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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 that the 2022 Hunga eruption drove a low-latitude jet phase with colder midlatitudes and reduced planetary wave activity

Supporting Information:

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

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Stratospheric Circulation in the Southern Hemisphere: Links to Tropical Winds, Ozone and the Hunga Eruption—Part II: Evidence From a Global Chemistry-Climate Model

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Abstract 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, coupled 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 polar vortex after sunlight returns in October. The 2022 Hunga eruption coincided with an anomalously strong LLJ year, and ensemble simulations show that the Hunga eruption shifted the SH winter circulation toward the LLJ state, although the ensemble-mean forced Hunga signal is small compared with the observed 2022 anomalies and is embedded within a large amount of stochastic variability. These results establish the LLJ as a robust mode of SH winter stratospheric variability and provide a new insight for interpreting the dynamical response to the Hunga eruption in the context of natural variability.

Plain Language Summary The strength and position of upper stratospheric winds in the Southern Hemisphere (SH) 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), with westerly anomalies centered near 30°–40°S, and a High-Latitude Jet (HLJ), with westerly anomalies located poleward near 60°–70°S. LLJ winters are associated with weaker planetary wave activity, a colder and stronger polar vortex, a deeper springtime ozone loss, and a positive phase of the southern annular mode, showing coupling between the stratospheric response and SH surface circulation. HLJ winters show the opposite behavior. The two SH winter stratospheric jet regimes 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 show that the eruption nudged the stratospheric circulation toward the LLJ pattern, in addition to the natural year-to-year variability.

1. Introduction

The Antarctic stratospheric 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 et al., 1987; Yu et al., 2025). The stratospheric polar vortex plays an important role in

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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 heterogeneous chemistry reactions to deplete ozone (Schoeberl & Hartmann, 1991; Solomon, 1999; Thompson & Solomon, 2002). 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 & Randel, 1988). In addition, the Antarctic stratospheric 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., 2018, 2019; Thompson & Wallace, 2000; Waugh et al., 2017; Yang et al., 2022). Improving our understanding of Antarctic stratospheric polar vortex variability has important implications for seasonal prediction and for society and ecosystems across the SH.

Observational studies have reported substantial interannual variability in the stratospheric polar vortex (Randel & Newman, 1998; Renwick, 2004). Shiotani et al. (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.

The latitudinal position of the stratospheric westerly jet influences the upward propagation of planetary waves. Specifically, planetary waves originate in the midlatitude upper troposphere and propagate upward only if their zonal scale is large and the westerly flow is weak relative to their phase speed (Charney & 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 (Lim et al., 2026; Newman & Randel, 1988). In spring, the SH anticyclones gradually develop over the pole as the Antarctic stratospheric polar vortex weakens, and the westerlies gradually weaken and reverse, with this transition descending from the upper to the lower stratosphere (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; X. Wang et al., 2023; Yu et al., 2023). While Yook et al. (2025) show that the shift of the stratospheric westerly jet was driven primarily by dynamical responses rather than direct radiative forcing of the Hunga volcanic plume, it remains uncertain whether the dynamical change was a forced response to the Hunga eruption or arises from 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, the Whole Atmosphere Community 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. Model Experiments and Methods

2.1. 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 $\times$ 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., 2022; Zhuo et al., 2025). There are two sets of experiments: the control case without SO_2 or H_2O (no volcanic forcing), and the $\text{SO}_2 + \text{H}_2\text{O}$ 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 versions of the model. 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) reanalysis products 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 10 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. 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.

