Topography dominates the hemispheric asymmetry of Stratospheric Sudden Warmings

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Key Points:

- Climate model simulations are used to quantify the impact of topography and ocean circulation on stratospheric sudden warmings.
- Topography is found to play a dominant role in shaping the hemispheric asymmetry of SSWs through its control on eddy heat flux.
- Topography amplifies eddy heat flux by increasing the amplitude of eddy meridional wind and temperature while decreasing their phase difference.

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Abstract

Stratospheric Sudden Warmings (SSWs) predominantly occur in the Northern Hemisphere with only 1 major event recorded in the Southern Hemisphere in the satellite era. Investigating factors that contribute to this asymmetry can help to reveal the cause of SSWs and lead to improved forecasts. Here we use climate model simulations to investigate the impact of boundary conditions (topography and ocean circulation) on the asymmetry. Flattening topography eliminates Northern Hemisphere SSWs, while removing the ocean meridional overturning circulation reduces their frequency by half. The SSW response to boundary conditions is controlled by the decrease in hemispheric asymmetry of eddy heat flux. The reduction is driven by a decrease in amplitude of both eddy meridional wind and eddy temperature, as well as an increase in the difference between their phases. The results suggest boundary conditions play an important role in shaping SSWs, especially topographic forcing, but that the boundary condition interactions are nonlinear.

Plain Language Summary

SSWs are powerful events that affect surface weather and climate. They mostly happen in the Northern Hemisphere, with very few occurring in the Southern Hemisphere. Understanding why this happens is important. Using climate model simulations, we quantify how boundary conditions, such as topography and ocean circulation, affect SSWs. The results suggest topography is the primary factor influencing the difference between hemispheres in SSWs. Topography is shown to control how much heat is transferred poleward by deviations from the zonal mean, which are known to drive SSWs. More specifically, flattening topography leads to changes in the wave phase and amplitude of meridional wind and temperature, which in turn causes a decrease in poleward eddy heat flux.

1 Introduction

Stratospheric Sudden Warmings (SSWs) represent dramatic and abrupt disruptions in the winter stratosphere, characterized by a rapid increase in temperature and a decrease in the zonal-mean zonal wind in the polar vortex region (Butler et al., 2015; Baldwin et al., 2021). SSWs impact weather and climate in the Northern Hemisphere (NH) (Baldwin & Dunkerton, 1999) and Southern Hemisphere (SH) (Thompson et al., 2005), by shifting jet streams and storm tracks (Baldwin & Dunkerton, 2001; Afargan-Gerstman & Domeisen, 2020), inducing precipitation and temperature anomalies (Lehtonen & Karpechko, 2016; Lim et al., 2019). Additionally, for the SH, it suppresses strong heterogeneous ozone depletion, consequently impeding the formation of the ozone hole (Varotsos, 2002).

A notable feature of SSWs is the distinct hemispheric asymmetry in their occurrence between the Northern and Southern Hemispheres (Krüger et al., 2005). The primary focus of SSWs has been on the NH, which occur roughly every 2 years (Baldwin et al., 2021). In contrast, only one major SSW in the Southern Hemisphere (SH) took place in September 2002 (Allen et al., 2003; Simmons et al., 2005; Allen et al., 2006), and a minor one occurred in September 2019 (Hendon et al., 2019; Yamazaki et al., 2020; Rao et al., 2020).

One of the primary factors contributing to SSWs is the breaking of planetary-scale waves that propagate upwards from the troposphere (Matsuno, 1971), an important source of stratospheric variability (Polvani & Waugh, 2004; Cohen & Jones, 2011; Shaw & Perlwitz, 2013, 2014; Sjoberg & Birner, 2012, 2014; Dunn-Sigouin & Shaw, 2015, 2018, 2020). It is expected that weaker winter stratospheric variability and much fewer SSWs in the SH are due to weaker tropospheric wave driving (Plumb, 1989). Stationary planetary waves in the troposphere can be triggered by various bottom boundary conditions (Held et al., 2002; Garfinkel et al., 2020), including large-scale topography (Charney & Eliassen, 1949), surface thermal forcing such as land-sea contrasts (Smagorinsky, 1953) and asymmetric

surface energy fluxes (Shaw et al., 2022), and the nonlinear interactions of synoptic-scale eddies (Scinocca & Haynes, 1998).

Previous research has primarily focused on investigating the impact of idealized topography on stratospheric variability. Dry dynamical core models show the seasonal and interannual variability of extratropical stratospheric circulation depends on the amplitude of idealized topography, and hence on topographically forced stationary waves (Taguchi & Yoden, 2002; Gerber & Polvani, 2009; Sheshadri et al., 2015; Lindgren et al., 2018; Dunn-Sigouin & Shaw, 2018, 2020). These studies have shown that increasing the amplitude of idealized wave-2 topography leads to the stratosphere entering a regime in which SSWs take place. Specifically, the small amplitude of topography corresponds to the SH where the polar night jet is strong and stratospheric variability is small while for large amplitude topography corresponding to the NH stratospheric variability is large. However, only a limited number of studies (e.g., Garfinkel et al., 2020) have examined the impact of realistic topography with land and compared the relative importance of different factors triggering tropospheric planetary waves that lead to SSWs. This research gap signals the need for a more comprehensive understanding of the various forcings contributing to the occurrence of SSWs.

