

CMIP6 Model Biases in Antarctic Stratospheric Vortex Dynamics and Their Implications for Southern Hemisphere Circulation Projections

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(Manuscript received 13 February 2026, in final form 5 May 2026, accepted 26 May 2026)

ABSTRACT: The springtime variability of the stratospheric polar vortex over Antarctica is an important source of predictability for the Southern Annular Mode (SAM) and associated Southern Hemisphere (SH) regional climate anomalies in austral spring–summer seasons. Variations in the Antarctic spring vortex often result from anomalous meridional shifts of the SH winter stratospheric jet maximum near the stratopause and associated wave–mean flow feedback. In this study, we evaluate 1) the ability of the models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) under historical forcings to simulate the observed dynamical chain of processes linking wintertime upper-stratospheric vortex anomalies to springtime surface climate anomalies; and 2) the influence of this ability on future projections of the SH stratospheric vortex and SAM under the highest greenhouse gas emission scenario [shared socioeconomic pathway (SSP) 5-8.5]. Our results show that many CMIP6 models are deficient in reproducing the observed dynamical evolution of SH vortex anomalies, mainly due to a systematic poleward bias in the mean position of the SH winter stratospheric jet maximum. These biases appear to significantly influence projected changes in the stratospheric zonal circulation and the associated SAM by the end of the twenty-first century. Therefore, model deficiencies in simulating the correct position of the SH winter stratospheric jet near the stratopause and the dynamical evolution of its anomalous meridional shift to a spring polar vortex strength anomaly constitute a key source of uncertainty in projections of the SAM and associated SH climate changes in austral spring.

SIGNIFICANCE STATEMENT: The Southern Annular Mode (SAM) is the leading mode of extratropical circulation variability in the Southern Hemisphere (SH) and significantly influences SH regional climate, ocean circulations, and Antarctic sea ice variations. Austral spring SAM variability is substantially driven by the SH springtime stratospheric polar vortex variability, which often follows anomalous meridional shifts of the preceding winter stratospheric jet and associated wave–mean flow interactions. We show that many climate models do not accurately simulate these stratospheric processes largely due to a systematic poleward bias in the mean position of the SH winter stratospheric jet maximum. These model deficiencies appear to be a key source of uncertainty in future projections of the SAM and associated SH climate changes in austral spring.

KEYWORDS: Antarctic Oscillation; Stratospheric circulation; Stratosphere-troposphere coupling; Climate change; Climate models; Model evaluation/performance

1. Introduction

In the Southern Hemisphere (SH), the stratospheric westerly vortex (commonly known as the polar vortex; e.g., Manney et al. 2022) generally starts to develop in austral autumn and peaks in winter with the jet maximum in the 40°–50°S latitude band near the stratopause at about the 1-hPa level [contours in Figs. 1a–d; adapted from Fig. 4 in Lim et al. (2018)]. It then gradually weakens in spring, becoming susceptible to vigorous interactions with planetary-scale waves propagating upward from the

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

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JCLI-D-26-0097.s1>.

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DOI: 10.1175/JCLI-D-26-0097.1

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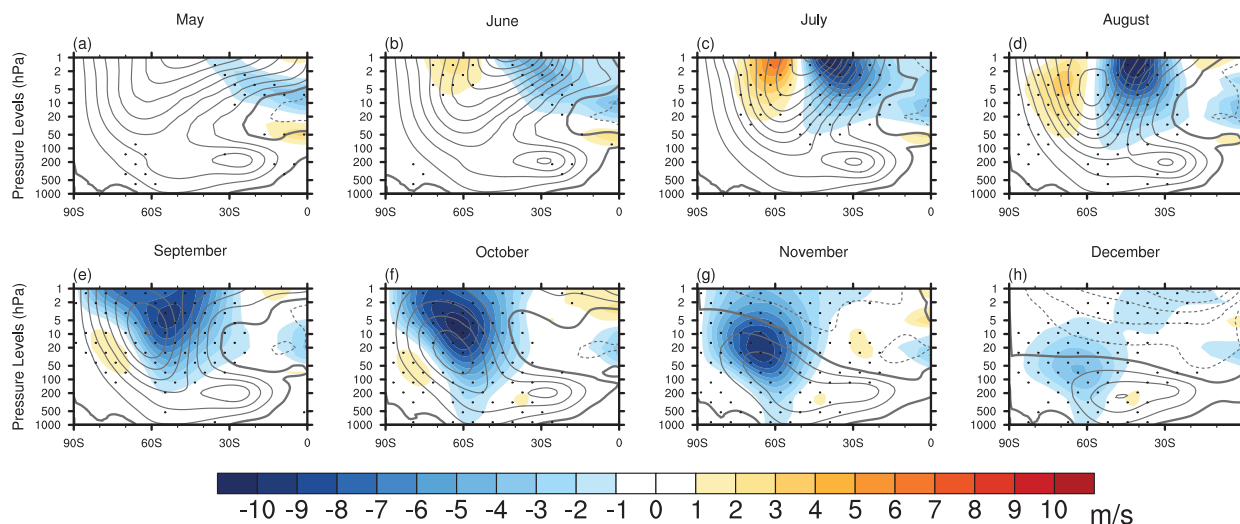


FIG. 1. Seasonal evolution of the SH stratospheric climatological mean zonal wind and anomalies associated with springtime polar vortex weakening [adapted and modified from Fig. 4 of Lim et al. (2018)]. Contours indicate climatological monthly mean zonal-mean zonal wind for 1979–2024. Color shading indicates regression coefficients of zonal-mean zonal wind anomalies onto the standardized and inversely signed spring polar vortex index for 1979–2024. Data are displayed as a function of pressure level (ordinate) and latitude (abscissa). Panels progress from (a) May to (h) December. Wind data are from the ERA5 (Hersbach et al. 2020) with 2000–06 data replaced by ERA5.1 (Simmons et al. 2020). The spring polar vortex index used for the regression was constructed from the September to November mean zonal-mean zonal winds at 60°S and 10 hPa over 1979–2024 (Seviour et al. 2014). The sign of the index was inverted to display the zonal-mean zonal wind changes associated with anomalous stratospheric polar vortex weakening. The regression coefficients are in the unit of meters per second per one standard deviation change of the index. The stippling indicates statistical significance of the regression at the 10% level, as estimated by a two-tailed Student's t test with 46 samples.

upper troposphere/lower stratosphere and equatorward in the upper stratosphere (e.g., Kuroda and Kodera 1998; Hio and Yoden 2005). These wave–mean flow interactions cause the vortex to contract toward the pole and move downward, resulting in its further weakening and warming through spring (Andrews et al. 1987; contours in Figs. 1d–g). The stratospheric polar vortex then completely breaks down in the upper to midstratosphere by late November–early December (e.g., Black and McDaniel 2007; Byrne and Shepherd 2018; Butler and Domeisen 2021; contours in Fig. 1h).

Interannual variability in the SH stratospheric polar vortex is dominated by variability in the pace of the seasonal evolution of the vortex (e.g., Hio and Yoden 2005; Byrne and Shepherd 2018). A faster-than-usual evolution is characterized by anomalous stratospheric polar vortex weakening and warming in spring, typically leading to an earlier-than-normal vortex breakdown (i.e., earlier transition of the polar vortex to its easterly summertime state) (blue shading in the regression patterns in Figs. 1e–h). Such anomalous polar vortex weakening in spring and early summer often follows an anomalous winter vortex contraction toward the South Pole, which is depicted by an anomalous poleward shift of the winter stratospheric jet in the upper stratosphere (i.e., weaker westerlies in the midlatitudes and stronger westerlies in the high latitudes than the climatological mean conditions; see color shading in Figs. 1b–d) (e.g., Shiotani et al. 1993; Kuroda and Kodera 1998; Gray et al. 2005; Lim et al. 2018). A poleward shift of the upper stratospheric jet in winter can promote anomalous upward and equatorward propagation

of planetary-scale waves, which positively feeds back to the poleward shift of the jet by depositing westerly momentum on the poleward side of the jet (as waves propagate equatorward in the upper stratosphere) and easterly momentum on the equatorward side of the jet (as waves break at the critical latitudes) (e.g., Lim et al. 2026). As the season transitions into spring, this anomalous positive feedback operates on weaker background zonal winds with the mean stratospheric jet shifting poleward and downward compared to winter (contours in Figs. 1e–g). Waves therefore break at lower levels and in higher latitudes in spring than in winter, resulting in easterly anomalies dominating in the mid- to high latitudes in the upper stratosphere. Meanwhile, meridional dipole anomalies of zonal winds in the high latitudes in the mid- to lower stratosphere move further poleward and downward from September to December (color shading in Figs. 1e–h) (e.g., Randel and Newman 1998; Shepherd 2000; Polvani and Waugh 2004; Newman and Nash 2005; Lim et al. 2021).

These zonal wind anomalies and associated temperature anomalies during a spring polar vortex weakening event usually induce higher-than-normal Antarctic ozone concentration in the lower stratosphere, which positively feeds back to the wind and temperature anomalies (e.g., Stolarski et al. 2005; Hendon et al. 2020; Oh et al. 2022). The resulting wind and temperature anomalies in the lower stratosphere eventually couple down to the surface, possibly via lowering the tropopause and therefore adiabatically warming the troposphere in the Antarctic region (e.g., Lorenz and DeWeaver 2007; Tomassini et al. 2012; Baldwin et al. 2024). This coupling subsequently shifts the tropospheric jet equatorward, which is expressed as a negative

phase of the Southern Annular Mode (SAM; Thompson and Wallace 2000; Fogt and Marshall 2020; Fig. S1 in the online supplemental material) in spring and summer (e.g., Baldwin and Dunkerton 2001; Thompson et al. 2005; Byrne and Shepherd 2018; Lim et al. 2018).