2.2. Eliassen–Palm Flux Divergence

The analyses are based on the transformed Eulerian mean (TEM) framework, where the governing equations are written as (Andrews et al., 1987). The zonal momentum, thermodynamics, and continuity equations are given below

$$\text{DF} = \frac{\partial \bar{u}}{\partial t} - \hat{f} \bar{v}^* \quad (1)$$

$$\frac{\partial \bar{T}}{\partial t} + \bar{v}^* \frac{1}{a} \frac{\partial \bar{T}}{\partial \phi} + \bar{w}^* S = \bar{Q} \quad (2)$$

$$\frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} (\bar{v}^* \cos \phi) + e^{\frac{\hat{z}}{H}} \frac{\partial}{\partial z} (\bar{w}^* e^{-\frac{\hat{z}}{H}}) = 0 \quad (3)$$

In these equations $\text{DF} = \left(\frac{e^{\frac{\hat{z}}{H}}}{a \cos \phi} \right) (\nabla \cdot \mathbf{F})$ is the scaled Eliassen–Palm (EP) flux divergence, where $\mathbf{F}$ is the EP flux vector: $F_\phi = e^{-Z/H} a \cos \phi \left[-\bar{u}' v' + \frac{\partial \bar{u}}{\partial t} \frac{\bar{v}' T'}{S} \right]$ and $F_z = e^{-Z/H} a \cos \phi \left[-\bar{u}' w' + \hat{f} \frac{\bar{v}' T'}{S} \right]$. $(\bar{v}^*, \bar{w}^*)$ is the residual mean circulation (RMC), $\hat{f} = f - \left(\frac{1}{a \cos \phi} \right) \frac{\partial}{\partial \phi} (\bar{u} \cos \phi)$, and S is a static stability term: $S = \frac{HN^2}{R}$, with $H = 7$ km and $R = 287 \text{ m}^2 \text{ s}^{-2} \text{ K}^{-1}$, and N^2 is the Brunt–Väisälä frequency squared.

2.3. Empirical Orthogonal Function (EOF)

The dominant variability of the stratospheric circulation is examined using an EOF analysis of the deseasonalized zonal mean zonal wind (U) at 2 hPa, defined as anomalies relative to the climatological July mean. The 2 hPa level is chosen to highlight the pattern of interest; however, the results are not sensitive to the specific pressure level selected within the upper stratosphere. The EOF methods represent U as a series of orthogonal functions, such that a minimal number of EOFs can reconstruct most of the variability (Baldwin et al., 2009). The leading EOFs

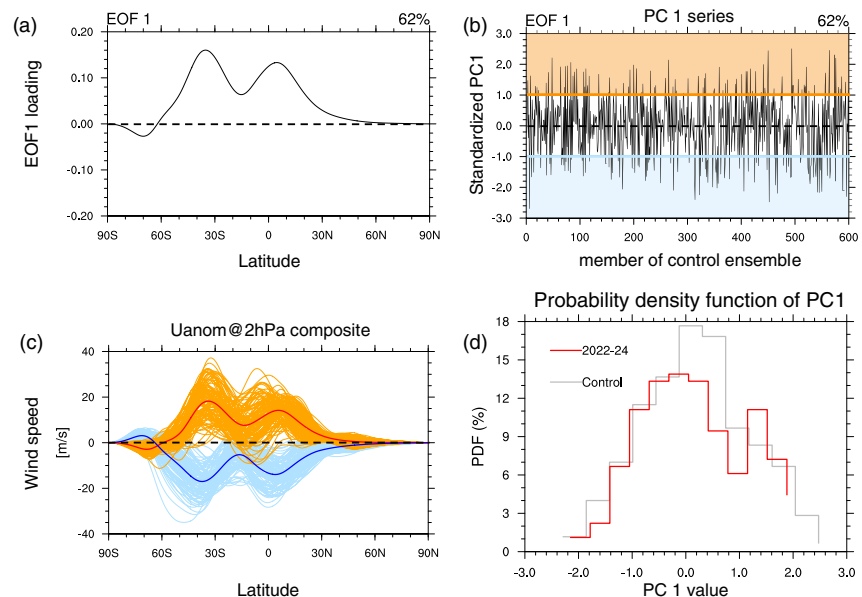


Figure 1. (a) Leading mode (EOF1) of variability in July zonal mean zonal wind (U) anomaly at 2 hPa over 2022 to 2031 in the WACCM control simulation (60 realizations), computed using zonal wind fields weighted by the cosine of latitude. (b) Standardized PC1 associated with EOF1. Orange and blue shading 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) Probability density function of the standardized PC1 values for July in the control ensemble (gray) and in the Hunga ensemble over the years 2022–2024 (red).

represent the dominant patterns of variability, with each EOF showing the spatial structure of the anomalies and its corresponding principal component (PC) quantifying the temporal amplitude and sign of that pattern. A positive PC corresponds to the EOF pattern and the negative PC corresponds to the opposite phase.

