Stratospheric Circulation in the Southern Hemisphere: links to tropical winds, ozone and the Hunga Eruption –Part II: Evidence from a Global Chemistry-Climate Model

Xinyue Wang[1], Wandi Yu[2], William Randel[3], Rolando Garcia[3], Paul Newman[4,5], Simone Tilmes[3], Ewa Bednarz[6,7], Yunqian Zhu[6,7], Jun Zhang[3], V. Lynn Harvey[8], Simchan Yook[9], Chengyun Yang[10], Zhihong Zhuo[11]

[1]Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, USA
[2]Lawrence Livermore National Laboratory, USA
[3]Atmospheric Chemistry Observations & Modeling Laboratory, NSF National Center for Atmospheric Research
[4]University of Maryland Baltimore County, USA
[5]NASA Goddard Space Flight Center, USA
[6]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, USA
[7]NOAA Chemical Sciences Laboratory, USA
[8]Laboratory for Atmospheric and Space Physics, University of Colorado, USA
[9]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, USA
[10]School of Earth and Space Sciences, University of Science and Technology of China, China
[11]University of Quebec a Montreal, Canada
Corresponding author: Xinyue Wang, xinyuew@colorado.edu

Key Points:

- In the austral winter, the leading stratospheric circulation variability is associated with the latitude of the zonal wind jet core.
- Austral winters with low-latitude jet cores link to spring polar cooling, stronger ozone loss, and a positive southern annular mode pattern.
- Model results show the 2022 Hunga eruption drove a low-latitude jet phase with colder midlatitudes and reduced planetary wave activity

Abstract (250 words)

The Southern Hemisphere (SH) stratospheric circulation can be categorized based upon the development of a low-latitude jet (LLJ) in the upper stratosphere during winter months. We analyze the dynamics of the LLJ based on a large ensemble of chemistry-climate model simulations, supported by reanalysis data. The LLJ is associated with westerly wind anomalies in the middle and upper stratosphere during mid-winter, together with weak planetary wave activity and a slower Brewer-Dobson circulation. Circulation effects extend into the tropical upper stratosphere, where the LLJ impacts the tropical semi-annual oscillation (SAO). Additionally, the LLJ is linked to a persistent, strong polar vortex in the lower stratosphere during October–December. This cold, strong vortex is associated with decreased ozone amounts in winter and spring; ozone radiative feedbacks reinforce the cold vortex after sunlight returns in October. The 2022 Hunga eruption coincided with an anomalously strong LLJ year, and ensemble simulations of Hunga impacts show that the eruption pushed the SH winter circulation towards LLJ behavior, although the ensemble-mean forced Hunga signal is small and embedded within a large amount of stochastic variability. These results advance our understanding of how LLJ dynamics connect to the large-scale stratospheric circulation and ozone depletion, with implications for predicting polar climate and composition.

Plain Language Summary

The strength and position of upper atmospheric winds in the Southern Hemisphere winter months show large variability. Using a large set of chemistry-climate model simulations, we studied the behavior of the upper stratospheric jet during austral winters. We found that the jet falls into two main patterns: a low-latitude jet (LLJ) and a high-latitude jet (HLJ). LLJ winters are associated with weaker planetary wave activity, a colder and stronger polar vortex, and deeper springtime ozone loss, and positive phase of the southern annular mode. HLJ winters show the opposite. These circulation patterns are also linked to wind anomalies in the tropical stratosphere. We further examined the stratospheric jet anomalies following the 2022 Hunga eruption, which injected large amounts of water vapor into the stratosphere. Our simulations suggest that the eruption nudged the stratospheric circulation toward the LLJ pattern, in addition to the natural year-to-year variability.

1 Introduction

The Antarctic polar vortex is associated with a large-scale westerly jet that encircles the polar cap region in the Southern Hemisphere (SH) stratosphere. It strengthens in winter with maximum winds at 40-50°S near 1-2 hPa (Andrews, Leovy, and Holton 1987). The polar vortex plays an important role in modulating the Antarctic ozone hole and the global climate system. A strong vortex effectively traps extremely cold air within its core, which creates conditions favorable for heterogenous chemistry reactions to deplete ozone. As a result, the variability in the strength and longevity of the polar vortex influences the extent and persistence of ozone depletion in springtime (Newman and Randel 1988). In addition, the Antarctic vortex is an important source of predictability of the state of the tropospheric Southern Annular Mode (SAM), which significantly impacts SH surface weather and climate, as well as oceanic circulations and sea-ice extent (Hartmann 2022; Hartmann et al. 2000; Lim et al. 2019; Lim, Hendon, and Thompson 2018; Thompson and Wallace 2000; Waugh, Sobel, and Polvani 2017; Yang et al. 2022).

Observational studies have reported substantial interannual variability in the stratospheric polar vortex (Randel and Newman 1998; Renwick 2004). Shiotani, Shimoda, and Hirota (1993) analyzed 10 years of Stratospheric Sounding Unit (SSU) data to investigate the interannual variability of the zonal mean wind in the stratosphere. They identified two categories of zonal mean westerly jets in the SH stratosphere based on the location of maximum westerlies near the stratopause: A High-Latitude Jet (HLJ), characterized by stronger westerlies at higher latitudes around 50°S, and a Low-Latitude Jet (LLJ) with westerlies centered at lower latitudes, around 40°S.