The stratosphere-driven negative SAM has important implications for surface climate and its predictability in the SH, acting as a key driver of hot, dry, and thus wildfire-conducive weather conditions in eastern Australia, while promoting cold and wet conditions in Patagonia in the austral late spring–early summer seasons (e.g., Garreaud et al. 2013; Bandoro et al. 2014; Lim et al. 2018, 2019). Colder and drier conditions also extend across the Antarctic Peninsula and Weddell Sea region, with related warmer, wetter conditions over the Ross–Amundsen Sea sector (Lim et al. 2018; Domeisen and Butler 2020; Kwon et al. 2020), which are caused by a stratosphere-led weakening and eastward displacement of the climatological Amundsen Sea low (England et al. 2016). These changes significantly impact regional Antarctic sea ice anomalies during the melt season (Mezzina et al. 2025).

Conversely, a slower-than-usual seasonal evolution of the stratospheric vortex typically follows an equatorward shift of the winter stratospheric jet maximum near the stratopause and associated reduced upward-propagating wave activity fluxes, which lead to a strong and persistent polar vortex and associated lower-than-normal Antarctic ozone concentration in spring. These circulation and ozone anomalies tend to drive a positive phase of the tropospheric SAM that can cause regional climate anomalies of opposite sign to those associated with the negative SAM (e.g., Yook et al. 2022; Lim et al. 2024).

These dynamical processes from winter to summer comprise the leading mode of interannual variability of the vertically coupled circulation around Antarctica. This mode is captured by empirical orthogonal function (EOF) analysis (North et al. 1982) on monthly mean zonal-mean zonal wind anomalies around 60°S at all available vertical levels from 1000 to 1 hPa and explains about 45% of the total zonal-mean zonal wind variance (Lim et al. 2018; Figs. S1a,b). The sequence of the dynamical events from winter to summer from the top of the stratosphere to the surface provides long-lead predictability of anomalies of the spring polar vortex and subsequent SAM and SH regional climate (Fig. S1c; e.g., Lim et al. 2021, 2024). Therefore, an accurate simulation of these processes in general circulation models is critical for skillful seasonal forecasts of spring-to-summer climate anomalies and also for reliable projections of the future climate in the SH, the latter of which is the focus of this study. Accordingly, the aims of the study are (i) to evaluate the ability of the climate models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring et al. 2016) to simulate this dynamical evolution of an anomalous SH polar vortex state and its impact on the surface SAM and (ii) to assess how this model performance affects future projections of the polar vortex and associated SAM by the end of the twenty-first century.

2. Data and methodology

We assess 42 CMIP6 models and all their available ensemble members (a total of 153 runs) under historical forcings for the “present day” climate of 1979–2014 and under the shared

socioeconomic pathway (SSP) 5-8.5 forcings for the future climate of 2065–2100. The highest greenhouse gas (GHG) emission scenario was chosen to detect a clear signal from increasing GHG forcing in the future climate simulations, although this scenario is unlikely to be eventualized (O'Neill et al. 2016; Riahi et al. 2017; IPCC 2023). A list of available models and number of common ensemble members is given in Table S1. Of the 42 models analyzed, only nine employ interactive atmospheric chemistry schemes that allow for two-way ozone–climate feedbacks; in 30 of the remaining models, ozone is prescribed with the CMIP6 ozone forcing dataset or similar (Hegglin et al. 2021; Simpson et al. 2023), while the other three models use simplified ozone schemes that do not fully represent interactive chemistry.

For the observational analysis, we used the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) data (Hersbach et al. 2020), including the corrected 2000–06 data produced from rectifying inappropriate data assimilation during this period in ERA5 (ERA5.1; Simmons et al. 2020). We analyzed monthly mean zonal-mean zonal wind (U), geopotential height (Z), and mean sea level pressure (MSLP) data from the models and ERA5. To estimate vertically propagating wave activity fluxes (Andrews et al. 1987; Peixoto and Oort 1992), we computed northward eddy heat fluxes $v'T'$ at 100 hPa, averaged over 45°–75°S, using daily mean meridional wind v and temperature T data from ERA5 and 28 of the selected CMIP6 models with available daily v and T data for 1979–2014 (see Table S1). Eddies ($'$) were departures from the zonal mean. In the NH, positive eddy heat flux ($v'T'$; i.e., northward) denotes poleward heat transport, for which the associated geostrophic and hydrostatic balances are aligned with a westward tilt of Rossby wave phase with height, a necessary condition for upward propagation of wave activity. Conversely, in the SH, positively signed $v'T'$ indicates equatorward eddy heat flux (EEHF) and therefore reduced upward-propagating wave activity flux (i.e., reduced wave drag).

Throughout this paper, we use the stratospheric zonal-mean zonal winds at 60°S to represent the strength of the polar vortex and refer to the June–August (JJA) stratospheric polar vortex at 1 hPa as JJA_SPV_{1hPa}. The JJA_SPV_{1hPa} should be distinguished from the winter stratospheric jet maximum, which is found at the top of the stratosphere in the midlatitudes at ~1 hPa (i.e., the maximum contour in each of the first row panels in Fig. 1, whose latitude and height vary with the seasonal cycle). The position of the winter stratospheric jet maximum is identified for each month as the latitude of the maximum zonal-mean zonal wind poleward of 40°S at 1 hPa. The September–November (SON) stratospheric polar vortex winds at 10 hPa and 60°S are referred to as SON_SPV_{10hPa} (e.g., Seviour et al. 2014). The surface SAM was obtained from the difference in normalized zonal-mean MSLP anomalies between 40° and 65°S, following the definition of Gong and Wang (1999). These diagnostics are summarized in Table 1.

All reanalysis and model data for the historical period were detrended to remove linear long-term trends driven by the shift of the interdecadal Pacific oscillation (Power et al. 1999) from a positive phase in the 1980–90s to a negative phase in the 2000–20s (e.g., Kosaka and Xie 2013; Yang et al. 2020) and/or increasing GHG concentrations (Eyring et al. 2021). We

TABLE 1. Diagnostics of Antarctic vortex dynamics and its downward coupling. The overbar denotes the time mean, and square brackets denote the zonal mean. The prime denotes departures from the zonal mean. The u , v , T , and MSLP represent zonal wind, meridional wind, temperature, and mean sea level pressure, respectively. The n denotes normalization by the standard deviation.

Diagnostic		Description	Mathematical notation
Winter stratospheric jet maximum	June–August maximum speed of zonal-mean zonal winds poleward of 40°S at 1 hPa		$\overline{[u_{max}]}_{1hPa}$
JJA_SPV _{1hPa}	June–August mean stratospheric polar vortex at 60°S and 1 hPa		$\overline{[u]}_{60^{\circ}S, 1hPa}$
JJA_EEHF _{100hPa}	June–August mean zonal-mean equatorward eddy heat flux averaged over 45°–75°S at 100 hPa		$\overline{[v'T']}_{45^{\circ}-75^{\circ}S, 100hPa}$
SON_SPV _{10hPa}	September–November mean stratospheric polar vortex at 60°S and 10 hPa		$\overline{[u]}_{60^{\circ}S, 10hPa}$
SON_SAM _{sfc}	September–November mean of the Southern Annular Mode index at the surface		$n[\overline{MSLP}]_{40^{\circ}S} - n[\overline{MSLP}]_{65^{\circ}S}$

then examined projected changes in zonal-mean zonal wind, temperature, and MSLP by calculating the mean difference in the raw fields between the late twenty-first century (2065–2100) and the historical period (1979–2014). Note, however, that our evaluation results are not sensitive to whether we retain the trend over the historical period or not. We also tested the effect of Antarctic ozone depletion in the 1980–90s and its recovery since 2000 on the variabilities of the observed indices by linearly removing the components associated with Antarctic equivalent effective stratospheric chlorine (EESC) (Engel et al. 2018; data courtesy of Doctor Paul Krummel at CSIRO). Although the impacts of the Antarctic ozone hole trends over these periods on the trends in SH polar vortex strength, vortex breakdown timing, and the surface SAM in austral late spring and summer seasons have been well known (e.g., Thompson et al. 2011; Banerjee et al. 2020; Zambri et al. 2021), the ozone hole trends had a minimal influence on the variabilities of the winter and spring polar vortex and heat flux diagnostics and the spring SAM over 1979–2024 in the ERA5 data (not shown).

Linear regression and Pearson correlations are used for the statistical analysis, with significance assessed using a two-tailed Student's t test and by bootstrapping years with replacement and recomputing the correlation 1000 times. The difference in projected changes between subsets of models is evaluated with a two-tailed Welch t test.

3. Results

a. Quantifying dynamical processes associated with a vortex anomaly in ERA5

To set benchmarks for the model evaluation of dynamical processes involved in a SH vortex anomaly, we first quantify the chain of processes discussed in the introduction by computing correlations between the diagnostic indices that monitor variations of the stratospheric and tropospheric circulations and wave activity fluxes using the reanalysis data. Hereafter, we will present results associated with a spring polar vortex weakening, without repeating the corresponding opposite-signed results for a strong and persistent spring polar vortex (e.g., Yook et al. 2022; Lim et al. 2024).