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 EOF analysis to deseasonalized July 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 (Bramberger & Bacmeister, 2025; Hall et al., 2021) causes the westerly jet axis to have unrealistically small variability.

The first EOF (EOF1), accounting for 62% of the interannual variance of the deseasonalized July U wind at 2 hPa, shows a pattern with a positive U anomaly centered at 30° – 40° S, a slight negative anomaly from 60° to 70° S, and an additional positive anomaly near the equator (Figure 1a). The corresponding standardized principal component (PC1) alternates between positive and negative phases, representing two distinct circulation regimes (Figure 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 Figure 1a, explaining 69% of the total variance (Figure S1 in Supporting Information S1). 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 Figure 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 (gray histogram in Figure 1d). The red histogram represents the distribution from the Hunga runs constructed from 180 samples from the years 2022–2024. The first 3 years were selected because they provide a sufficient sample size (180 members) to construct a robust

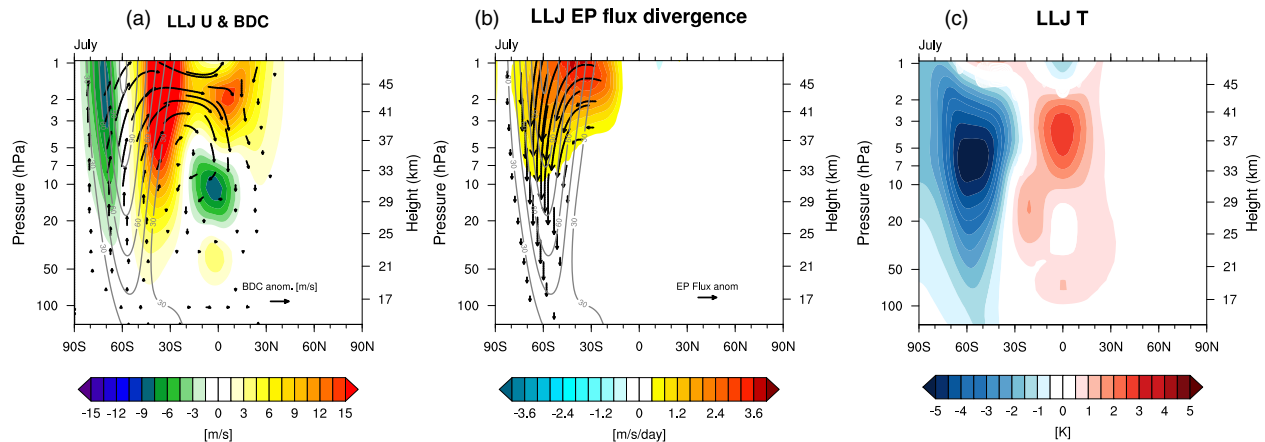


Figure 2. July composites for LLJ cases showing (a) zonal mean zonal wind anomaly (color: m/s) and residual circulation anomalies (vector: m/s); (b) The zonal-mean zonal wind tendency due to the EP flux divergence (color: m/s/day) and scaled EP flux anomalies by the air density (vectors, m³/s²); (c) Temperature anomalies (color: K). All variables are shown at the 95% significance level.

PDF of standardized PC1 values while retaining the Hunga-forced signal. The Hunga PDF departs noticeably from Gaussian behavior and is discussed in detail in Section 3.5.

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 43-year of ERA5 data in Yu25. The 600-member ensemble analyzed here provides a sample size 15 times larger than the available reanalysis record and demonstrates that the LLJ is consistently reproduced in the global climate model, confirming that it is a robust mode of climate variability. The large sample size also enables a quantitative characterization of the statistical distribution of the LLJ and HLJ regimes, which has not previously been possible because of the limited length of the observational records. 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.