Planetary waves originate in the midlatitude upper troposphere and propagate upward only if their zonal scale is large and the flow is weak westerly relative to their phase speed (Charney and Drazin 1961). During winter, when stratospheric westerlies are prevalent, planetary waves can propagate into the stratosphere and interact with the background mean flow (Andrews et al. 1987). When the westerly jet remains at lower latitudes, it alters waveguides and regions where planetary waves are reflected or dissipated in the stratosphere. Variations in planetary wave activity can further drive anomalies in temperature, circulation and ozone across the Antarctic region, with polar cooling (warming) associated with weaker (stronger) poleward wave activity (Newman and

Randel 1988). In spring, the SH anticyclones gradually develop over the pole as the Antarctic vortex weakens, and westerlies retreat downward in late winter and gradually weaken and reverse (Harvey et al. 2002).

In January 2022, the Hunga Tonga-Hunga Ha'apai (Hunga) volcanic eruption injected large amounts of water vapor (H_2O) and a moderate amount of the aerosol precursor sulfur dioxide (SO_2) into the SH stratosphere (Zhu et al. 2022). Observational studies have shown an unusual strengthening and equatorward shift of the winter stratospheric jet during the winter of 2022 (Coy et al. 2022; Wang et al. 2023; Yu et al. 2023). However, it remains uncertain whether the observed shift of the stratospheric westerly jet was primarily driven by volcanic forcing from the Hunga eruption or by internal variability within the stratospheric climate system.

This paper investigates in detail the interannual variability of the stratospheric circulation in the SH using a 60-member ensemble of 10-year simulations carried out with a global chemistry-climate model. We will focus on internal variability in this large ensemble, including relationships between the location of extratropical zonal mean zonal wind anomalies at 2 hPa, planetary wave activity, and the global residual circulations. In addition, we examine the seasonally varying linkages between the extratropical zonal wind and tropical wind anomalies, as well as the persistence of the springtime polar vortex and ozone depletion over Antarctica. We then analyze the possible relationship with the Hunga volcanic eruption using an additional 60-member ensemble of simulations of the year 2022 with imposed Hunga forcings of H_2O and SO_2. A companion study (Yu et al., 2025, hereafter Yu25) provides a complementary observational analysis using 46 years of reanalysis data, confirming similar variability in the location of the stratospheric westerly jet and coupling to planetary waves and global circulation.

2 WACCM6

We use the Community Earth System Model, version 2 (CESM2), with the Whole Atmosphere Community Climate Model version 6 (WACCM6) as the atmosphere component (Gettelman et al. 2019). WACCM has a horizontal resolution of 0.9° latitude × 1.25° longitude, utilizing a finite volume dynamical core. The model has 70 vertical levels, with a vertical resolution of ~1 km in the lower stratosphere and ~1.75 km in the upper stratosphere. In the free-

running simulations, the model produces an internally generated quasi-biennial oscillation (QBO) (Gettelman et al. 2019; Mills et al. 2017). The aerosol is interactively simulated using a four-mode modal aerosol module (MAM4; Liu et al., 2012, 2016; Mills et al., 2016) with the nucleation scheme of Vehkamäki et al. (2002).

We analyze the model simulations submitted to the Hunga Tonga-Hunga Ha'apai Volcano Impact Model Observation Comparison (HTHH-MOC) Project (Zhu et al., 2025; Zhuo et al., 2025). There are two sets of experiments: the control case without SO_2 or H_2O (no volcanic forcing), and the $SO_2 + H_2O$ case with both SO_2 and H_2O injections, which mimics the total forcing of the Hunga eruption (Zhu et al. 2022). The simulations are also carried out using either the atmosphere-only or coupled-ocean. Each ensemble consists of 10-year realizations. The winds and temperatures in WACCM are nudged toward the Goddard Earth Observing System (GEOS) Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) throughout January 2022 to better represent the background climate state and the initial evolution of volcanic clouds (Gelaro et al. 2017). The point at which nudging ends varies by ensemble member, ranging from late January and mid-March 2022. Once the nudging period ends, the model is free running for ten years (2022-2031).

Our focus is on the internal dynamical variability during SH winter, especially during the months of July-August that exhibit LLJ behavior in the upper stratosphere (Yu25). We analyze variability based on 60 members of the control ensemble (each of which is an independent, 10-year simulation). This provides a total of 600 annual realizations, with monthly output used to calculate the unperturbed climate and quantify its internal variability. A separate ensemble examines response to the Hunga forcing during 2022, the year most strongly affected by the volcanic forcing. These simulations are compared to the control runs; there are 60 realizations with Hunga forcing included in these comparisons.

3 Results

3.1 Interannual variability of the stratospheric jet in WACCM

To characterize the interannual variability of upper stratospheric westerlies during SH winter in WACCM, we apply empirical orthogonal function (EOF) analysis to deseasonalized July

zonal-mean zonal wind (U) anomalies at 2 hPa. The U field is multiplied by the cosine of latitude before EOF analysis to account for area weighting of winds associated with each latitude band. As a note, we focus on deseasonalized wind anomalies rather than the full wind field as in Yu25, because the persistent and strong SH polar vortex in WACCM (Hall et al. 2021) causes the westerly jet axis to have unrealistically small variability.