Here we seek to address the following questions: (a) What are the relative contributions of boundary conditions, including topography and the ocean meridional overturning circulation, to the hemispheric asymmetry of SSWs? (b) Through what mechanisms do boundary conditions affect stratospheric variability? Our approach to answering these questions involves examining SSWs in climate model simulations with modified surface (land and ocean) boundary conditions.

2 Data and Methods

2.1 Climate Model Simulations

We make use of the ECHAM6 slab-ocean atmosphere general circulation model simulations previously reported by Shaw et al. (2022). The model incorporates a realistic land surface featuring topography, a 50 meter mixed layer ocean depth, and has prescribed monthly varying observationally-derived surface energy fluxes over the ocean. The observationally-derived surface energy fluxes are quantified by the difference of NASA CERES TOA radiative flux and the atmospheric energy flux divergence derived from ERA-Interim reanalysis data (Frierson et al., 2013; Shaw et al., 2022). Similar results are found when the surface energy fluxes are q-flux derived from an prescribed sea surface temperature simulation.

The impact of boundary conditions on the hemispheric asymmetry of SSWs, is quantified by comparing 60-year simulations with realistic boundary conditions to simulations with flattened topography and symmetric surface energy fluxes. As discussed in Shaw et al. (2022), the flattened topography experiment involves setting the surface geopotential and mean orography to zero in the surface boundary condition input file. The symmetrized surface energy flux experiment involves setting the surface energy flux at each latitude to the average of the surface energy flux (over the ocean) for the Northern Hemisphere and Southern Hemispheres. Symmetrizing the surface energy fluxes removes the ocean meridional overturning circulation (Frierson et al., 2013) and east-west sea-surface temperature gradients.

2.2 Reanalysis

The ERA5 reanalysis (Hersbach et al., 2020) from 1958-2022 is used in this study. We used daily zonal and meridional wind and temperature to evaluate the model's ability to simulate a reasonable frequency of SSWs and eddy meridional heat flux.

2.3 SSW and eddy heat flux definitions

The identification of a major SSW in both hemispheres follows the method in Charlton and Polvani (2007). A major SSW is identified when the zonal mean westerlies at 60°N/60°S and 10 hPa change to easterlies during winter (November-March for the Northern Hemisphere, May-September for the Southern Hemisphere) and lasts for at least 3 days. The date of the wind reversal is designated as the onset date. Subsequent SSW events are not considered if they occur within 20 days following the most recent onset date. Events where zonal-mean easterlies fail to revert to westerlies before April are also excluded.

We calculate the monthly mean meridional eddy heat flux $\overline{v^*T^*}$ at 100 hPa to quantify the wave activity entering the stratosphere (Polvani & Waugh, 2004). Here, v and T are the meridional wind and temperature, respectively, while the overline and asterisk denote the monthly mean and deviations from the zonal mean. Additionally, v and T at 60°N and 100 hPa are decomposed into different wavenumbers. The amplitude and phase for each wave component are calculated following Watt-Meyer and Kushner (2018).

3 Results

3.1 The evaluation of the climate model

In ERA5, the frequency of SSWs per year (f_{SSW}) in the NH is approximately 0.61/year while there is only 1 major SSW in the SH, consistent with previous studies (Butler et al., 2015; Baldwin et al., 2021). The model forced with realistic boundary conditions, including observationally derived climatological surface energy fluxes, hereafter referred to as ALL, reproduces the observed f_{SSW} in the NH (Table 1 ALL), outperforming most CMIP5/6 simulations (Rao & Garfinkel, 2021). Additionally, it accurately simulates the hemispheric asymmetry in f_{SSW}, as the model simulation does not produce any SSWs in the Southern Hemisphere.

Table 1. Frequency of SSW (f_{SSW}) in Northern and Southern Hemisphere in ERA5 reanalysis (1958-2022) and in the climate model simulations forced with realistic boundary conditions, including observationally derived climatological surface energy fluxes (ALL). Frequency of SSW is also shown for simulations with perturbed boundary conditions: flattened topography (FLAT), symmetrized surface energy fluxes (SYMS), and flattened topography and symmetrized surface energy fluxes (F+S).

	NH	SH
ERA5	40/65	1/65
ALL	40/60	0/60
FLAT	1/60	0/60
SYMS	22/60	0/60
F+S	0/60	0/60

Our simulations do not simulate any SSWs in the SH. At first glance this might seem like a model bias, however we consider this outcome to be not unexpected. Jucker and Reichler (2023) demonstrate the occurrence of 161 SSWs in the SH through a 9990-year coupled climate model simulation, with a frequency of one event every 62 years. Hence, it is plausible for no SSWs to manifest within a 60-year simulation period.