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 Figure 2a. The BDC anomaly 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° and 30°S, coupled with a weakening between 60° and 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 (Figure 1c). Notably, this equatorial westerly anomaly is asymmetric about the equator, with its maximum shifted toward the Northern Hemisphere (NH) in the upper stratosphere. Close to the equator the positive westerly anomaly extends into the NH consistent with the effect of the anomalous northward residual circulation $\bar{v}^*$ (Figure 2a) in the TEM momentum equation $\frac{\partial \bar{u}}{\partial t} = \hat{f} \bar{v}^* + \text{DF}$ (Equation 1), as discussed further below.

The coupling of stratospheric mean flow and planetary waves is a well-known feature of the winter stratosphere (Andrews et al., 1987; Holton & Mass, 1976; Randel & 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

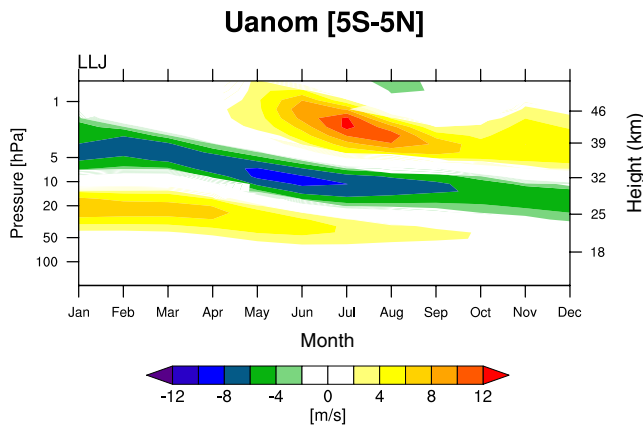


Figure 3. Monthly evolution of zonal wind anomalies (color: m/s) averaged over 5°S–5°N, composited for years with July LLJ events. Anomalies with respect to the climatological monthly mean are shown for the months before and after the July LLJ. The anomalies are plotted only where they exceed the 95% significance level according to Student's *t*-test.

divergence induces a poleward flow that in turn leads to upwelling in the tropics and downwelling at high latitudes (Haynes et al., 1991; Newman et al., 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 RMC through the Coriolis force, such that, in the low-frequency limit, $-\hat{f}v^* \sim (a \cos \theta)^{-1} \cdot DF$ (Equation 1). 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 (Figure 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 Figure 2c. A pronounced cold anomaly is observed between 60° and 40°S, centered near 5–10 hPa. In contrast, a warm anomaly appears near the equator, centered between ~50 hPa and 2 hPa.

These temperature anomalies are in consistency with the zonal wind anomalies in Figures 2a and 2b. Tropical westerly (easterly) wind anomalies are accompanied by downward (upward) motion near the equator, leading to warm (cold) temperature anomalies that peak at specific pressure levels where the vertical wind shear is strong (Anstey et al., 2022). The stratospheric cooling at 40°–60°S is consistent with the anomalous upwelling that opposes and weakens the normal background equator to pole circulation (Figure 2a), which enhances adiabatic cooling (Figure 2b). Similarly, the warming seen in the Tropics is consistent with anomalous downwelling (weaker upwelling in the BDC).

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 (as shown in Figure S2 in Supporting Information S1). The temporal evolution of the composites over specific regions will be discussed in the following sections.

3.3. 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.

Enhanced tropical westerlies above 5 hPa emerge in early austral winter (June) and peak in July and August in the composite of LLJ years. The timing and vertical structure coincide with the development of the low-latitude BDC anomalies tied to LLJ events (Figure 2a), indicating that the enhanced tropical upper stratospheric westerlies are a dynamical response to 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 Figure 2a. Our results (Figure 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 et al., 2023).