The first EOF (EOF1), accounting for 62 % of the variance, shows a pattern with a positive U anomaly centered at 30°-40°S, a slight negative anomaly from 60°-70°S, and an additional positive anomaly near the equator (Fig. 1a). The corresponding standardized principal component (PC1) alternates between positive and negative phases, representing two distinct circulation regimes (Fig. 1b). More specifically, one regime has maximum zonal wind anomalies centered equatorward of 40°S, corresponding to the LLJ regime, whereas in the opposite phase (the HLJ regime), the low latitude westerly wind weakens and there is a slight enhancement of westerly wind that peaks south of 60°S. The August U anomaly shows an EOF1 that is very similar to that in Fig. 1a, explaining 69% of the total variance (not shown). For further analysis, we define LLJ and HLJ events as those with standardized PC1 values greater than +1 or less than –1, respectively. These events are shown in Fig. 1c, with orange lines representing LLJ events (ensemble mean in red) and blue lines representing HLJ events (ensemble mean in navy). The probability density function (PDF) of standardized PC1 values for July from the 600-member control ensemble, plotted using 12 bins in the interval (-3, +3), resembles a Gaussian distribution (grey histogram in Fig. 1d). The red histogram represents the distribution from the Hunga runs constructed from 180 samples from the years 2022-2024; the Hunga PDF departs noticeably from Gaussian behavior and is discussed in detail in Section 3.4.

The large fraction of variance captured by EOF1 is consistent with the two regimes identified by Shiotani et al. (1993) and with the classification using ERA5 data in Yu25. The location and strength of the stratospheric jet is coupled with zonal mean temperatures, planetary waves and residual circulation, as shown in the following section, where we examine the circulation composites based on the two regimes, HLJ and LLJ, of the stratospheric jet location.

Figure 1. (a) Leading mode (EOF1) of variability in July zonal mean zonal winds (U) at 2 hPa over 2022 to 2031 in the WACCM control simulation, computed using zonal wind fields weighted by the cosine of latitude. (b) Standardized PC1 associated with EOF1. Orange and blue shading indicate values exceeding ±1 standard deviation, respectively. (c) Composite U anomaly profiles weighted by cosine of latitude for LLJ (orange lines) and HLJ (blue lines), with ensemble means indicated by the red and navy lines, respectively. (d) PDF of the standardized PC1 values for July in the control ensemble (grey) and in the Hunga ensemble over the years 2022-2024 (red).

3.2 LLJ composites for Austral Winters

We apply composite analysis to identify the circulation patterns associated with the LLJ events. First, monthly anomalies are described as deviations from the climatological July mean of the 600-member annual control ensemble defined in Section 2.1. Then, these anomalies are averaged across all LLJ events, identified by PC1 values exceeding +1 standard deviation. For significance testing, we compare the LLJ composite to the variability associated with the full July climatology.

The July zonal wind and the Brewer-Dobson circulation (BDC) anomalies composited for the LLJ events are shown in Fig. 2a. The BDC is characterized by anomalous high-latitude upwelling and low-latitude downwelling that counteract the normal background equator-to-pole circulation pattern. A strengthening of the zonal-mean westerlies between 50°S and 30°S, coupled with a weakening between 60°-80°S, shows an equatorward shift of the stratospheric westerly wind compared to the climatology. In the tropical stratosphere (1–50 hPa), wind anomalies form a vertical tripole structure with alternating westerly, easterly, and westerly anomalies. The enhanced westerly anomalies near 2 hPa are captured in EOF1 (Fig. 1c). Notably, this equatorial westerly anomaly is asymmetric about the equator, with its maximum shifted toward the Northern Hemisphere (NH). Close to the equator the positive westerly anomaly extends into the NH consistent with the effect of the anomalous northward residual circulation $\bar{v}^*$ (Fig. 2a) in the TEM momentum equation $\frac{\partial \bar{u}}{\partial t} = \bar{v}^*(f - U_y) + \nabla \cdot F$ (Andrews et al. 1987; Shiotani and Hirota 1985).

The coupling of stratospheric mean flow and planetary waves is a well-known feature of the winter stratosphere (Andrews et al. 1987; Holton and Mass 1976; Randel and Newman 1998). Planetary waves propagate from the troposphere into the stratosphere, disrupting the radiative balance of the vortex and distorting its shape from a circular symmetry around the pole (Waugh et al. 2017). The dissipation of vertically propagating planetary waves is a principal forcing of the residual circulation in the polar lower stratosphere. In particular, negative EP flux divergence induces a poleward flow that in turn leads to upwelling in the tropics and downwelling at high latitudes (Haynes et al. 1991; Newman, Nash, and Rosenfield 2001). In the winter extratropical stratosphere, EP flux divergence is typically negative (wave drag), as westward momentum is deposited into the mean zonal wind. This deceleration of the zonal-mean westerlies induces a poleward residual mean circulation through the Coriolis force, such that, in the low-frequency limit, $-(f - U_y)\bar{v}^* \sim (\rho_0 a cos\theta)^{-1} \nabla \cdot F$ (Eq. 3.5.2a of Andrews et al. 1987). During LLJ cases, the EP flux anomalies oppose and weaken the climatological pattern, with downward EP flux anomalies over 50°-70°S below ~5 hPa and poleward flux anomalies in the upper stratosphere. These anomalies result in reduced EP flux divergence and diminished westward momentum deposition in the stratosphere, leading to a positive (westerly) tendency in the zonal-mean zonal wind (Fig. 2b). As a result, the stratospheric westerlies strengthen and shift equatorward relative to the climatology.