To further assess the model's capability in simulating stratospheric variability, Fig. 1 illustrates the monthly distribution of SSW frequency in the NH. In contrast to a common bias observed in CMIP5/6 simulations, where SSWs are most frequent in late winter (February-March) rather than midwinter (January-February) (Wu & Reichler, 2020; Rao & Garfinkel, 2021), the model's climatology simulation (ALL) exhibits SSWs predominantly in midwinter.

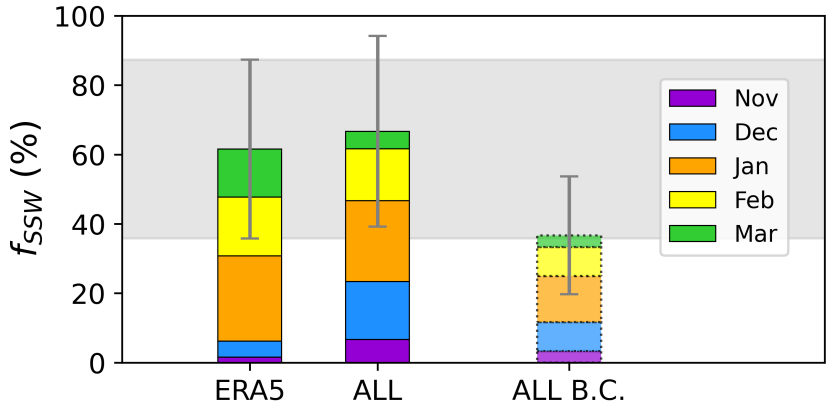

Figure 1. Monthly Distribution of the SSW frequency (f_{SSW}) in the NH of ERA5 (1958–2022) and climate model simulations (ALL). The third column (ALL B.C.) is the bias corrected ALL simulation where the daily zonal-mean zonal wind climatology at 10 hPa and 60°N (U_{1060}) is corrected by replacing it with ERA5. The gray shading represents the 95% confidence interval of ERA5 and the gray whisker on each bar represents the 95% confidence interval of each simulation.

The simulated f_{SSW} can be affected by biases in the climatological mean state of the polar vortex (Scaife et al., 2010). When the ALL daily zonal-mean zonal wind climatology at 10 hPa and 60°N is replace by that from ERA5 f_{SSW} decreases (Fig. 1, ALL B.C.), indicating an underestimation of U_{1060} (Fig. S1a,m). Despite the presence of a bias in the magnitude of the climatological zonal mean zonal wind, the model effectively captures the vertical profile (Fig. S1) and seasonality of U1060 (Fig. 1). Thus, while there may be discrepancies in certain aspects, the model remains a valuable tool for investigating the frequency of SSWs under varied boundary conditions as it outperforms many CMIP5/6 models.

3.2 The impact of boundary conditions on SSWs

When topography is flattened in the model, the occurrence of SSWs in the NH nearly vanishes and so does the SSW asymmetry between the hemisphere (Table 1 FLAT), with only one SSW occurring during February in the NH. When the model is forced with symmetrized surface energy fluxes, which eliminates the ocean meridional overturning circulation, SSWs in the Northern Hemisphere decrease by half (Table 1 SYMS). When topography is flattened and symmetrized surface energy fluxes are applied (Table 1 F+S), no SSWs are observed throughout the 60-year simulation period in either hemisphere. The simulations suggest topography dominates the SSW hemispheric asymmetry with a smaller contribution from the ocean circulation. The results also indicate the boundary conditions interact nonlinearly.

3.3 The asymmetry of meridional eddy heat flux

To explain the changes in SSW frequency across our simulations, we next consider the meridional eddy heat flux, a representation of the upward propagation of planetary waves from the troposphere. The distribution of NH eddy heat flux at 100 hPa is positively skewed in ERA5 (Fig. 2a). The ALL simulation captures the ERA5 distribution well (Fig. 2b). The skewed distribution, particularly the long tail, implies that there is ample opportunity for internal variability to trigger a strong pulse of planetary wave forcing which can induce a SSW (Matsuno, 1971; Watt-Meyer & Kushner, 2018).

When the topography is flattened (Fig. 2c, e), the median value of the eddy heat flux distribution decreases, implying a reduced likelihood of upward wave propagation, consistent with the decrease in SSW frequency in the NH. However, symmetrizing the surface energy flux (Fig. 2d) exhibits a non-statistically significant impact on the wave forcing in the NH even though the SSW frequency decreases by 1/3 in the NH, consistent with the decrease in median value from 7.13 to 6.66 Km/s and 7% decrease in heat flux values exceeding 10Km/s. When topography is flattened and the surface energy fluxes are symmetrized the median value is once again significantly reduced suggesting topography is the dominant influence on the distribution.