Starting earlier in the year, tropical zonal wind anomalies exhibit 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). Butchart (2022) notes strong links between QBO winds and the Antarctic polar vortex in the dynamically active spring season (November), but less coherence during midwinter. Consistent with our composites of LLJ (HLJ) cases, the SH stratospheric westerly jet strengthens (weakens) at 30°–40°S during westerly (easterly) QBO phases at 20 hPa in austral winter months, accompanied by suppressed (enhanced)

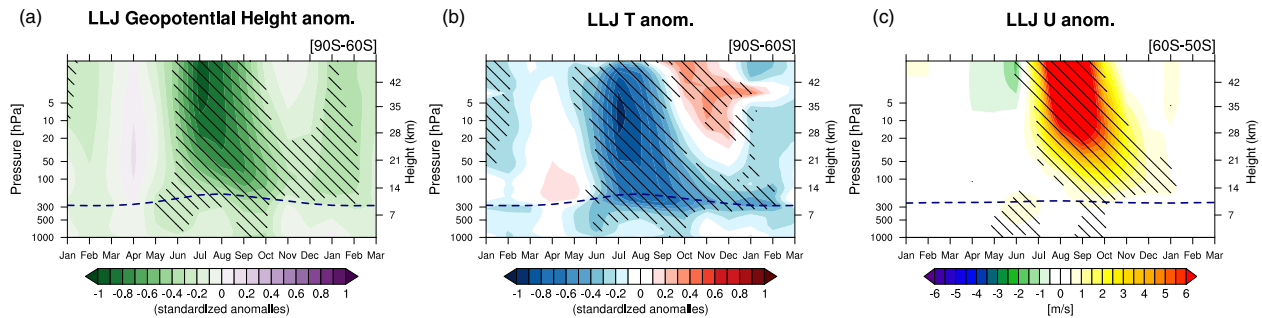


Figure 4. Monthly evolution of (a) standardized geopotential height anomalies, (b) standardized temperature anomalies, both averaged over 60° – 90° S, and (c) zonal-mean zonal wind anomalies averaged over 50° – 60° S associated with LLJ events in July. The dashed line indicates the tropopause height averaged over the corresponding region. Statistically significant anomalies at the 95% confidence level are denoted by hatching.

upward planetary wave propagation and EP flux convergence. This signal is robust across multiple reanalysis data sets 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; Z. Wang et al., 2025). A QBO-induced meridional circulation might modify the temperature gradient in the low latitudes through thermal wind balance, thereby affecting wave–mean flow interaction and contributing to changes in the strength and seasonal downward evolution 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 occurs during austral winter, supporting the development of the LLJ. However, this vertical structure differs from our model results, which show the dominant westerly anomalies at 20 hPa. The correlation between the austral winter stratospheric jet and QBO resembles the Holton-Tan effect during the NH winter (Holton & Tan, 1980). However, there are inconsistencies across models, reanalysis data sets, 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.

3.4. 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 & 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 (90° – 60° S, Figures 4a and 4b). 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, Figure 4c), the polar vortex strengthens and geopotential height decreases. The associated upward vertical velocity anomaly over the polar region (Figure 2a) contributes to the cold anomalies through adiabatic cooling. 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 & Hartmann, 1991). The midlatitude 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 (Figure 4c). These enhanced westerlies persist into late spring and early summer and gradually descend over time, and Figure 4 shows that effects extend below the tropopause to near surface levels.

Coinciding with the persisting wind anomalies, cold temperature anomalies extend into spring in the lower stratosphere (Figure 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), for example, Solomon (1999). As a result, unusually cold stratospheric winters associated with LLJ events cause deeper and more prolonged ozone reduction over 60° – 90° S, and the low ozone values persist in the lower stratosphere into December (Figure 5).