The latitudinal-height structure of temperature anomalies associated with LLJ events during July is shown in Fig. 2c. A pronounced cold anomaly is observed between 60°S and 40°S, centered near 5-10 hPa. In contrast, a warm anomaly appears near the equator, centered between ~30 hPa and 2 hPa. These temperature anomalies are in thermal wind balance with the zonal wind anomalies in Figs. 2a-b. The stratospheric cooling at 40°-60°S is consistent with the anomalous upwelling that opposes and weakens the normal background equator to pole circulation (Fig. 2a), which enhances adiabatic cooling (Fig. 2b). Similarly, the warming seen in the Tropics is consistent with anomalous downwelling (weaker upwelling in the BDC).

Figure 2. July composites for LLJ cases showing (a) zonal mean zonal wind anomaly (color: m/s) and residual circulation anomalies (vector: m/s); (b) The zonal-mean zonal wind tendency due to the EP flux divergence (color: m/s/day) and scaled EP flux anomalies by the air density (vectors, m^3/s^2); (c) Temperature anomalies (color: K). All variables are shown at the 95% significance level.

The above results show composite patterns based on LLJ events in July, but similar patterns are found when using August LLJ events (not shown). In contrast to LLJ events, HLJ events are characterized by an opposite circulation anomaly pattern (not shown). The temporal evolution of the composites over specific regions will be discussed in the following sections.

3.4 LLJ composites for tropical wind anomalies

In this section, we examine the evolution of tropical wind anomalies associated with LLJ events and their underlying mechanisms. The composite evolution of the equatorial U anomalies (Uanom), averaged over 5°S–5°N, before and after July LLJ events is shown in Figure 3.

Figure 3. Monthly evolution of Uanom (color: m/s) averaged over 5°S–5°N, composited for years with July LLJ events. Anomalies with respect to the climatological monthly mean are shown for the months before and after the July LLJ. The anomalies are plotted only where they exceed the 95% significance level.

Enhanced tropical westerlies above 5 hPa emerge in early austral winter (June) and peak in July and August during years with LLJ events. The timing coincides with the development of the BDC anomalies tied to LLJ events (Fig. 2a), indicating that the enhanced tropical upper stratospheric westerlies are not a driver of the anomalous residual circulation. These tropical upper stratospheric winds represent a modulation of the (austral winter) easterly phase of the equatorial semi-annual oscillation (SAO) (e.g. Kawatani et al. 2020), wherein LLJ events reduce the strength of the SAO easterlies via advection of westerly zonal mean momentum by the anomalous tropical $\bar{v}^*$ seen in Fig. 2a. Our results (Fig. 3) are also consistent with recent observational evidence that suggests the westerly phase of the SAO is strengthened when the QBO at 10 hPa is in the easterly phase through filtering of the upward-propagating gravity-wave spectrum (Smith, Gray, and Garcia 2023).

Starting earlier in the year, Uanom exhibits a QBO-like vertical structure, with easterly anomalies near 2–5 hPa and westerly anomalies around 15–30 hPa centered around the equator, which gradually descend in altitude over time. The relationship between QBO-like tropical wind anomalies and the location of the Antarctic polar jet maximum has been documented in several studies, but the dynamical mechanism remains unclear (Li et al. 2020). Consistent with our composites of LLJ (HLJ) cases, the SH stratospheric westerly jet strengthens (weakens) during westerly (easterly) QBO phases at 20 hPa in austral winter months, accompanied by suppressed (enhanced) upward planetary wave propagation and EP flux convergence. This signal is robust across multiple reanalysis datasets and is captured qualitatively by a few CMIP5/6 models, although the simulated response is often weak in magnitude or not statistically significant (Rao et al. 2023; Wang et al. 2025). A QBO-induced meridional circulation might modify the temperature structure in the low latitudes, which in turn affects the strength and timing of the polar night jet (Yamashita et al. 2018). Yu25 performed a composite analysis based on the westerly QBO phase at 10 hPa and found that the QBO secondary circulation and its associated cooling is extended to the mid-latitudes when it happens during austral winter, connecting to the LLJ feature.

The correlation between the austral winter stratospheric jet and QBO resembles the Holton-Tan effect during the NH winter (Holton and Tan 1980). However, there are inconsistencies across model, reanalysis datasets, and previous studies in both the location of tropical westerly anomalies and how the QBO phase is defined, meaning that the impact of the QBO on the SH winter stratospheric jet remains uncertain.

3.3 LLJ composites for the polar region

The location of the core of the stratospheric westerly jet defines the edge of the polar vortex, and its strength strongly influences the dynamical and thermal conditions that precondition the Antarctic stratosphere for ozone depletion (Schoeberl and Hartmann 1991; Thompson and Solomon 2002). We next examine the polar atmospheric conditions associated with years with LLJ events.

Geopotential height and temperature anomalies at high latitudes composited for LLJ show early signals of negative and cold anomalies in the upper stratosphere polar cap (60°-90°S, Figs.

4a & b). Specifically, a significant signal emerges in the upper stratosphere in June, with the strongest anomalies developing during July and August. The coupling between geopotential height and temperature follows from hydrostatic balance and the ideal gas law, whereby temperature is directly related to the vertical gradient of geopotential in log-pressure coordinates. As the stratospheric westerlies intensify in subpolar latitudes (50°-60°S, Fig. 4c), the polar vortex strengthens and geopotential height decreases. The associated upward vertical velocity anomaly, co-located with cold anomalies over the polar region (Fig. 2a), leads to adiabatic cooling that enhances the radiative cooling that occurs during the polar night. The strength and persistence of the polar vortex play a key role in maintaining these low temperatures by isolating polar air from midlatitude mixing and limiting dynamical warming (Schoeberl and Hartmann 1991). The high-latitude zonal-mean zonal wind in LLJ years exhibits a prominent positive anomaly that emerges in the upper stratosphere in July and strengthens through August and September (Fig. 4c). These enhanced westerlies persist into late spring and early summer and gradually descend over time, and Fig. 4 shows that effects extend below the tropopause to near surface levels.