1) STRATOSPHERIC PROCESSES

As discussed in the introduction, an anomalous poleward shift of the winter stratospheric jet near the stratopause,

which is captured by an increase in zonal-mean zonal winds at 60°S and 1 hPa (i.e., a positive amplitude of the JJA_SPV_{1hPa} index; hereafter JJA_SPV_{1hPa}), can be a precursor of anomalous spring polar vortex weakening, as observed in the two most extreme SH stratospheric vortex weakening and warming events in 2002 and 2019 (e.g., Nishii and Nakamura 2004; Scaife et al. 2005; Lim et al. 2021). The JJA zonal wind anomalies regressed onto JJA_SPV_{1hPa} (time series displayed in Fig. S2a) show a poleward shift of the zonally averaged upper-stratospheric jet, indicating a contraction of the winter vortex toward the South Pole (Fig. 2a). Zonally symmetric meridional shifts of the winter stratospheric jet maximum are, in fact, depicted by the leading EOF mode of zonal wind variability poleward of 20°S at 1 hPa, which explains 66% of the winter variance (Fig. S3a; also Lim et al. 2026).

The JJA_SPV_{1hPa} is significantly anticorrelated with the time series of the JJA equatorward eddy heat fluxes averaged over 45°–75°S and measured at 100 hPa (JJA_EEHF_{100hPa}; Fig. S2b) at -0.55 for the period 1979–2024, confirming the notion that the background westerly flow must fall within a specific range of speeds for planetary-scale waves to propagate vertically (Charney and Drazin 1961; Matsuno 1970). A poleward shift of the winter stratospheric jet maximum satisfies this requirement and allows more waves to propagate upward into the upper stratosphere, which is represented by decreased equatorward eddy heat fluxes (i.e., increased poleward eddy heat fluxes) at 100 hPa. The midstratospheric eddy geopotential height anomalies associated with the decreased JJA_EEHF_{100hPa} ($v'T' < 0$ in the SH) show a clear wave-1 pattern, which is a typical wave scale that propagates into the stratosphere (Fig. 2b; e.g., Randel 1988). Year-to-year variations of JJA_EEHF_{100hPa} are then positively correlated with those of SON_SPV_{10hPa} (Fig. S2c) at 0.6 for the same 46-yr period. This suggests that reduced equatorward eddy heat fluxes (i.e., enhanced poleward eddy heat fluxes and upward-propagating wave activity) in winter tend to weaken the polar vortex in spring, when the background westerlies are weaker than those in winter and therefore vertically propagating waves encounter a critical layer at lower levels (e.g., Matsuno 1971; Randel and Newman 1998; Baldwin et al. 2021; Fig. 2c). Consequently, a poleward shift of the winter stratospheric jet maximum at 1 hPa (positive JJA_SPV_{1hPa}) tends to lead to weakening of the spring polar vortex (negative SON_SPV_{10hPa}) ($r = -0.47$), as demonstrated in Fig. 1. These correlations between the diagnostic indices are tabulated in Fig. 3.

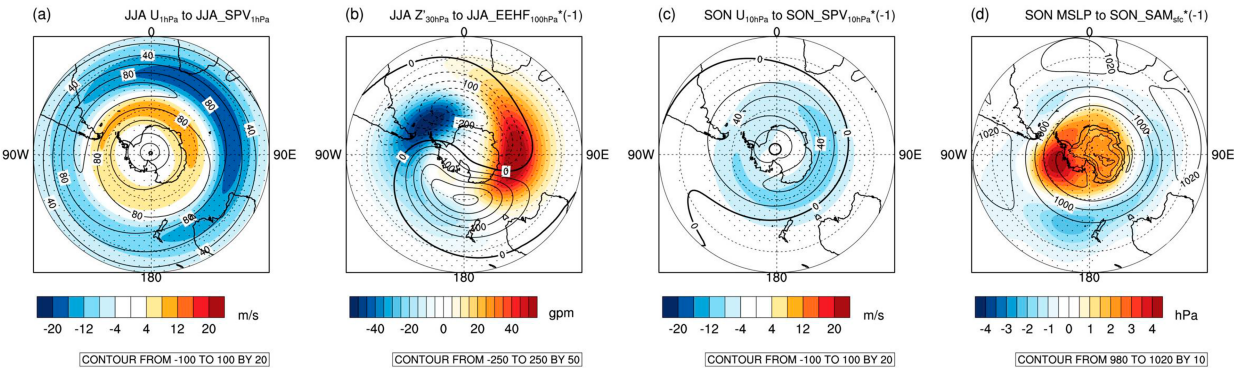


FIG. 2. Regression patterns of ERA5 (a) JJA zonal winds (U) at 1 hPa onto JJA_SPV_{1hPa}, (b) JJA eddy geopotential height (Z') at 30 hPa onto sign-inverted JJA_EEHF_{100hPa}, (c) SON U at 10 hPa onto sign-inverted SON_SPV_{10hPa}, and (d) SON MSLP onto sign-inverted SON_SAM_{sfc} obtained over 1979–2024 (color shading). The panels are ordered to reflect the temporal progression of dynamical processes from JJA to SON. The signs of the JJA_EEHF_{100hPa}, SON_SPV_{10hPa}, and SON_SAM_{sfc} indices were inverted to display the circulation anomalies following a poleward shift of the winter stratospheric jet maximum at 1 hPa shown in (a). Contours show climatological means, and stippling indicates statistical significance at the 10% level with 46 samples.

2) STRATOSPHERE–TROPOSPHERE COUPLING

Next, weaker SON_SPV_{10hPa} is highly correlated with the negative phase of the surface SAM (Fig. 2d) in the same season (SON_SAM_{sfc}; Fig. S2d) at 0.73 for 1979–2024 (Fig. 3). The significant correlation between SON_SPV_{10hPa} and the surface SAM lasts until the following summer (Fig. S4), stressing that an anomalous springtime polar vortex condition is an important predictor of the SH surface climate variations in austral warm seasons, in agreement with the wider literature (e.g., Thompson et al. 2005; Son et al. 2013; Seviour et al. 2014; Byrne and Shepherd 2018; Ceppi and Shepherd 2019; Mindlin et al. 2021; Rao and Garfinkel 2021; Breul et al. 2022).

This chain of processes leads to statistically significant correlation between JJA_SPV_{1hPa} and SON_SAM_{sfc} of -0.47 . It is worth mentioning that JJA_SPV_{1hPa} and JJA_EEHF_{100hPa} are more correlated with SON_SAM_{sfc} (-0.47 and 0.60 , respectively) than with the concurrent JJA_SAM_{sfc} (-0.33 and 0.26 , respectively). These results suggest that weaker stratospheric background zonal winds in spring should be an important contributor to the downward coupling of the stratospheric vortex anomalies by setting the critical layer poleward and downward for the wave–mean flow feedback (e.g., Lim et al. 2026). Thus, the lagged relationships from a poleward-shifted winter stratospheric jet at the top of the stratosphere (i.e., a contracted winter vortex) to a weaker spring polar vortex and ultimately to a negatively phased SAM at the surface provide long-lead predictability of the surface SAM and associated SH surface climate anomalies in austral spring and early summer (e.g., Lim et al. 2018; Li and Strode 2025).

We have repeated the same correlation analysis for 1979–2014 to enable a direct comparison with the model historical simulations presented in the next subsection. The correlation coefficients for this 36-yr period (lower-left boxes in Fig. 3) closely match those for the extended 46-yr period through 2024 (upper-right boxes in Fig. 3), confirming that these dynamical relationships are robust through different time periods. It is also worth noting that the relationships presented here are not sensitive to

whether a linear trend and/or the trend associated with the EESC is removed from these indices or not. Moreover, although the relationships weaken slightly when the extreme stratospheric vortex weakening and warming events in 2002 and 2019 are excluded, they remain statistically significant (not shown).

Given that these correlations effectively capture the dynamics of the anomalous vortex evolution from winter to spring in the reanalysis, how well do the state-of-the-art climate models reproduce these relationships?