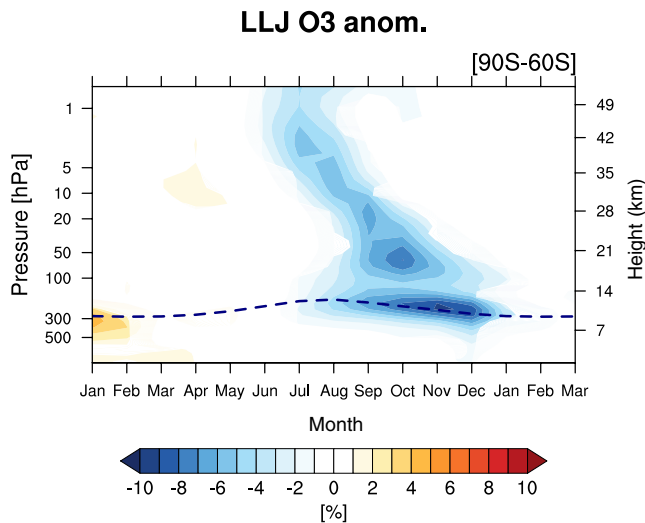


Figure 5. Monthly evolution of percentage ozone anomalies associated with July LLJ events, averaged over 60°–90°S. The dashed line indicates the pressure level of the tropopause. Anomalies not significant at the 95% confidence level are masked in white.

3.5. The 2022 Hunga Eruption

The Hunga volcanic eruption of January 2022 produced large composition changes in the stratosphere, characterized by an unprecedented 150 Tg increase in H₂O and a relatively modest increase of sulfate aerosol from the

0.5–1 Tg SO₂ (X. Wang & Coy, 2025). Satellite data and global data assimilation systems during SH winter 2022 show an unusually strong LLJ event (X. Wang & Coy, 2025; X. Wang et al., 2023; Yu et al., 2023, 2025), motivating an investigation into whether the Hunga forcing shifted the stratospheric circulation toward the LLJ regime. A 60-member ensemble of chemistry-climate model simulations for 2022 using realistic Hunga forcings of H₂O and SO₂ (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 (SO₂ + H₂O) forcing in July 2022 are shown in Figure 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 Figure 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 (Figure 7c) and reduced residual circulation (Figure 7a) and divergence of EP fluxes (Figure 7b) in the SH winter months of 2022.

As shown above, LLJ behavior is characterized by cold subpolar temperatures, coupled with weak stratospheric wave activity (EP flux), and we analyze here the two-dimensional distribution of these statistics for background (control) and Hunga simulation (Figure 8). The control simulations show overall positive relationship between these statistics that reflect 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 Figure 8) exhibit a shift in the distribution of toward colder temperatures and weaker EP fluxes, representing a fingerprint of the simulated response to the Hunga eruption (X. Wang et al., 2023; Yu et al., 2023). Specifically, 38 out of 60

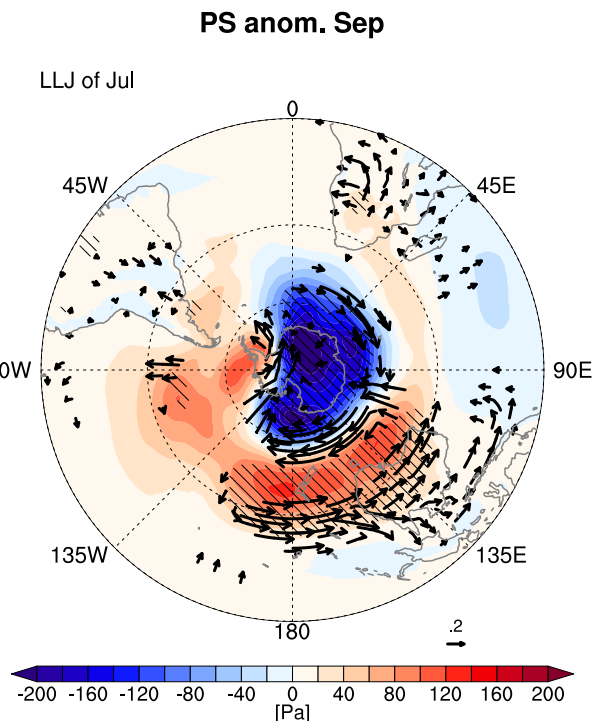


Figure 6. September composites for July LLJ cases showing surface pressure (color: Pa) and wind anomalies (vector: m/s), with regions exceeding 95% significance level hatched.