Figure 4. Monthly evolution of (a) standardized geopotential height anomalies, (b) standardized temperature anomalies, both averaged over 60°S–90°S, and (c) zonal-mean zonal wind anomalies averaged over 50°S–60°S associated with LLJ events in July. The dashed line indicates the tropopause height. Statistically significant anomalies are denoted by hatching.

Coinciding with the persisting wind anomalies, cold temperature anomalies extend into spring in the lower stratosphere (Fig. 4b), playing a crucial role in setting the stage for Antarctic ozone depletion once sunlight returns and temperatures remain low (typically August through mid-October), e.g. Solomon (1999). As a result, unusually cold stratospheric winters associated with LLJ events cause deeper and more prolonged ozone holes, and the low ozone values persist in the

lower stratosphere into December (Fig. 5). Reduced ozone also produces radiative feedback on stratospheric temperature causing further stratospheric cooling. Residual vertical velocity anomalies over the polar cap show no significant changes in late spring (not shown), indicating limited dynamical contributions during this period. The anomalous cooling persists into summer after the polar vortex breaks down, suggesting that radiative effects from ozone loss play a more dominant role than dynamical processes in SH late spring/summer (Figs. 4b & 5).

Figure 5. Monthly evolution of percentage ozone anomalies associated with July LLJ events, averaged over 60°S–90°S. The dashed line indicates the pressure level of the tropopause. Anomalies not significant at the 95% confidence level are masked in white.

The zonal wind anomalies move down towards the troposphere and surface by September (Fig. 4c), where surface patterns resemble the positive phase of the SAM (Fig. 6). Positive SAM patterns are also observed in October (not shown). This indicates that surface circulation patterns are strongly influenced by the strength and position of the stratospheric westerly jet up to three months earlier, highlighting the importance of stratosphere in forecasting near-surface conditions. A similar relationship was documented by Thompson, Baldwin, and Solomon (2005), who showed that both weakening and strengthening of the polar vortex lead to persistent, similarly signed tropospheric anomalies that closely resemble the SAM. The coupling between geopotential height, temperature, and ozone, as well as their lead–lag relationships, is also found by Yu25 in long-term reanalysis data and ozone observations.

Figure 6. September composites for July LLJ cases showing surface pressure (color: Pa) and wind anomalies (vector: m/s), with regions exceeding 95% significance level hatched.

3.4 The 2022 Hunga eruption

The Hunga volcanic eruption of January 2022 produced large composition changes in the stratosphere. Atmospheric observations during SH winter 2022 show an unusually strong LLJ event (Wang et al., 2023; Yu et al., 2023), raising the question of an association with the Hunga eruption. A 60-member ensemble of chemistry-climate model simulations for 2022 using realistic Hunga forcings of H_2O and SO_2 (see Section 2.1) is analyzed here to evaluate possible impacts on the LLJ. The ensemble-average Hunga zonal wind anomalies (with respect to the 2022 control ensemble) due to the (SO_2 + H_2O) forcing in July 2022 are shown in Fig. 7a. There is a strengthening and equatorward shift of the winter westerlies in response to the Hunga forcing, with patterns similar to the LLJ composites in Fig. 2a, although the ensemble-mean anomaly is only about one third the magnitude of the LLJ composite anomalies. In addition, the Hunga forcing results in colder midlatitude temperature (Fig. 7b) and reduced residual circulation (Fig. 7a) and planetary wave EP fluxes (not shown, but similar to Fig. 2b) in the SH winter months of 2022.

Figure 7. The 60-member ensemble mean July (a) zonal wind difference (color: m/s) and residual circulation changes (vector: m/s) and (b) temperature difference (color: K) between Hunga and control runs. Hatched regions indicate where the differences are statistically significant at the 95% confidence level according to Student's t-test.

An additional measure of LLJ behavior is provided by the distribution of high latitude temperature versus lower stratosphere wave activity (EP flux), as shown in Fig. 8 for the control (grey) and Hunga (red) statistics. The overall positive relationship between these statistics (for the control simulations) reflects the natural variability of the SH winter circulation, and LLJ events occupy the lower left quadrant of the distribution (cold temperatures and weak wave fluxes). The statistics derived from the Hunga simulations (red in Fig. 8) exhibit a shift in the distribution of temperature and wave activity, representing a fingerprint of the simulated response to the Hunga eruption (Wang et al., 2023; Yu et al., 2023). However, there is large stochastic variability among the ensemble members. While individual Hunga realizations show temperature cooling comparable to that observed (consistent with Yu et al., 2023), the ensemble-mean Hunga response (Fig. 7) is relatively small compared with both the observation and the LLJ events (Fig. 2).

Figure 8. Distribution of July average temperatures at 10 hPa and upward EP flux at 70 hPa over 55°S–65°S. Contours indicate the density of the data points. Red contours show results for the anomalies with respect to the control ensemble in the Hunga simulations, based on 60 ensemble members for July 2022 (denoted by red dots). Grey contours represent deviations from the control ensemble mean across July averages from 2022 to 2031 (60 ensemble members x 10 years, denoted by grey dots).