In the SH, characterized by lower orographic features and a scarcity of SSWs, the meridional eddy heat flux distribution has a smaller median value and fewer extreme values (Fig. 2f, g). When topography is flattened the median value of the eddy heat flux distribution decrease (Fig. 2h) but it is weak and insignificant. Symmetrizing the surface energy flux also results in a decrease of the median of the eddy heat flux distribution (Fig. 2i, j). This is likely due to the predominance of oceanic areas in the SH, where applying symmetric surface energy flux average out the zonal differences in the surface energy flux, consequently weakening the stationary circulation.

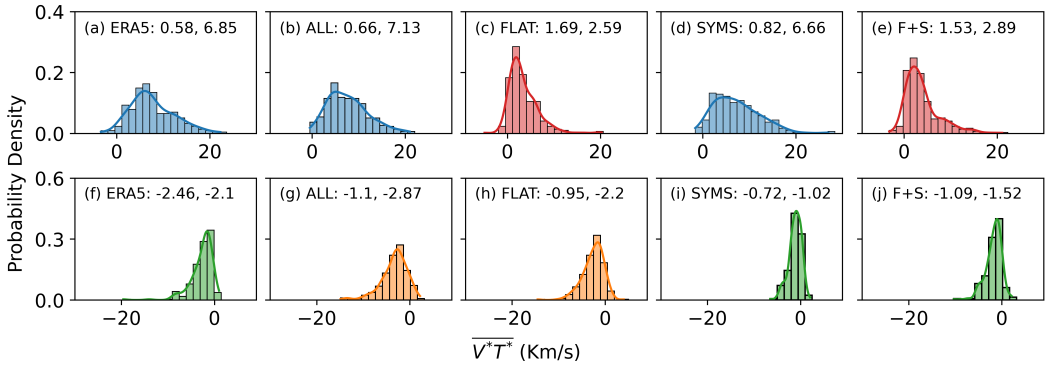

Figure 2. Distribution of monthly mean meridional eddy heat flux ($\overline{v^*T^*}$, Km s^{-1}) at 100 hPa averaged poleward of 45°N in SSW related season (Northern Hemisphere: Nov-Mar, Southern Hemisphere: May-Sep) in (a)(f) ERA5 and (b)(g) ALL , (c)(h) FLAT, (g)(i) SYMS, and (e)(j) F+S simulations. The top row is for Northern Hemisphere and the bottom row is for Southern Hemisphere. The value at the top of each panel are the skewness and median value of the distribution, respectively. Distributions that are significantly different from ALL (statistical significance at 95% level based on K-S test) have different colors .

To further investigate the impact of boundary conditions on the meridional eddy heat flux we examine its vertically-integrated spatial structure. The NH eddy heat flux in ERA5 (Fig. S2a) is large in the mid-latitude region (30°N-60°N) across various longitudes, especially around 120°E, which is captured by ALL (Fig. S2d). In contrast, the eddy heat

flux in the SH is small and doesn't exhibit significant longitudinal structure (Fig. S2b, e). Therefore, the simulation with topography reveals the most substantial asymmetry around 120°E (Fig. 3a, b, d), aligning with the downstream location of the Tibetan Plateau. Averaged over the extratropics (20 to 90 degrees) the asymmetry is 40%, comparable with $\sim 50\%$ in ERA5 (Fig. 3f).

When topography is flattened, the hemispheric asymmetry significantly reduces across all longitudes (Fig. 3c, e). In particular, the extratropical asymmetry decreases from around 40% to 3%, which is consistent with the decrease of eddy heat flux in the NH at 100 hPa (Fig. 2c, e). The impact of topography on the asymmetry of eddy heat flux is evident at 850hPa (Fig. S3), 300 hPa (Fig. S4) and 100 hPa (Fig. S5), rather than being confined to a single level. Notably, the reduction in asymmetry is primarily due to the decrease in the NH, particularly around longitudes where significant topographical features exist (e.g., 120°E and 100°W), while the change in the SH is negligible.

In contrast, when surface energy fluxes are symmetrized the eddy heat flux asymmetry is not significantly reduced (Fig. 3d). Consistently the extratropical asymmetry is still 37% (Fig. 3f). Symmetrizing decreases the meridional eddy heat flux in both hemispheres across all levels (Fig. S3h, S4h, S5h). Finally, when topography is flattened in the presence of symmetrized surface energy fluxes the meridional eddy heat flux asymmetry is once again negligible across all longitudes (Fig. 3e). Consistently, the extratropical asymmetry decreases to 7% (Fig. 3f). This shows that the boundary conditions interact non linearly in terms of their influence on the meridional eddy heat flux.

3.4 Understanding how topography affects the eddy heat flux asymmetry

The simulations show flattening exerts a dominant control on SSWs and the meridional eddy heat flux hemispheric asymmetry. Given the weak and negligible impact of topography on the distribution of eddy heat flux in the SH, we explore how topography affects the meridional eddy heat flux asymmetry, particularly focusing on its reduction in the NH. If v^* and T^* are represented using the complex exponential representation of a Fourier series, their covariance $\overline{v^*T^*}$ can be written as

$$\overline{v^*T^*} = A_v A_T e^{i(\theta_v - \theta_T)} \tag{1}$$

where A_v and A_T are the amplitude of v^* and T^*, θ_v and θ_t are the phase of v^* and T^*.

