in SST between the equatorial eastern and western Pacific) instead of our warm pool area index, we note that the results are qualitatively similar in the regions highlighted above. Nonetheless, we acknowledge that the choice of index impacts the magnitudes as well as results in other regions (such as the tropical Pacific), which are not the focus of this study (not shown).

It is also worth noting that the warm pool size bias in CMIP6 models produces symmetric impacts in SH winter. In the climatology for the SH winter (JJA), the Pacific STJ is stronger in the large warm pool group, similar to the NH winter response (Figure S7, left column in Supporting Information S1). For the precipitation field, models with a smaller warm pool tend to simulate more precipitation along the southwest coast of South America (Figure S7, right column in Supporting Information S1), which is also roughly at the same latitude as the precipitation signal over the northwestern United States in NH winter. In the future response for the SH winter (JJA), the Asian STJ strengthens more in the small warm pool group (analogous to what is seen in NH winter), and there are larger decreases in precipitation in the small warm pool group along the west coast of South America (analogous to what is seen in Mexico) (Figure S8 in Supporting Information S1). These interesting symmetric features in the two hemispheres give us more confidence that the warm pool size biases in CMIP6 models are useful for constraining future projections of the STJ and midlatitude precipitation.

In conclusion, our study provides insights on constraining future projections of the STJ and precipitation using the warm pool size in the present-day climate, suggesting that an accurate model simulation of the Indo-Pacific warm pool in the present-day climate is important for future projections of the STJ and precipitation.

Data Availability Statement

CMIP6 model output is freely available from the Lawrence Livermore National Laboratory (https://esgf-node.llnl.gov/search/cmip6/). CMIP6 models used in this study are listed in Table S1 in Supporting Information S1. ERA5 reanalysis data are freely available from the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2019; https://doi.org/10.24381/cds.6860a573).

HadISST data are freely available from Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadisst/). Monthly precipitation datasets are freely available from NOAA Physical Sciences Laboratory (https://psl.noaa.gov/data/gridded/data.gpcp.html).

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