The Hunga-induced shift in circulation statistics is also evident in the distribution of U anomalies for the first three years after the eruption (Fig. 1d). EOF analysis was applied to the U anomalies with respect to the control climatology for the first three years of the Hunga simulations and a PDF of the resulting PC loadings was constructed. We used three years of data to avoid the too coarse distribution that results from taking only 60 samples for the year 2022. The resulting distribution is not Gaussian and shows a secondary peak beyond the +1 threshold, attributable to the Hunga forcing, suggesting that the Hunga forcing biases the system toward the LLJ state. Overall, the ensemble-mean response to Hunga forcing is characterized as a strong LLJ event in terms of the equatorward shift in westerly wind, weakened residual circulation, and reduced planetary wave drag.

4 Conclusion

This study investigates the interannual variability of the Southern Hemisphere stratospheric jet and its implications for large-scale circulation anomalies and polar ozone depletion, with a

particular focus on the anomalous winter of 2022. Using a large ensemble of chemistry–climate simulations from WACCM6, we identify two dominant regimes of the stratospheric westerly jet—Low-Latitude Jet (LLJ) and High-Latitude Jet (HLJ). LLJ is characterized by an equatorward shift and intensification of the subtropical westerlies in the upper stratosphere, reduced planetary wave drag, and a weakened residual circulation. The circulation impacts extend into the tropical upper stratosphere, where LLJ events result in weakened easterly phase of the tropical semi-annual oscillation during SH winter. The large ensemble of model simulations also shows weak but significant correlations to QBO winds in the tropics over ~20-35 km (Fig. 3), although causality is not completely understood. In the polar region, LLJ events precondition the stratosphere for enhance springtime ozone depletion by strengthening and prolonging the polar vortex into December. This persistent cold, isolated vortex promotes the formation of polar stratospheric clouds and supports catalytic ozone loss, with radiative feedbacks further reinforcing the vortex. The LLJ-related wind anomalies descend into the troposphere over subsequent months, projecting onto the positive phase of the SAM, indicating significant surface impacts.

Atmospheric observations during 2022 showed a large LLJ event, suggesting possible links to the Hunga volcanic eruption (Wang et al., 2023; Yu et al., 2023; Yook et al., 2025). Our simulations of Hunga effects (from a 60-member ensemble for 2022) produced a measurable equatorward shift and strengthening of the winter westerlies, along with reduced planetary wave drag and midlatitude cooling—mirroring the LLJ composite pattern, but at about one-third the magnitude (compare Figs. 2 and 7). Probability density analysis suggests that Hunga volcanic foring nudged the circulation system towards LLJ behavior. Some individual realizations produce cooling of comparable magnitude to that observed in 2022, consistent with results in (Yu et al., 2023). Overall, the forced signal is embedded withing a substantial amount of natural variability, at least in the WACCM model simulations.

Data Availability Statement

[Software] CESM2/WACCM6 is an open-source community model, which was developed with support primarily from the National Science Foundation. See Gettelman et al. (2019).

Acknowledgement

NCAR's Community Earth System Model project is supported primarily by the National Science Foundation (NSF) under Cooperative Agreement No. 1852977. Computing and data storage resources, including the Derecho supercomputer (doi:10.5065/qx9a-pg09), were provided by the Computational and Information Systems Laboratory (CISL) at NCAR. XW's model simulations were supported through NSF NCAR Strategic Capability (NSC) projects and by the help of Garth D'Attilo. WY's work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. YZ acknowledges the National Oceanic and Atmospheric Administration (grant nos. 03-01-07-001, 60 NA17OAR4320101, and NA22OAR4320151). VLH acknowledges support from NASA grants 80NSSC22K1074, 80NSSC22K0017, 80NSSC23K0848, and 80NSSC24K0269 and NSF grant AGS2411429.

Reference:

Andrews, David G., Conway B. Leovy, and James R. Holton. 1987. *Middle Atmosphere Dynamics*. Vol. 40. Academic press.

Charney, Jule G., and Philip G. Drazin. 1961. "Propagation of Planetary-scale Disturbances from the Lower into the Upper Atmosphere." *Journal of Geophysical Research* 66(1):83–109.

Coy, Lawrence, Paul A. Newman, K. Wargan, G. Partyka, S. E. Strahan, and Steven Pawson. 2022. "Stratospheric Circulation Changes Associated with the Hunga Tonga-Hunga Ha'apai Eruption." *Geophysical Research Letters* 49(22):e2022GL100982.

Gelaro, Ronald, Will McCarty, Max J. Suárez, Ricardo Todling, Andrea Molod, Lawrence Takacs, Cynthia A. Randles, Anton Darmenov, Michael G. Bosilovich, and Rolf Reichle. 2017. "The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)." *Journal of Climate* 30(14):5419–54.

Gettelman, A., M. J. Mills, D. E. Kinnison, R. R. Garcia, A. K. Smith, D. R. Marsh, S. Tilmes, F. Vitt, C. G. Bardeen, and J. McInerny. 2019. "The Whole Atmosphere Community Climate Model Version 6 (WACCM6)." *Journal of Geophysical Research: Atmospheres* 124(23):12380–403.

Hall, Richard J., Daniel M. Mitchell, William J. M. Seviour, and Corwin J. Wright. 2021. "Persistent Model Biases in the CMIP6 Representation of Stratospheric Polar Vortex Variability." *Journal of Geophysical Research: Atmospheres* 126(12):e2021JD034759.