Consequently, the decrease in eddy heat flux ($\overline{v^*T^*}$) when topography is flattened might arise from various factors, including a decline in amplitude of eddy meridional wind (v^*) and/or eddy temperature (T^*), as well as a increase in the difference between their phases, namely the two variables becoming out of phase.

Fig. 4 shows the probability distribution of the amplitude, and phase difference of monthly mean eddy meridional wind and eddy temperature at 100 hPa and 60°N across the climate model simulations following Watt-Meyer and Kushner (2018). Flatenning topography results in a decrease of over 30% in the median value of the wave-1 amplitude for both eddy meridional wind (Fig. 4a) and eddy temperature (Fig. 4b). Furthermore, the phase difference between the two variables becomes slightly larger when topography is removed (Fig. 4c).

For the wave-2 component, the mode of the amplitude distributions decreases by over 20% when topography is removed (Fig. 4d, e) while the change in the median value is less significant compared to the wave-1 component. In contrast, the eddy meridional wind and temperature become more out of phase in the absence of topography (Fig. 4f). The phase difference increases by approximately 40% following flattening topography, thereby contributing to the decline in eddy heat flux in the Northern Hemisphere. Moving towards larger wavenumber components, a reduction in the amplitude of eddy temperature (Fig. S6b, e) is evident. However, variations in other components remain relatively modest.

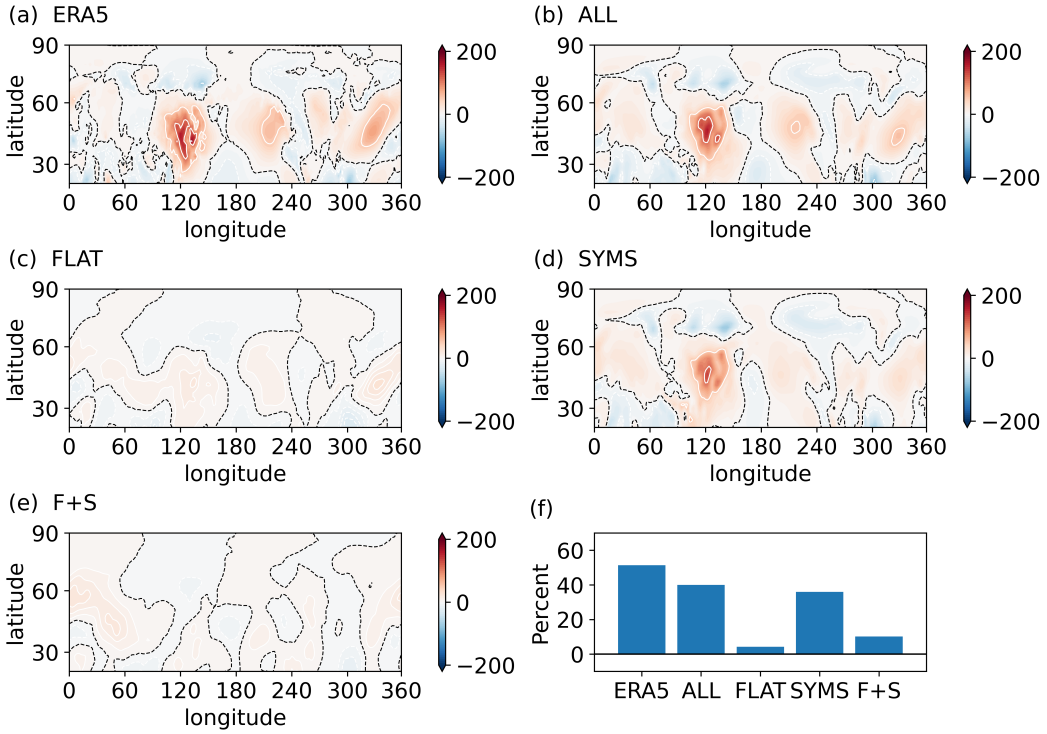

Figure 3. Difference of the vertically integrated monthly mean meridional eddy heat flux ($\overline{v^*T^*}$, Km s^{-1}) between Northern and Southern Hemispheres in SSW related season (NH: Nov-Mar, SH: May-Sep) in (a) ERA5, (b) ALL, (c) FLAT, (d) SYMS and (e) F+S simulations. The dashed black lines indicates where $\overline{v^*T^*}$ is equal to 0 MJ m^{-2}. (f) Percentage difference of zonal-mean, vertically integrated stationary eddy heat flux ($\overline{v^*T^*}$, Km s^{-1}) (difference of the absolute value of Northern and Southern Hemisphere divided by Northern Hemisphere) averaged over poleward of 20° across the simulations.