1979–2024	JJA_SPV _{1hPa}	JJA_EEHF _{100hPa}	SON_SPV _{10hPa}	SON_SAM _{sfc}
1979–2014				
JJA_SPV _{1hPa}	1.0	-0.55	-0.47	-0.47
JJA_EEHF _{100hPa}	-0.54	1.0	0.60	0.42
SON_SPV _{10hPa}	-0.48	0.54	1.0	0.73
SON_SAM _{sfc}	-0.44	0.39	0.71	1.0

FIG. 3. Correlation coefficients capturing dynamics of the anomalous vortex evolution, using the ERA5 reanalysis data. Correlations on the right-hand side of the diagonal cells were computed over 1979–2024, whereas those on the left-hand side were computed over 1979–2014 and are used as benchmarks for the model evaluation over this common historical period. The $|0.29|$ and $|0.33|$ correlation coefficients are statistically significant at the 5% level, given 46 and 36 independent samples, respectively, as estimated by a two-tailed Student’s t test. Cell shading represents correlation magnitude, with color intensity increasing for stronger correlations.

b. Model simulations of the observed relationships

In stark contrast to the reanalysis that shows a significant negative correlation between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{SON_SPV}_{10\text{hPa}}$ (Fig. 3), the majority of the 42 CMIP6 models simulate significant positive ensemble-mean correlations over 1979–2014, with a multimodel mean (MMM) correlation of 0.24 (Fig. 4a). Most individual model means fall well outside the observational uncertainty range (indicated by the gray line overlaid on the black bar). However, seven models (ACCESS-ESM1-5, EC-Earth3, EC-Earth3-CC, EC-Earth3-Veg, INM-CM5-0, MIROC6, and MPI-ESM1-2-HR) do simulate negative ensemble-mean correlations, though they substantially underestimate the magnitude compared to ERA5 with only one member exhibiting a correlation as high as observed (Fig. 4a). We hereafter refer to these seven models as “blue models” and the remaining models as “red models.” Note that none of these blue models include interactive stratospheric ozone chemistry schemes, which suggests (to first order) that the ability of models to capture this relationship is not due to their treatment of ozone. Nevertheless, the substantial underestimation of the anticorrelation strength between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{SON_SPV}_{10\text{hPa}}$ in the blue models could partly reflect the lack of positive feedback between the stratospheric circulation and ozone during late winter and spring (e.g., Hendon et al. 2020).

Among the 28 models with available daily data, 21 models simulate unrealistic positive correlations between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{JJA_EEHF}_{100\text{hPa}}$, indicating that increased JJA polar vortex wind speeds at 60°S in the upper to midstratosphere (positive $\text{JJA_SPV}_{1\text{hPa}}$) are linked to reductions in upward-propagating wave activity fluxes represented by positive $\text{JJA_EEHF}_{100\text{hPa}}$ (i.e., $v'T' > 0$ in the SH), contrary to the observed relationship. Only seven models simulate the observed negative correlation between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{JJA_EEHF}_{100\text{hPa}}$ (Fig. 4b), with substantial underestimations in ~70% of associated runs. Of these seven models, only two (~30% of runs) reproduce a correlation magnitude within the ERA5 uncertainty bounds, with six runs from ACCESS-ESM1-5 and FGOALS-g3 overestimating the relationship and falling in the upper bounds of this range.

On the other hand, most models correctly simulate the observed positive relationship between $\text{JJA_EEHF}_{100\text{hPa}}$ and $\text{SON_SPV}_{10\text{hPa}}$, with 80% of runs within the ERA5 uncertainty range (Fig. 4c). Therefore, it is the wintertime wave–mean flow feedback bias (between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{JJA_EEHF}_{100\text{hPa}}$) in many models that accounts for the evolution bias between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{SON_SPV}_{10\text{hPa}}$. This seemingly erroneous wintertime wave–mean flow feedback in most of the models is explained by the distinctively different regression patterns of zonal-mean zonal wind anomalies onto $\text{JJA_SPV}_{1\text{hPa}}$ in ERA5 and in the MMM (Fig. 5): While increases in winter vortex winds at 60°S at 1 hPa are associated with a poleward shift of the winter stratospheric jet maximum in ERA5, they are associated with an equatorward shift of the winter stratospheric jet maximum in the MMM, for which the climatological mean is erroneously located near 60°S (Figs. 5a,b). This equatorward shift of the winter stratospheric jet is then related to the quiescence of upward-propagating

wave activity, allowing the strong winter vortex to persist into spring in the MMM (Figs. 5e). In contrast, the blue-model mean appears to better simulate the observed poleward shift of the winter stratospheric jet maximum with the meridional dipole of zonal wind anomalies (Fig. 5c) and therefore reproduce the observed dynamical linkages among $\text{JJA_SPV}_{1\text{hPa}}$, $\text{JJA_EEHF}_{100\text{hPa}}$, and $\text{SON_SPV}_{10\text{hPa}}$, although the magnitudes of the model correlations are apparently weaker than those of the observed correlations (Figs. 4 and 5c,f).

In contrast to the strong model bias in the wintertime wave–mean flow feedback, models demonstrate better skill in reproducing the observed stratosphere–troposphere coupling with positive correlations between the polar vortex at 10 hPa and the surface SAM in spring (Fig. 4d). However, the correlation strength is notably underestimated (0.50 MMM correlation compared to 0.70 for ERA5). In addition, as mentioned in section 2, we tested these model relationships without linear detrending and after removing the observed EESC or the 5-yr running means, the latter of which could better capture Antarctic ozone depletion and recovery trends in individual models, and found no significant differences (Fig. S5).

To identify possible sources of the model errors in simulating upper-stratospheric processes, we examined the models' climatological jet positions during the historical period at 1 hPa, where the observed winter stratospheric jet maximum is found (e.g., Figs. 1b–d). Figure 6 shows that many models exhibit significant biases in the mean location of the winter jet, simulating, on average, a maximum near 55°S rather than near 45°S as in the reanalysis (thick black solid line in Fig. 6a). The MMM (thick black dotted line in Fig. 6a) shows 8.3° mean poleward shift in May–July relative to ERA5. This significant jet position bias appears to be dominantly attributable to the red models (Fig. 6a, thick dashed red line), which also simulate the erroneous positive relationship between the winter polar vortex at 1 hPa and the spring polar vortex at 10 hPa (Fig. 4a). In contrast, the blue models, which correctly capture the signs of the vortex evolution processes in the upper stratosphere, also more skillfully simulate the winter maximum jet location in the mid-latitudes (Fig. 6a, thick dashed blue line), with a bias, on average, of 3.8° or approximately half the magnitude of the winter MMM error. This relationship is further evidenced by a statistically significant intermodel correlation ($r = -0.64$) between the magnitudes of the models' mean winter maximum jet position biases and their misrepresentation of the dynamical evolution from $\text{JJA_SPV}_{1\text{hPa}}$ anomalies to $\text{SON_SPV}_{10\text{hPa}}$ anomalies (Fig. 6b). That is, models that displace the winter stratospheric jet maximum farther poleward than observed tend to produce stronger erroneous positive correlations between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{SON_SPV}_{10\text{hPa}}$, suggesting that the winter maximum jet position bias is an important source of the evolution bias in the variability of the SH polar vortex in these CMIP6 models.

As three of the seven blue models are the EC-Earth3 models, one may wonder whether this intermodel relationship is somewhat biased by a single model family. Our additional analysis confirms that the relationship between the winter jet position biases and the biases in the dynamical evolution of vortex anomalies is insensitive to the choice of models, whether we