Hartmann, Dennis L. 2022. "The Antarctic Ozone Hole and the Pattern Effect on Climate Sensitivity." *Proceedings of the National Academy of Sciences* 119(35):e2207889119.

Hartmann, Dennis L., John M. Wallace, Varavut Limpasuvan, David W. J. Thompson, and James R. Holton. 2000. "Can Ozone Depletion and Global Warming Interact to Produce Rapid Climate Change?" *Proceedings of the National Academy of Sciences* 97(4):1412–17.

Harvey, V. Lynn, R. Bradley Pierce, T. Duncan Fairlie, and Matthew H. Hitchman. 2002. "A Climatology of Stratospheric Polar Vortices and Anticyclones." *Journal of Geophysical Research: Atmospheres* 107(D20):ACL-10.

Haynes, P. H., M. E. McIntyre, T. G. Shepherd, C. J. Marks, and K. Po Shine. 1991. "On the 'Downward Control' of Extratropical Diabatic Circulations by Eddy-Induced Mean Zonal Forces." *Journal of the Atmospheric Sciences* 48(4):651–78.

Holton, James R., and Clifford Mass. 1976. "Stratospheric Vacillation Cycles." *Journal of Atmospheric Sciences* 33(11):2218–25.

Holton, James R., and Hsiu-Chi Tan. 1980. "The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 Mb." *Journal of Atmospheric Sciences* 37(10):2200–2208.

Kawatani, Yoshio, Toshihiko Hirooka, Kevin Hamilton, Anne K. Smith, and Masatomo Fujiwara. 2020. "Representation of the Equatorial Stratopause Semiannual Oscillation in Global Atmospheric Reanalyses." *Atmospheric Chemistry and Physics* 20(14):9115–33.

Li, Zimu, Xinzhao Chu, V. Lynn Harvey, Jackson Jandreau, Xian Lu, Zhibin Yu, Jian Zhao, and Weichun Fong. 2020. "First Lidar Observations of Quasi-Biennial Oscillation-Induced Interannual Variations of Gravity Wave Potential Energy Density at McMurdo via a Modulation of the Antarctic Polar Vortex." *Journal of Geophysical Research: Atmospheres* 125(16). doi:10.1029/2020JD032866.

Lim, E-P, Harry H. Hendon, and David W. J. Thompson. 2018. "Seasonal Evolution of Stratosphere-troposphere Coupling in the Southern Hemisphere and Implications for the Predictability of Surface Climate." *Journal of Geophysical Research: Atmospheres* 123(21):12.

Lim, Eun-Pa, Harry H. Hendon, Ghyslaine Boschat, Debra Hudson, David W. J. Thompson, Andrew J. Dowdy, and Julie M. Arblaster. 2019. "Australian Hot and Dry Extremes Induced by Weakenings of the Stratospheric Polar Vortex." *Nature Geoscience* 12(11):896–901.

Mills, Michael J., Jadwiga H. Richter, Simone Tilmes, Ben Kravitz, Douglas G. MacMartin, Anne A. Glanville, Joseph J. Tribbia, Jean-François Lamarque, Francis Vitt, and Anja Schmidt. 2017. "Radiative and Chemical Response to Interactive Stratospheric Sulfate Aerosols in Fully Coupled CESM1 (WACCM)." *Journal of Geophysical Research: Atmospheres* 122(23):13–61.

Newman, Paul A., Eric R. Nash, and Joan E. Rosenfield. 2001. "What Controls the Temperature of the Arctic Stratosphere during the Spring?" *Journal of Geophysical Research: Atmospheres* 106(D17):19999–10.

Newman, Paul A., and William J. Randel. 1988. "Coherent Ozone-dynamical Changes during the Southern Hemisphere Spring, 1979–1986." *Journal of Geophysical Research: Atmospheres* 93(D10):12585–606.

Randel, William J., and Paul A. Newman. 1998. "The Stratosphere in the Southern Hemisphere." Pp. 243–82 in *Meteorology of the Southern Hemisphere*. Springer.

Rao, Jian, Chaim I. Garfinkel, Rongcai Ren, Tongwen Wu, and Yixiong Lu. 2023. "Southern Hemisphere Response to the Quasi-Biennial Oscillation in the CMIP5/6 Models." *Journal of Climate* 36(8):2603–23.

Renwick, James A. 2004. "Trends in the Southern Hemisphere Polar Vortex in NCEP and ECMWF Reanalyses." *Geophysical Research Letters* 31(7).

Schoeberl, Mark R., and Dennis L. Hartmann. 1991. "The Dynamics of the Stratospheric Polar Vortex and Its Relation to Springtime Ozone Depletions." *Science* 251(4989):46–52.

Shiotani, M., and I. Hirota. 1985. "Planetary Wave-mean Flow Interaction in the Stratosphere: A Comparison between Northern and Southern Hemispheres." *The Quarterly Journal of the Royal Meteorological Society* 111(464):309–34. doi:10.1002/qj.49711146804.

Shiotani, Masato, Naoki Shimoda, and Isamu Hirota. 1993. "Interannual Variability of the Stratospheric Circulation in the Southern Hemisphere." *Quarterly Journal of the Royal Meteorological Society* 119(511):531–46.