Overall, the reduction in wave-1 heat flux is due to a reduction in the amplitude of v^*, T^*, and an increase in the phase difference, while the reduction in wave-2 median heat flux is driven mainly by the phase difference.

4 Discussion

In this study, we used climate model simulations to quantify the impact of boundary conditions on the hemispheric asymmetry of SSWs. Our approach aligns with prior studies that used climate models to understand the impact of boundary conditions on the hemispheric asymmetry of atmospheric features (Manabe & Terpstra, 1974; Frierson et al., 2013; Shaw et al., 2022). More specifically we quantified the impact of topography by flattening it, and the impact of the ocean meridional overturning circulation by symmetrizing the surface energy fluxes in the slab ocean (Stevens et al., 2013).

Our goal was to answer the two questions posed in the Introduction. Namely (1) What are the relative contributions of boundary conditions, including topography and the ocean meridional overturning circulation, on the hemispheric asymmetry of SSWs? (2) Through what mechanisms do boundary conditions affect stratospheric variability?

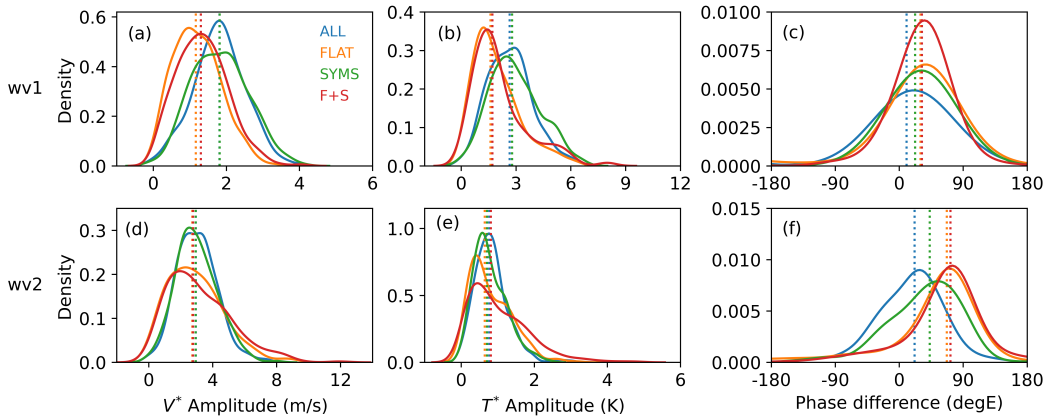

Figure 4. Probability distribution of the amplitude of monthly mean eddy meridional wind (v^*, m s^{-1}) (the first column) and monthly mean eddy temperature (T^*, K) (the second column), and the phase difference between the two variables (the third column) in the NH for (a)-(c) wave-1 and (d)-(f) wave-2 component at 60°N and 100 hPa in SSW related season (Northern Hemisphere: Nov-Mar) for ALL (blue), FLAT (orange), SYMS (green), and F+S (red) simulations. The dotted lines represents the median value for each distribution.

The answer to the first question is that topography dominates the hemispheric asymmetry of SSWs while the asymmetric surface energy fluxes plays a smaller role in the presence of topography. Topography essentially eliminates SSWs in the NH and eliminates the hemispheric asymmetry. Symmetrizing surface energy fluxes only reduces NH SSWs by 1/3. Notably, the impact of topography on the asymmetry percentage of eddy heat flux is substantial, exceeding 35%, with non-additive contributions from various boundary forcings indicating nonlinear interactions among them. Although our results demonstrate that the boundary conditions interact nonlinearly in terms of their impact on SSWs, it is clear that topography is the more significant factor.

The answer to the second question is that topography affects stratospheric variability by increasing the amplitude of eddy temperature and meridional winds, and decreasing their phase difference. Specifically, removal of topography results in a decrease in the median value of the amplitude for both eddy meridional wind and eddy temperature, particularly for wave number 1. This reduction is accompanied by an increase in the phase difference between the two variables, namely they becomes more out of phase with each other. These changes in both amplitude and phase induced by topography lead to a regional increase in eddy heat flux, especially over Eurasia, which indicates upward propagation of planetary waves into the stratosphere, thereby disturbing the polar vortex and causing more SSWs.

Our results are consistent with previous work that demonstrated topography significantly affects stationary wave features (Manabe & Terpstra, 1974; Held, 1983; Garfinkel et al., 2020). It is commonly assumed that both topography and land-ocean contrast contribute to the hemispheric asymmetry of SSWs and eddy heat flux. However, our analysis shows topography is the dominant factor.

While our simulations do not specifically isolate the impact of thermal forcing from land-sea contrast, our result suggest that the hemispheric asymmetry of SSWs are minimal with flattened topography even in the presence of land-sea contrast. Furthermore the fact that the eddy heat flux asymmetry in the simulation with flattened topography is small strongly suggests that topography exerts a more substantial influence than land-sea contrast. By flattening the topography, the contributions of both the topography and

nonlinear interaction between topographic and thermal forcings are excluded, leaving only the minor contribution from thermal forcing. Reproducing these results in other climate models is important to ensure their robustness.