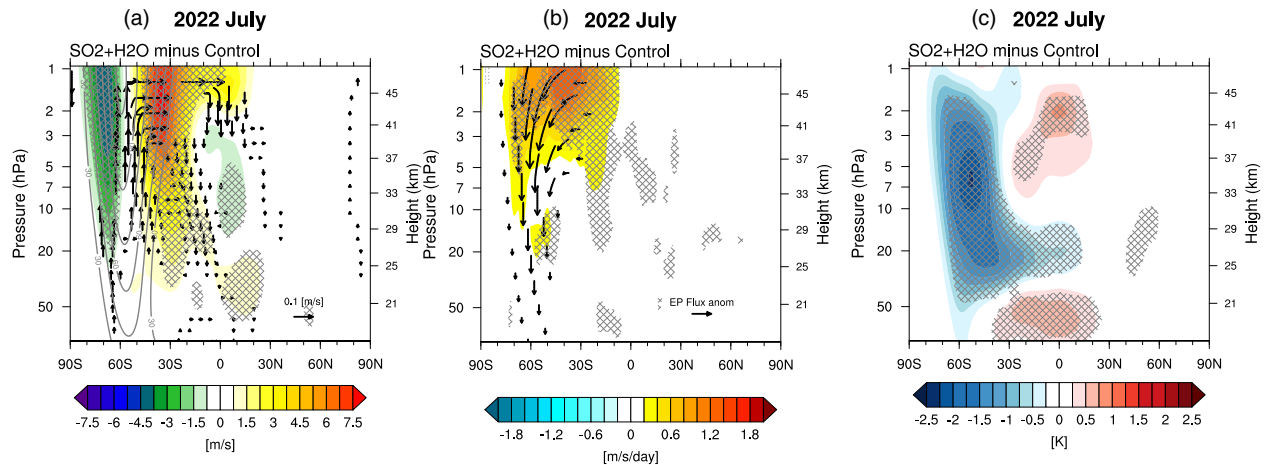


Figure 7. The 60-member ensemble mean July (a) zonal wind difference (color: m/s) and residual circulation changes (vector: m/s), (b) The zonal-mean zonal wind tendency due to the EP flux divergence (color: m/s/day), and (c) temperature difference (color: K) between Hunga and control runs. Hatched regions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

ensemble members (63%) in the 2022 Hunga run show both colder temperatures and reduced upward EP fluxes, and several simulations produce temperature and wave responses comparable to the observation (black dot in Figure 8). In contrast, in the control runs for 2022, 21 out of 60 members (35%) display an LLJ-like pattern, consistent with the background frequency of 40% due to internal variability. We interpret this shift as a fingerprint of the Hunga forcing in the WACCM simulations. However, there is large stochastic variability among the ensemble members in both control and Hunga simulations. While some individual Hunga realizations show temperature cooling comparable to that observed as shown in Yu et al. (2023), the ensemble-mean forced response to the Hunga eruption (Figure 7) is relatively small, approximately one-half the magnitude of typical LLJ events (Figure 2), which include contributions from internal variability.

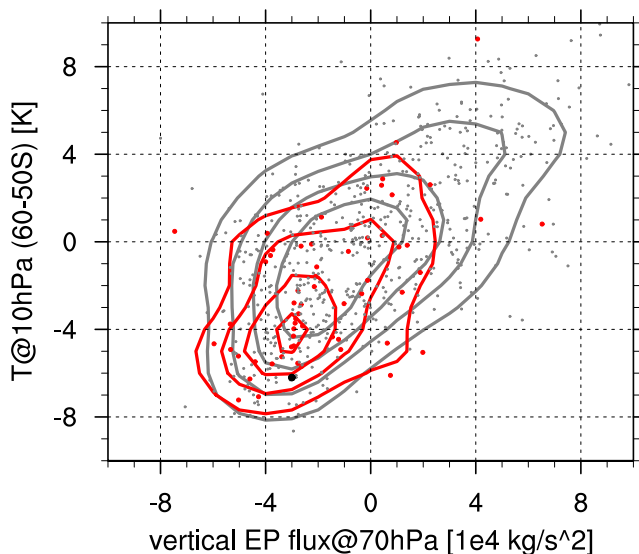


Figure 8. Distribution of July temperature anomalies over 50°–60°S at 10 hPa and upward EP flux anomalies at 70 hPa over 55°–65°S. Contours indicate the density of the data points. Red contours show results for the anomalies with respect to the control ensemble in the Hunga simulations, based on 60 ensemble members for July 2022 (denoted by red dots). Gray contours represent deviations from the control ensemble mean across July averages from 2022 to 2031 (60 ensemble members $\times$ 10 years, denoted by gray dots). The black dot indicates the July 2022 value from ERA5.