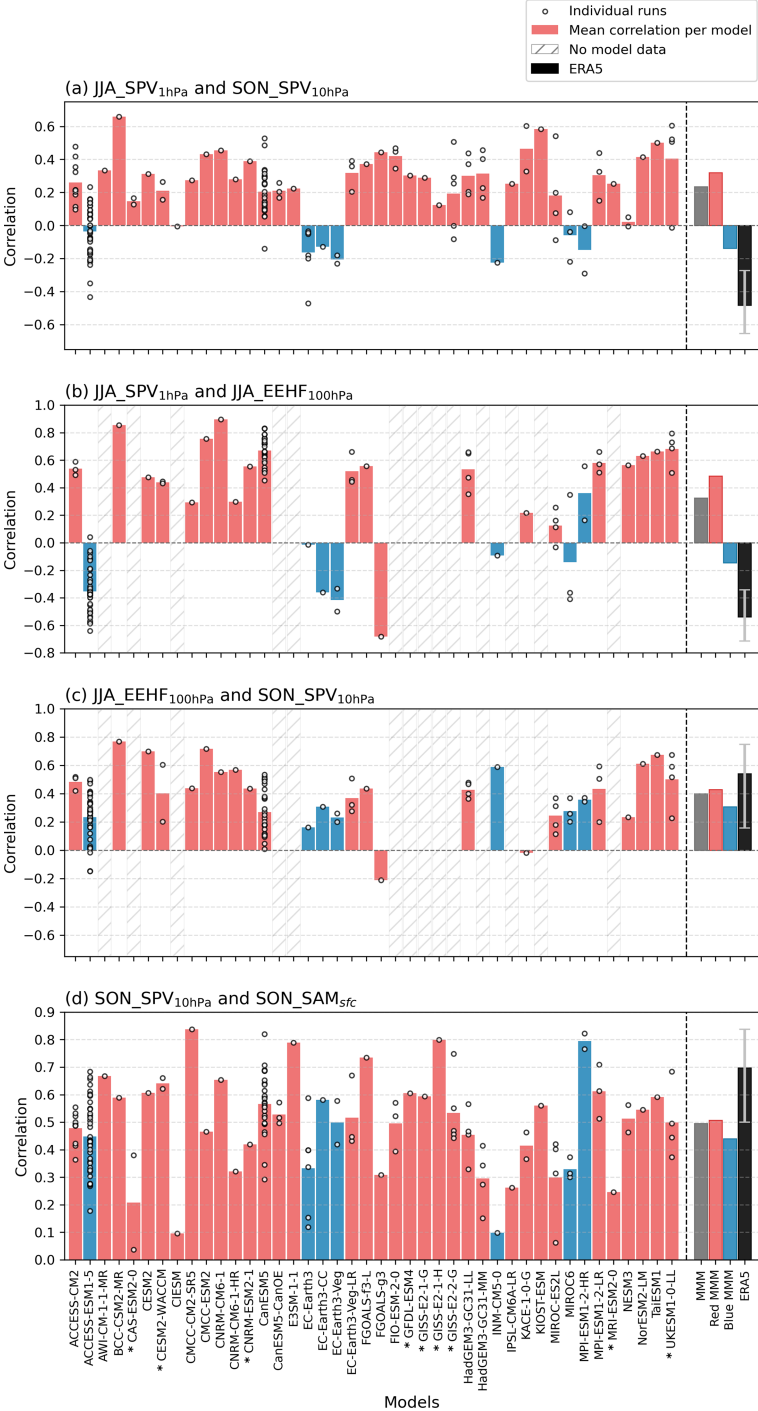


FIG. 4. Correlations between (a) JJA_SPV_{1hPa} and SON_SPV_{10hPa}, (b) JJA_SPV_{1hPa} and JJA_EEHF_{100hPa}, (c) JJA_EEHF_{100hPa} and SON_SPV_{10hPa}, and (d) SON_SPV_{10hPa} and SON_SAM_{sfc} over the 1979–2014 period. Individual ensemble members (circles) and model mean correlations (bars) are shown for each CMIP6 model over 1979–2014, with red and blue bars denoting “red” and “blue” model classifications, respectively [based on the sign of the associated mean correlation in (a)]. Right panels display the MIM correlation (gray), subset means across red and blue models (red and blue, respectively), and the ERA5 reanalysis correlation (black). The gray error line shows the 95% confidence interval of the ERA5 correlation estimated by bootstrapping the 36 years with replacement and recalculating the correlation 1000 times. Models that include an interactive chemistry scheme are marked with an asterisk.

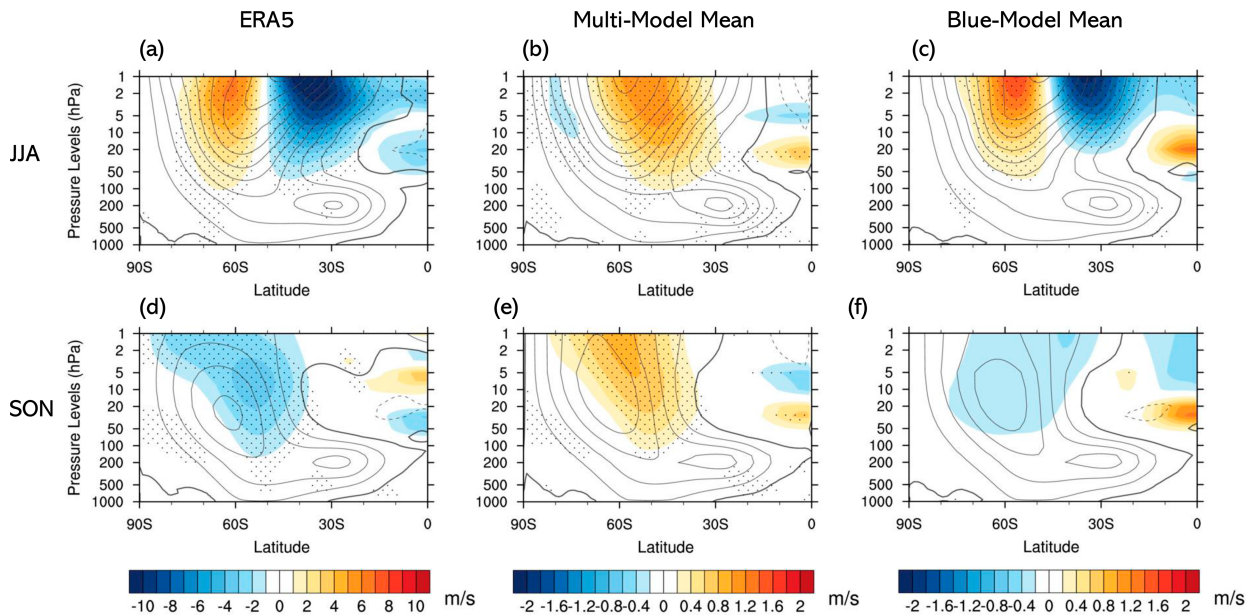


FIG. 5. Regression patterns of JJA and SON zonal-mean zonal wind anomalies onto standardized JJA_SPV_{1hPa} in (a),(d) ERA5, (b),(e) the MMM, and (c),(f) the blue-model mean over 1979–2014. Contours in each panel show the respective climatological mean winds. Thick contours indicate zero, and solid and dashed lines indicate westerlies and easterlies, respectively. Stippling denotes statistical significance of the regression at the 10% level, assessed by a two-tailed Student's *t* test, given 36 samples.

include all models, one representative model per family, or an ensemble mean across each family (not shown).

Regarding the position of the winter stratospheric jet maximum, its spatial structure and interannual variability are significantly influenced by gravity waves, as demonstrated in high-resolution simulations (e.g., Watanabe et al. 2008). However, the gravity wave parameterizations used in most climate models lack the lateral propagation effect of gravity waves (e.g., Sato et al. 2009, 2012) and gravity wave sources around 60°S (e.g., McLandress et al. 2012; Bramberger and Bacmeister 2025). The resultant insufficient gravity wave forcing generally causes a poleward bias in the SH winter stratospheric jet maximum (e.g., Garcia et al. 2017). MIROC6, one of the blue models, uses nonorographic gravity wave source constraints derived from a high-resolution simulation at 70 hPa (Watanabe 2008) and correctly simulates the location of the SH jet at the stratopause (Tatebe et al. 2019). Similarly, Bramberger and Bacmeister (2025) reported a substantial reduction in the poleward bias in the location of the SH winter stratospheric jet maximum by incorporating a new source of gravity waves into the parameterization scheme in a development version of the Community Atmospheric Model (CAM), version 7. Their new parameterization was designed to represent low-frequency gravity waves excited by frontal systems, which led to successful simulations of the tilt of the SH winter stratospheric jet from around 60°S in the midstratosphere to around 45°S at the top of the stratosphere and the strength of the polar vortex. These results suggest that improved gravity wave parameterizations could be critical for reducing winter stratospheric jet position biases in climate models.

To further understand whether planetary-scale resolved wave activity propagating from the lower stratosphere/upper

troposphere also contributes to the winter maximum jet position biases in our ensemble of CMIP6 models, we examined the climatological locations of the minimum magnitude of EEHF_{100hPa} (i.e., maximum magnitude of poleward eddy heat fluxes in the SH at 100 hPa) in the reanalysis and the models. The result shows that the climatological monthly mean locations of the minimum EEHF_{100hPa} in the MMM are equatorward-biased compared to that of the reanalysis especially during early spring from August to October (Fig. S6). It is notable that both blue and red models exhibit nearly identical seasonal cycles of the heat flux biases, and blue models appear to have somewhat larger biases in this metric. Therefore, these biases associated with resolved waves are unlikely to explain the difference in the winter maximum jet position between the blue- and red-model means (Fig. 6a), and hence are not a primary source of the winter jet position biases.

Given the close relationship between the winter jet position biases and the vortex evolution biases, one may also question whether the models' winter jet strength can affect its vortex evolution. The MMM tends to simulate a weaker stratospheric jet maximum than observed in early winter (May–June) but a stronger jet maximum in spring, with blue models again performing slightly better than the red models (Fig. 6c). However, the intermodel relationship between the jet strength biases and the anomalous vortex evolution biases is weak and not statistically significant ($r = 0.24$) (Fig. 6d).

c. Future projections for the SH polar vortex and its downward coupling

The findings of the previous subsection then raise a critical question: Does a model's ability to correctly simulate the mean