Smith, Anne K., Lesley J. Gray, and Rolando R. Garcia. 2023. "Evidence for the Influence of the Quasi-Biennial Oscillation on the Semiannual Oscillation in the Tropical Middle Atmosphere." *Journal of the Atmospheric Sciences* 80(7):1755–69. doi:10.1175/JAS-D-22-0255.1.

Solomon, Susan. 1999. "Stratospheric Ozone Depletion: A Review of Concepts and History." *Reviews of Geophysics* 37(3):275–316.

Thompson, David W. J., and Susan Solomon. 2002. "Interpretation of Recent Southern Hemisphere Climate Change." *Science* 296(5569):895–99.

Thompson, David W. J., and John M. Wallace. 2000. "Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability." *Journal of Climate* 13(5):1000–1016.

Wang, Xinyue, William Randel, Yunqian Zhu, Simone Tilmes, Jon Starr, Wandi Yu, Rolando Garcia, Owen B. Toon, Mijeong Park, and Douglas Kinnison. 2023. "Stratospheric Climate Anomalies and Ozone Loss Caused by the Hunga Tonga-Hunga Ha'apai Volcanic Eruption." *Journal of Geophysical Research: Atmospheres* 128(22):e2023JD039480.

Wang, Zhe, Jiankai Zhang, Siyi Zhao, and Douwang Li. 2025. "The Joint Effect of Mid-Latitude Winds and the Westerly Quasi-Biennial Oscillation Phase on the Antarctic Stratospheric Polar Vortex and Ozone." *Atmospheric Chemistry and Physics* 25(6):3465–80. doi:10.5194/acp-25-3465-2025.

Waugh, Darryn W., Adam H. Sobel, and Lorenzo M. Polvani. 2017. "What Is the Polar Vortex and How Does It Influence Weather?" *Bulletin of the American Meteorological Society* 98(1):37–44.

Yamashita, Yousuke, Hiroaki Naoe, Makoto Inoue, and Masaaki Takahashi. 2018. "Response of the Southern Hemisphere Atmosphere to the Stratospheric Equatorial Quasi-Biennial Oscillation (QBO) from Winter to Early Summer." *Journal of the Meteorological Society of Japan* 96(6):587–600. doi:10.2151/jmsj.2018-057.

Yang, Chengyun, Tao Li, Dexin Lai, Xinyue Wang, Xianghui Xue, and Xiankang Dou. 2022. "The Delayed Response of the Troposphere-stratosphere-mesosphere Coupling to the 2019 Southern SSW." *Geophysical Research Letters* 49(23):e2022GL101759.

Yook, Simchan, Susan Solomon, and Xinyue Wang. 2025. "The Impact of 2022 Hunga Tonga-hunga Ha'apai (Hunga) Eruption on Stratospheric Circulation and Climate." *Journal of Geophysical Research: Atmospheres* 130(6):e2024JD042943.

Yu, Wandi, Rolando Garcia, Jia Yue, Anne Smith, Xinyue Wang, William Randel, Zishun Qiao, Yunqian Zhu, V. Lynn Harvey, and Simone Tilmes. 2023. "Mesospheric Temperature and Circulation Response to the Hunga Tonga-Hunga-Ha'apai Volcanic Eruption." *Journal of Geophysical Research: Atmospheres* 128(21):e2023JD039636.

Zhu, Yunqian, Charles G. Bardeen, Simone Tilmes, Michael J. Mills, Xinyue Wang, V. Lynn Harvey, Ghassan Taha, Douglas Kinnison, Robert W. Portmann, and Pengfei Yu. 2022. "Perturbations in Stratospheric Aerosol Evolution Due to the Water-Rich Plume of the 2022 Hunga-Tonga Eruption." *Communications Earth & Environment* 3(1):248.

Zhu, Yunqian, Hideharu Akiyoshi, Valentina Aquila, Elizabeth Asher, Ewa M. Bednarz, Slimane Bekki, Christoph Brühl, Amy H. Butler, Parker Case, Simon Chabrillat, Gabriel Chiodo, Margot Clyne, Peter R. Colarco, Sandip Dhomse, Lola Falletti, Eric Fleming, Ben Johnson, Andrin Jörimann, Mahesh Kovilakam, Gerbrand Koren, Ales Kuchar, Nicolas Lebas, Qing Liang, Cheng-Cheng Liu, Graham Mann, Michael Manyin, Marion Marchand, Olaf Morgenstern, Paul Newman, Luke D. Oman, Freja F. Østerstrøm, Yifeng Peng, David Plummer, Ilaria Quaglia, William Randel, Samuel Rémy, Takashi Sekiya, Stephen Steenrod, Timofei Sukhodolov, Simone Tilmes, Kostas Tsigaridis, Rei Ueyama, Daniele Visioni, Xinyue Wang, Shingo Watanabe, Yousuke Yamashita, Pengfei Yu, Wandi Yu, Jun Zhang, and Zhihong Zhuo. 2025. "Hunga Tonga–Hunga Ha′apai Volcano Impact Model Observation Comparison (HTHH-MOC) Project: Experiment Protocol and Model Descriptions." *Geoscientific Model Development* 18(17):5487–5512. doi:10.5194/gmd-18-5487-2025.

Zhuo, Z., Wang, X., Zhu, Y., Bednarz, E. M., Fleming, E., Colarco, P. R., ... & Pausata, F. S. (2025). Comparing Multi-Model Ensemble Simulations with Observations and Decadal Projections of Upper Atmospheric Variations Following the Hunga Eruption.