5 Data Availability Statement

The data analyzed in this study is available through Shaw et al., 2022.

References

Afargan-Gerstman, H., & Domeisen, D. I. (2020). Pacific modulation of the north atlantic storm track response to sudden stratospheric warming events. *Geophysical Research Letters*, *47*(2), e2019GL085007.

Allen, D. R., Bevilacqua, R. M., Nedoluha, G. E., Randall, C. E., & Manney, G. L. (2003). Unusual stratospheric transport and mixing during the 2002 antarctic winter. *Geophysical Research Letters*, *30*(12).

Allen, D. R., Coy, L., Eckermann, S. D., McCormack, J. P., Manney, G. L., Hogan, T. F., & Kim, Y.-J. (2006). Nogaps-alpha simulations of the 2002 southern hemisphere stratospheric major warming. *Monthly weather review*, *134*(2), 498–518.

Baldwin, M. P., Ayarzagüena, B., Birner, T., Butchart, N., Butler, A. H., Charlton-Perez, A. J., ... others (2021). Sudden stratospheric warmings. *Reviews of Geophysics*, *59*(1), e2020RG000708.

Baldwin, M. P., & Dunkerton, T. J. (1999). Propagation of the arctic oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research: Atmospheres*, *104*(D24), 30937–30946.

Baldwin, M. P., & Dunkerton, T. J. (2001). Stratospheric harbingers of anomalous weather regimes. *Science*, *294*(5542), 581–584.

Butler, A. H., Seidel, D. J., Hardiman, S. C., Butchart, N., Birner, T., & Match, A. (2015). t. *Bulletin of the American Meteorological Society*, *96*(11), 1913-1928.

Charlton, A. J., & Polvani, L. M. (2007). A new look at stratospheric sudden warmings. part i: Climatology and modeling benchmarks. *Journal of climate*, *20*(3), 449–469.

Charney, J. G., & Eliassen, A. (1949). A numerical method for predicting the perturbations of the middle latitude westerlies. *Tellus*, *1*(2), 38–54.

Cohen, J., & Jones, J. (2011). Tropospheric precursors and stratospheric warmings. *Journal of climate*, *24*(24), 6562–6572.

Dunn-Sigouin, E., & Shaw, T. (2018). Dynamics of extreme stratospheric negative heat flux events in an idealized model. *Journal of the Atmospheric Sciences*, *75*(10), 3521–3540.

Dunn-Sigouin, E., & Shaw, T. (2020). Dynamics of anomalous stratospheric eddy heat flux events in an idealized model. *Journal of the Atmospheric Sciences*, *77*(6), 2187–2202.

Dunn-Sigouin, E., & Shaw, T. A. (2015). Comparing and contrasting extreme stratospheric events, including their coupling to the tropospheric circulation. *Journal of Geophysical Research: Atmospheres*, *120*(4), 1374–1390.

Frierson, D. M., Hwang, Y.-T., Fučkar, N. S., Seager, R., Kang, S. M., Donohoe, A., ... Battisti, D. S. (2013). Contribution of ocean overturning circulation to tropical rainfall peak in the northern hemisphere. *Nature Geoscience*, *6*(11), 940–944.

Garfinkel, C. I., White, I., Gerber, E. P., Jucker, M., & Erez, M. (2020). The building blocks of northern hemisphere wintertime stationary waves. *Journal of Climate*, *33*(13), 5611-5633.

Gerber, E. P., & Polvani, L. M. (2009). Stratosphere–troposphere coupling in a relatively simple agcm: The importance of stratospheric variability. *Journal of Climate*, *22*(8), 1920-1933.

Held, I. M. (1983). Stationary and quasi-stationary eddies in the extratropical troposphere: Theory. *Large-scale dynamical processes in the atmosphere*, *127*, 168.

Held, I. M., Ting, M., & Wang, H. (2002). Northern winter stationary waves: Theory and modeling. *Journal of climate*, *15*(16), 2125–2144.

Hendon, H. H., Thompson, D., Lim, E.-P., Butler, A. H., Newman, P. A., Coy, L., & Scaife, A. (2019). Rare forecasted climate event under way in the southern hemisphere. *Nature*, *573*(7775), 495–496.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... others (2020). The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049.

Jucker, M., & Reichler, T. (2023). Life cycle of major sudden stratospheric warmings in the southern hemisphere from a multimillennial gcm simulation. *Journal of Climate*, *36*(2), 643–661.

Krüger, K., Naujokat, B., & Labitzke, K. (2005). The unusual midwinter warming in the southern hemisphere stratosphere 2002: A comparison to northern hemisphere phenomena. *Journal of the atmospheric sciences*, *62*(3), 603–613.

Lehtonen, I., & Karpechko, A. Y. (2016). Observed and modeled tropospheric cold anomalies associated with sudden stratospheric warmings. *Journal of Geophysical Research: Atmospheres*, *121*(4), 1591–1610.