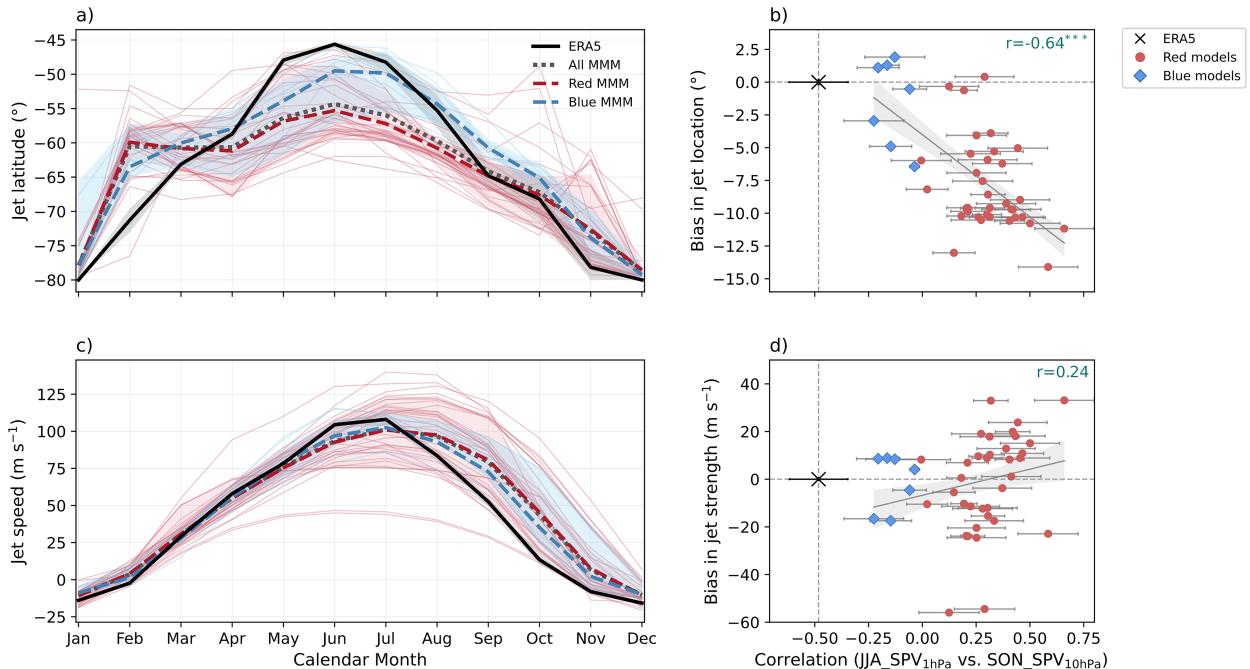


FIG. 6. Climatological upper-stratospheric jet position and strength and their wintertime relationships to biases in anomalous vortex evolution from winter to spring in the historical simulations (1979–2014). (a) Latitudes and (c) speeds of the upper-stratospheric monthly mean jet (i.e., locations and strengths of the maximum zonal-mean zonal wind at 1 hPa) for individual models (thin lines), the MMM across all models (thick dotted black line), the blue-model subset mean (thick dashed blue line), and the red-model subset mean (thick dashed red line). Red and blue shadings illustrate the ensemble spread for red and blue models, respectively. The ERA5 climatology is overlaid in thick black line, with the gray shading indicating the 95% confidence interval estimated via monthly bootstrap resampling (1000 iterations). Cross-model relationship between $\text{JJA_SPV}_{1\text{hPa}}$ – $\text{SON_SPV}_{10\text{hPa}}$ correlations (abscissa; from Fig. 4a) and (b) JJA jet position biases (ordinate) or (d) JJA jet strength biases (ordinate), both relative to ERA5. Error bars represent uncertainty due to internal variability following Simpson et al. (2021): standard deviations estimated from 1000 subsampled members from three representative large-ensemble models (ACCESS-CM2, ACCESS-ESM1-5, and CanESM5), scaled by each of the three models' ensemble size (Table S1). Note that the vertical error bars are not visible given their range from 0.03° to 0.20° in (b) and from 0.08 to 0.55 m s^{-1} in (d). Each dot represents one CMIP6 model (blue or red); the black X indicates ERA5. Thick gray lines show least squares best-fit relationships, with the cross-model correlation coefficient shown in the top-right corner of each panel. The three asterisks in (b) indicate the correlation being statistically significant at the 1% level according to a two-tailed Student's t test, given 42 samples.

position of the winter stratospheric jet maximum and the corresponding meridional dipole structure of the winter stratospheric jet anomalies and subsequent vortex evolution affect the model's projections of future polar vortex and SAM changes? To address this, we assessed the models' projected changes in zonal-mean zonal winds, temperatures, and MSLP from the historical period (1979–2014) to the end of the twenty-first century climate simulations (2065–2100) under the high SSP5-8.5 scenario, when increasing GHGs become the dominant external forcing, overtaking the effect of Antarctic ozone recovery (e.g., Fogt and Marshall 2020; Butler et al. 2026) (Figs. 7–9). As shown in Fig. 7a, the MMM of CMIP6 models projects extensive cooling in the mid- to upper stratosphere particularly over Antarctica, while projecting warming in the troposphere, which constitutes a well-established first-order response to increasing GHG forcing (e.g., Manabe and Wetherald 1975; Santer et al. 1996; Randel et al. 2009) (Fig. 7, left panels). Projected temperature changes are similar in spring except for the moderate but statistically significant warming in the lower stratosphere over Antarctica, which is presumably a signature of the recovery

of Antarctic ozone to 1980s historical levels by the mid-twenty-first century (e.g., Chipperfield et al. 2022; WMO 2022; Fig. 7b). Consequently, the SH winter stratospheric jet is projected to strengthen in the upper stratosphere and shift somewhat equatorward in the mid- to lower stratosphere, which appears to be linked to the strengthening of the SH tropospheric mid-latitude jet (Fig. 8a, e.g., Fyfe et al. 1999; Lu et al. 2008; Mindlin et al. 2020; Deng et al. 2022). Similar robust zonal-mean zonal wind changes are projected for spring (Fig. 8b). The SAM is projected to be more positive in all seasons by the end of the twenty-first century under high GHG emission scenarios (e.g., Miller et al. 2006; Lim et al. 2016; Purich et al. 2026), and this is confirmed for spring in Fig. 9a.

Interestingly, the blue models project notably different future changes from those of the red models. In comparison to the mean projection of all models (Fig. 8a), the blue-model mean projection indicates a stronger poleward shift of the winter stratospheric jet maximum (Fig. 8c). Given that the blue-model mean is able to simulate the negative correlation between $\text{JJA_SPV}_{1\text{hPa}}$ and $\text{SON_SPV}_{10\text{hPa}}$ during the historical

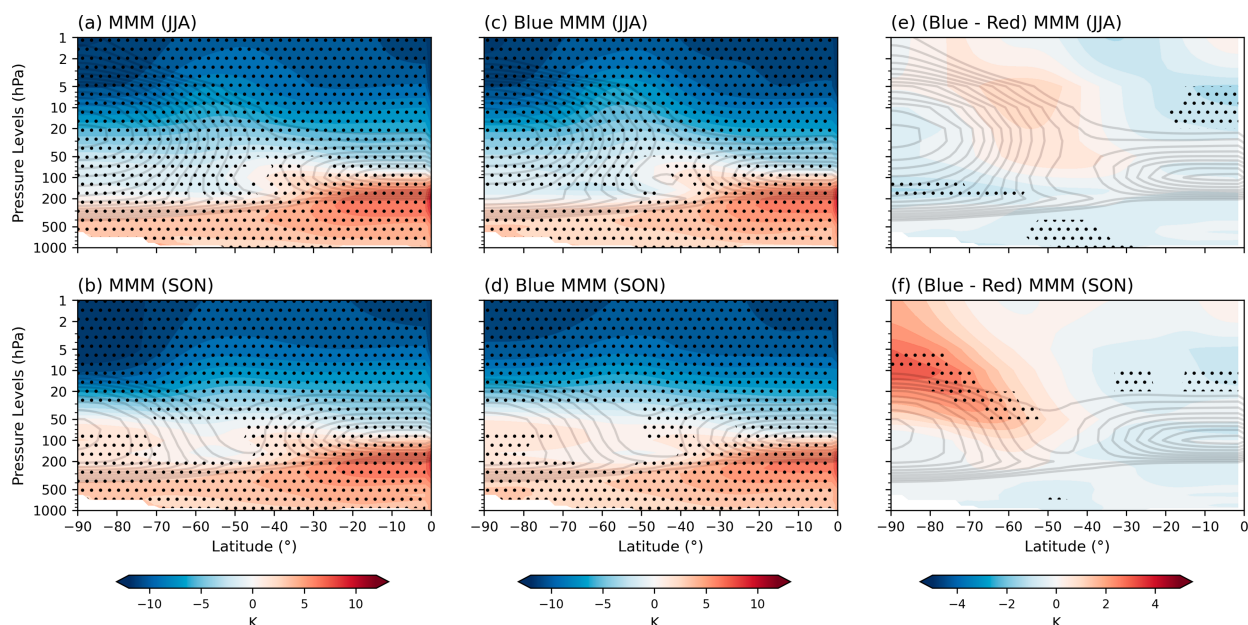


FIG. 7. Projected change in austral winter and spring zonal-mean temperatures from 1979–2014 to 2065–2100, shown as the MMM across (a),(b) all models, (c),(d) the blue models, and (e),(f) the differences between the blue- and red-model means. Data are displayed as a function of pressure level (ordinate) and latitude (abscissa). Contours show climatological mean temperatures over 1979–2014, and stippling in (a)–(d) indicates regions where the temperature change is statistically significant at the 10% level, based on a one-sample t test across model ensembles. In (e) and (f), stippling indicates regions where the difference is statistically significant at the 10% level, based on a two-sample Welch t test comparing blue- and red-model ensembles.

period (despite an overall underestimation of the correlation strength), this projected poleward shift of the winter stratospheric jet maximum (i.e., increase in JJA_SPV_{1hPa}) should act to dynamically weaken the subsequent spring polar vortex, resembling the change from winter to spring anomalies shown in

Figure 5 (from 5a to 5d and 5c to 5f), for example. Indeed, the blue-model mean projects considerably weaker positive changes in spring zonal winds compared to the all-model mean (Fig. 8d vs Fig. 8b), likely due to this “dynamically driven” weakening offsetting the well-established thermally driven strengthening of