The Hunga-induced shift in circulation statistics is also evident in the distribution of *U* anomalies for the first 3 years after the eruption (Figure 1d). EOF analysis was applied to the *U* anomalies with respect to the control climatology for the first 3 years of the Hunga simulations and a PDF of the resulting PC loadings was constructed. We used 3 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, showing 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.

It is also worth noting that the Hunga eruption occurred during a westerly QBO phase at ~20 hPa in early 2022 (X. Wang & Coy, 2025), which corresponds to the preferred QBO phase associated with LLJ cases in our composite analysis (Figure 3). This phase alignment shows that the background QBO state may have preconditioned the stratospheric circulation in a manner favorable for the development of the observed LLJ event. However, the dynamical pathway linking the QBO phase and the Hunga forcing remains unclear, and we note that observations do not show an obvious impact of Hunga on the QBO (X. Wang & Coy, 2025).

The LLJ-like circulation response is also consistent with low polar cap ozone anomalies in 2022 (Figure S3 in Supporting Information S1), showing that the Hunga induced circulation anomalies favored enhanced springtime ozone

depletion and delayed ozone recovery, while the direct chemical effects of the eruption were minor (Bednarz et al., 2026; Zhang et al., 2024).

Although the SH experienced a positive SAM phase in 2022 (Yu et al., 2025), attributing any fraction of that surface pressure anomaly to the Hunga eruption remains challenging. The first-year circulation changes in the stratosphere do not produce a robust surface response, demonstrating that the Hunga-forced signal remains small relative to the surface internal variability, consistent with recent multi-model studies (Bednarz et al., 2025; Schoeberl et al., 2025).

Overall, WACCM simulations indicate a robust coupling between the Hunga forcing and the LLJ-like circulation response. However, the ensemble mean model response to Hunga is relatively weak (approximately one-half compared to background LLJ amplitude), and the physical mechanisms responsible for initiating this coupling are not well understood.

4. Summary

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 unique 600-member chemistry-climate model ensemble from WACCM6, we demonstrate that the two dominant regimes of the SH stratospheric winter westerly jet—Low-Latitude Jet (LLJ) and High-Latitude Jet (HLJ)—identified from the 43-year ERA5 reanalysis in our companion study, Yu25, are consistently reproduced in the model, confirming that these two regimes represent a robust mode of SH winter stratospheric variability. 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 enables us to explore potential precursors of LLJ and HLJ events. In particular, the model simulations show weak but significant correlations to QBO winds in the tropics over ~20–35 km (Figure 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.

Another novel aspect of this study is to provide a new framework for interpreting the dynamical response to the Hunga eruption in the context of the SH stratospheric westerly jet variability. Atmospheric observations during 2022 showed a large LLJ event, suggesting possible links to the Hunga volcanic eruption (X. Wang et al., 2023; Yook et al., 2025; Yu et al., 2023). 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 Figures 2 and 7). Probability density analysis demonstrates that Hunga volcanic forcing nudged the circulation system toward 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. The physical processes that drive the coupling between Hunga forcing and LLJ-like stratosphere remain unclear and require further investigation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

This work used JASMIN, the UK's collaborative data analysis environment (<https://www.jasmin.ac.uk>). All data used in this study are publicly available but require a JASMIN account for access. The data are archived under /gws/ssde/j25b/htmp.

CESM2/WACCM6 is an open-source community model, which was developed with support primarily from the National Science Foundation. CESM2-WACCM6 code are available from <https://www.cesm.ucar.edu/models/cesm2/>. See Gettelman et al. (2019).

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