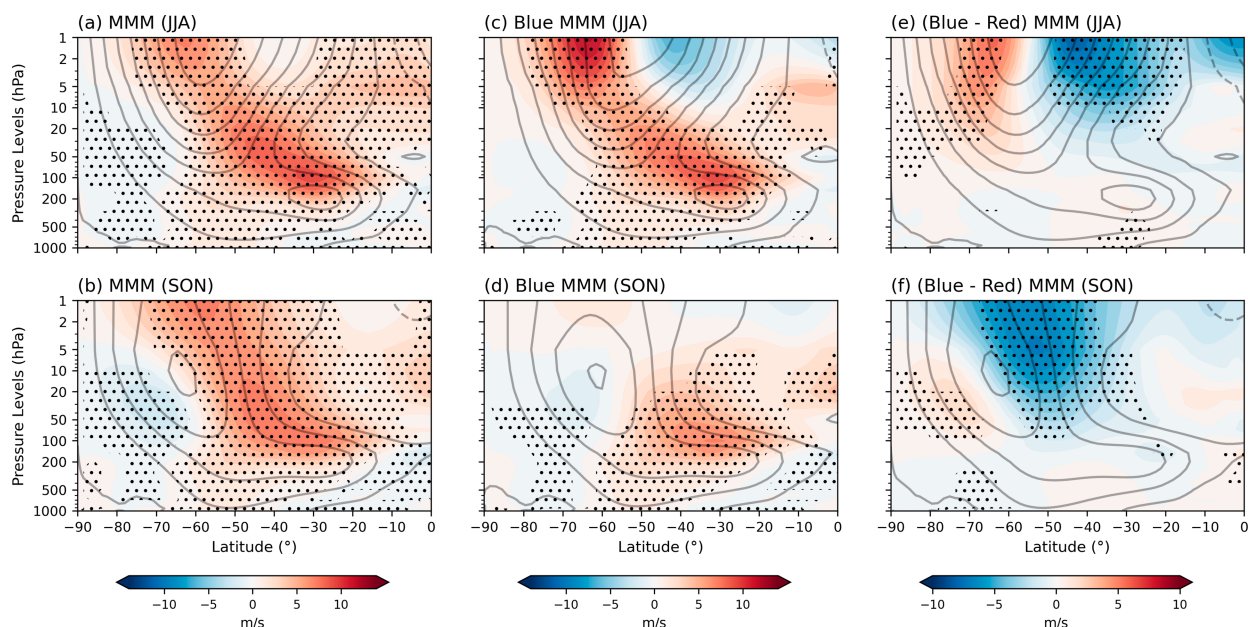


FIG. 8. As in Fig. 7, but for zonal winds.

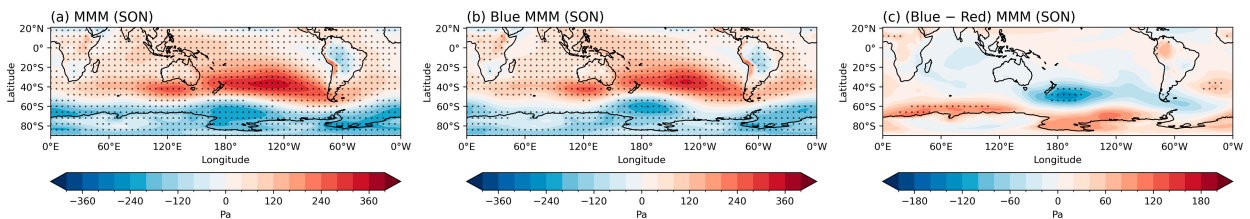


FIG. 9. As in Fig. 7, but for MSLP changes in austral spring (SON).

the vortex in spring. The differences between the blue- and red-model mean projections for JJA and SON (Figs. 8e,f) are remarkably similar to the observed and blue-model mean vortex evolutions associated with an anomalous poleward shift of the winter jet in the upper stratosphere and a subsequent weakening of the spring polar vortex shown in Fig. 5. The temperature differences between the blue- and red-model mean projections for winter and spring are also consistent with the zonal wind differences: higher temperatures in the node of the meridional dipole of the zonal wind differences being indicative of a more poleward-shifted jet in the upper stratosphere in winter (Lim et al. 2026) (Fig. 7e), and those over the Antarctic mid- to lower stratosphere being in balance with the weaker polar vortex in spring (e.g., Hendon et al. 2020) (Fig. 7f). Therefore, the ability of models to simulate the seasonal evolution of the polar vortex anomalies with correct latitudinal structures does influence the future changes in zonal-mean zonal winds they project under the highest emission scenario in a consistent manner with the dynamics of wave-mean flow interaction. This link is quantified in Fig. 10, which shows a significant positive correlation between the models' climatological mean jet position biases at 1 hPa in winter in the historical period and their projected spring zonal wind strengths at 20°–60°S ($r \approx 0.5$ – 0.6). That is, models that more strongly misplace the winter stratospheric jet and misrepresent the anomalous winter-to-spring vortex evolution in the historical period tend to simulate a stronger springtime polar vortex in their future projections.

Because spring zonal-mean zonal wind changes in the SH stratosphere are weaker in the blue-model mean (Fig. 8d), their spring positive SAM projections are also weaker than the all-model mean (Fig. 9b vs Fig. 9a). Consequently, the difference in MSLP changes in spring between the blue- and red-model means broadly resembles a negative SAM pattern, with higher pressure along the Antarctic coast and lower pressure in the 40°–60°S latitude band (Fig. 9c, cf. stratosphere-driven negative SAM in the reanalysis in Fig. S1c). Figure 10 also shows a poleward shift of the projected tropospheric eddy-driven jet correlated with the historical winter stratospheric jet position bias in the models. Therefore, the strong and robust positive SAM projection in the all-model mean for spring (Fig. 9a) could be partly influenced by the winter stratospheric maximum jet position bias and associated vortex evolution bias characterized by unrealistic persistence of winter polar vortex anomalies to spring in most models. However, it is noteworthy that the MSLP difference between the blue- and red-model means is not statistically significant over most of the SH extratropics, suggesting that

other processes such as changes in tropical sea surface temperatures and their teleconnections and/or changes in the Antarctic sea ice extent may also influence the lower atmospheric circulation in the two model groups.

4. Concluding remarks

In this study, we have examined the dynamical evolution of the SH polar vortex anomalies using ERA5 over 1979–2024, the full period available at the time of analysis, and over 1979–2014, which is used to represent the “present day” climate consistent with the CMIP6 historical simulations. We evaluated the ability of 42 CMIP6 model ensembles to simulate this evolution over 1979–2014 and explored how model skill in reproducing the vortex dynamics during the historical period relates to projections of the SH polar vortex and its downward coupling under the highest GHG emission scenario, SSP5-8.5, by the end of the twenty-first century, with

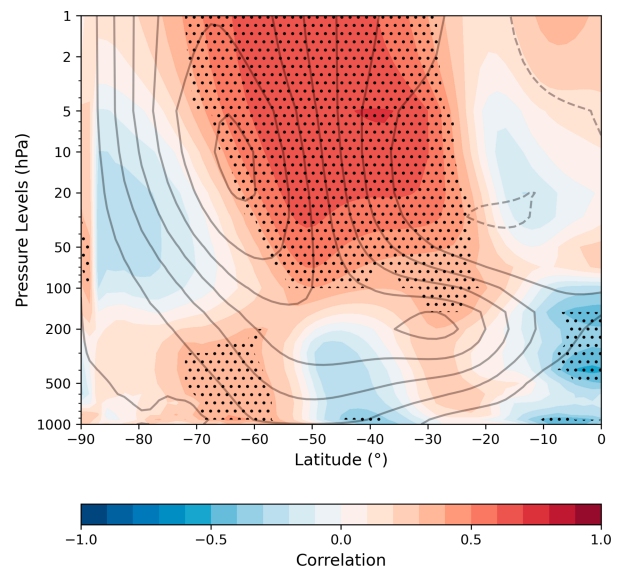


FIG. 10. Intermodel correlation between the mean bias in the location of the winter stratospheric jet maximum at 1 hPa as an index [multiplied by (-1) so that a positive amplitude of the index corresponds to a poleward bias] and the projected changes in zonal-mean zonal winds during spring at different pressure levels and latitudes. Contours show the MMM climatology of zonal-mean zonal winds during spring (SON) over 1979–2014. Stippling indicates statistical significance at the 5% level according to a two-tailed Student's t test, given 42 samples.

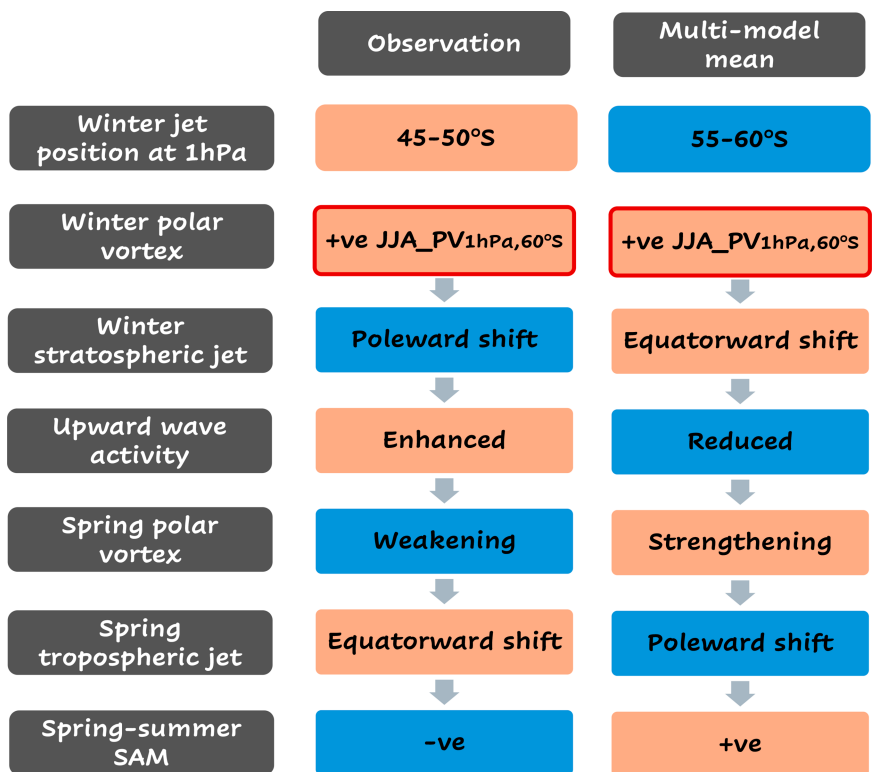


FIG. 11. Summary of the dynamical evolution of an Antarctic polar vortex anomaly from winter to spring in ERA5 and the CMIP6 MMM for the period 1979–2014. The +ve and –ve denote positive and negative, respectively.

increasing GHGs dominating the external forcing (e.g., Fogt and Marshall 2020; Purich et al. 2026). We have shown that the chain of the dynamical processes linked to a spring polar vortex anomaly often begins with an anomalous meridional shift of the winter stratospheric jet maximum and associated wave–mean flow feedback and ends with a SAM anomaly at the surface in spring. These sequential processes are effectively captured by a set of correlations, which we have used as benchmarks to evaluate the models’ performance in simulating this leading mode of stratosphere–troposphere coupled variability. The observed and modeled processes discussed in section 3 are summarized schematically in Fig. 11.

We have found that most CMIP6 models are deficient in simulating the observed linkage between meridional shifts of the winter stratospheric jet at the top of the stratosphere and the subsequent spring polar vortex anomalies as depicted by a negative correlation between the winter polar vortex at 1 hPa and the spring polar vortex at 10 hPa. Instead, they tend to simulate positive correlations between the winter and spring polar vortices because their winter polar vortex anomalies persist into spring with limited poleward movement unlike the observed anomalies. This bias in the dynamical vortex evolution associated with the vortex variability appears to arise from a systematic bias in the climatological position of the winter stratospheric jet maximum, even though its climatological strength is close to observed. In contrast, the models correctly simulate the observed linkage between the polar

vortex and the surface SAM in spring but with an overall underestimation of its strength.

Under the SSP5-8.5 highest emission scenario, the CMIP6 multimodel mean projects the SH stratospheric jet to strengthen in the upper stratosphere and to shift equatorward in the mid- to lower stratosphere in both winter and spring and the SAM to become more positive by the end of the twenty-first century in spring. On the other hand, in a subset of models that realistically simulate the climatological location of the winter stratospheric jet maximum and anomalous winter-to-spring vortex evolution (i.e., “blue” models), the mean position of the winter stratospheric jet is projected to shift poleward relative to that of the present climate, and the change in spring polar vortex strength is projected to be minimal. These changes projected by the blue-model mean, which are distinctively different from those of the all-model mean, are dynamically consistent with the winter–spring vortex relationship found in the reanalysis. The lack of substantial change in the spring polar vortex in the blue-model mean leads to a more moderate positive trend in the spring SAM than in the all-model mean.

A positive trend in SAM all year-round has been a robust feature of future climate change projections driven by increasing GHGs in successive generations of global coupled climate models (e.g., Fyfe et al. 1999; Cai et al. 2003; Arblaster and Meehl 2006; Miller et al. 2006; Simpkins and Karpechko 2012; Lim et al. 2016; Fogt and Marshall 2020; Purich et al. 2026). Its cause has been widely understood to be the GHG-driven radiation changes that would result in a maximum warming in the tropical upper

troposphere and a strong polar stratospheric cooling, both of which would increase the equator-to-pole meridional temperature gradient and shift the tropospheric midlatitude jet poleward in the SH (e.g., [Butler et al. 2010](#); [Ceppi and Shepherd 2019](#); [Mindlin et al. 2020](#); [Jucker et al. 2021](#)).

However, this GHG forcing on the SAM is expected to be substantially offset by the forcing from projected Antarctic ozone recovery especially during austral spring and summer throughout the remainder of the twenty-first century, imposing large uncertainty on future trends in the SAM and associated regional climate (e.g., [Mindlin et al. 2021](#); [Keeble et al. 2021](#); [Chipperfield et al. 2022](#); [Ivanciu et al. 2022](#); [Purich et al. 2026](#)). The projected loss of Antarctic sea ice has also been identified as a source of uncertainty by acting to partially offset a positive SAM trend, primarily via a weakening of the tropospheric jet strength in association with a reduced low-level meridional temperature gradient ([Bader et al. 2013](#); [Bracegirdle et al. 2015](#); [England et al. 2018](#); [Williams et al. 2024](#)). More fundamentally, SH tropospheric jet position and intensity biases ([Kidston and Gerber 2010](#); [Swart et al. 2015](#); [Simpson and Polvani 2016](#)) remain a persistent source of spread in SAM projections.

Bearing this in mind, our results identify another cause of uncertainty in model projections for the SAM change in austral spring, which stems mainly from the model biases in the simulations of the winter stratospheric maximum jet position and their impacts on subsequent dynamical evolution of the SH vortex anomalies. These model biases, in turn, can have a deleterious effect on the projected rate of Antarctic ozone recovery, as SH stratospheric polar vortex conditions are closely tied to Antarctic stratospheric ozone concentrations through strong positive feedback during spring (e.g., [Stolarski et al. 2005](#); [Keeble et al. 2014](#); [Garny et al. 2022](#)). Consequently, biases in the SH polar vortex dynamics in the climate models coupled with interactive ozone chemistry might amplify stratospheric forcing errors that affect the surface SAM during austral warm seasons ([Li and Strode 2025](#)). Because the SAM is associated with significant impacts on the SH regional climate, ocean circulations, and Antarctic sea ice variations (e.g., [Sen Gupta and England 2006](#); [Gillett et al. 2006](#); [Ciasto et al. 2011](#); [Simpkins et al. 2012](#); [Purich et al. 2026](#)), reducing the model biases that affect the dynamics governing the SAM will directly improve the reliability of projections of future climate and its impacts in the SH.

On improving simulations of the SH stratospheric vortex, previous studies have demonstrated that improving gravity wave parameterization by better representing nonorographic gravity waves ([Watanabe 2008](#); [Watanabe et al. 2008](#)), orographic gravity waves ([Garcia et al. 2017](#); [Calvo et al. 2012](#)), and low-frequency gravity waves emanating from frontal systems ([Bramberger and Bacmeister 2025](#)) has significantly reduced the SH winter stratospheric jet maximum bias (too poleward) and the polar vortex bias (too strong and cold). In addition, [Alexander et al. \(2010\)](#) reported that improving orographic and nonorographic gravity wave parameterizations could have a significant impact on SH climate simulations via affecting the transport of trace constituents and ozone-depleting processes. All these efforts to improve gravity wave parameterizations are promising for more skillful simulations of the SH stratospheric vortex evolution and its downward coupling and thus for more reliable future climate projections. Analyses of large ensembles from models with interactive chemistry (e.g., [Butler et al. 2026](#)) may

also provide additional insight into potential future changes in the stratospheric polar vortex in winter and spring and the associated SAM.

Acknowledgments. This study is part of the Victorian Water and Climate Initiative (VicWaCI), funded by the Department of Energy, Environment, and Climate Action; the National Environmental Science Program (NESP), funded by the Department of Climate Change, Energy, the Environment and Water; and the Australian Research Council Special Research Initiative for Securing Antarctica's Environmental Future (SAEF) Program (SR200100005). I. R. S. is supported by the NSF National Center for Atmospheric Research which is a major facility sponsored by the National Science Foundation under Cooperative Agreement 1852977. S. W. was supported by MEXT-Program for the Advanced Studies of Climate Change Projection (SENTAN) Grant JPMXD0722681344 and JSPS KAKENHI Grant JP22H00169. N. C. acknowledges support from the projects RecO3very: PID2021-12477OB-I00 and RETO-PV: PID2024-158151NB-I00, from the Spanish Ministry of Science and Innovation. A. Y. K. was supported by the Research Council of Finland (Grants 354331 and 364657). R. S. W. was supported by the European Union's Horizon 2020 research and innovation framework programme under Grant Agreement 101003590 (PolarRES). J. M. acknowledges the Saxon State Ministry for Science, Culture and Tourism (SMWK) – (3-7304/44/4-2023/8846). This research was undertaken on the NCI National Facility in Canberra, Australia, which is supported by the Australian Commonwealth Government. The NCAR Command Language (NCL; <http://www.ncl.ucar.edu>) version 6.6.2 and Python version 3.11 were used for data analysis and visualization of the results. We acknowledge ECMWF and the Copernicus Climate Change Service for producing and archiving the ERA5 reanalysis. We also acknowledge the World Climate Research Programme (WCRP), which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. The authors thank Drs. Sugata Narsey and Matthew Wheeler at the Bureau of Meteorology for their insightful feedback on the early version of the manuscript, Editor Professor Darryn Waugh for convening the peer-review process, and three anonymous reviewers for their thorough reviews and valuable and constructive feedback on the manuscript. The authors declare no conflicts of interest related to this work.

Data availability statement. The ERA5 and ERA5.1 hourly and monthly reanalysis data are available at Catalogue—Climate Data Store. The CMIP6 data are available at <https://wcrp-cmip.org/cmip-data-access/>. NCL and Python scripts used for the analysis and visualization are also available upon request.

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