Lim, E.-P., Hendon, H. H., Boschat, G., Hudson, D., Thompson, D. W., Dowdy, A. J., & Arblaster, J. M. (2019). Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. *Nature Geoscience*, *12*(11), 896–901.

Lindgren, E., Sheshadri, A., & Plumb, R. (2018). Sudden stratospheric warming formation in an idealized general circulation model using three types of tropospheric forcing. *Journal of Geophysical Research: Atmospheres*, *123*(18), 10,125-10,139.

Manabe, S., & Terpstra, T. B. (1974). The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments. *Journal of Atmospheric Sciences*, *31*(1), 3–42.

Matsuno, T. (1971). A dynamical model of the stratospheric sudden warming. *Journal of Atmospheric Sciences*, *28*(8), 1479–1494.

Plumb, R. A. (1989). On the seasonal cycle of stratospheric planetary waves. *Pure and applied geophysics*, *130*, 233-242.

Polvani, L. M., & Waugh, D. W. (2004). Upward wave activity flux as a precursor to extreme stratospheric events and subsequent anomalous surface weather regimes. *Journal of Climate*, *17*(18), 3548-3554.

Rao, J., & Garfinkel, C. I. (2021). Cmip5/6 models project little change in the statistical characteristics of sudden stratospheric warmings in the 21st century. *Environmental Research Letters*, *16*(3), 034024.

Rao, J., Garfinkel, C. I., White, I. P., & Schwartz, C. (2020). The southern hemisphere minor sudden stratospheric warming in september 2019 and its predictions in s2s models. *Journal of Geophysical Research: Atmospheres*, *125*(14), e2020JD032723.

Scaife, A. A., Woollings, T., Knight, J., Martin, G., & Hinton, T. (2010). Atmospheric blocking and mean biases in climate models. *Journal of Climate*, *23*(23), 6143–6152.

Scinocca, J., & Haynes, P. (1998). Dynamical forcing of stratospheric planetary waves by tropospheric baroclinic eddies. *Journal of the Atmospheric Sciences*, *55*(14), 2361–2392.

Shaw, T. A., Miyawaki, O., & Donohoe, A. (2022). Stormier southern hemisphere induced by topography and ocean circulation. *Proceedings of the National Academy of Sciences*, *119*(50), e2123512119.

Shaw, T. A., & Perlwitz, J. (2013). The life cycle of northern hemisphere downward wave coupling between the stratosphere and troposphere. *Journal of climate*, *26*(5), 1745–1763.

Shaw, T. A., & Perlwitz, J. (2014). On the control of the residual circulation and stratospheric temperatures in the arctic by planetary wave coupling. *Journal of the Atmospheric Sciences*, *71*(1), 195–206.

Sheshadri, A., Plumb, R. A., & Gerber, E. P. (2015). Seasonal variability of the polar stratospheric vortex in an idealized agcm with varying tropospheric wave forcing. *Journal of the Atmospheric Sciences*, *72*(6), 2248–2266.

Simmons, A., Hortal, M., Kelly, G., McNally, A., Untch, A., & Uppala, S. (2005). Ecmwf

analyses and forecasts of stratospheric winter polar vortex breakup: September 2002 in the southern hemisphere and related events. *Journal of the Atmospheric Sciences*, *62*(3), 668–689.

Sjoberg, J. P., & Birner, T. (2012). Transient tropospheric forcing of sudden stratospheric warmings. *Journal of the Atmospheric Sciences*, *69*(11), 3420–3432.

Sjoberg, J. P., & Birner, T. (2014). Stratospheric wave–mean flow feedbacks and sudden stratospheric warmings in a simple model forced by upward wave activity flux. *Journal of the Atmospheric Sciences*, *71*(11), 4055–4071.

Smagorinsky, J. (1953). The dynamical influence of large-scale heat sources and sinks on the quasi-stationary mean motions of the atmosphere. *Quarterly Journal of the Royal Meteorological Society*, *79*(341), 342–366.

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., ... others (2013). Atmospheric component of the mpi-m earth system model: Echam6. *Journal of Advances in Modeling Earth Systems*, *5*(2), 146–172.

Taguchi, M., & Yoden, S. (2002). Internal interannual variability of the troposphere–stratosphere coupled system in a simple global circulation model. part i: Parameter sweep experiment. *Journal of the Atmospheric Sciences*, *59*(21), 3021-3036.

Thompson, D. W., Baldwin, M. P., & Solomon, S. (2005). Stratosphere–troposphere coupling in the southern hemisphere. *Journal of the atmospheric sciences*, *62*(3), 708–715.

Varotsos, C. (2002). The southern hemisphere ozone hole split in 2002. *Environmental Science and Pollution Research*, *9*, 375–376.

Watt-Meyer, O., & Kushner, P. J. (2018). Why are temperature and upward wave activity flux positively skewed in the polar stratosphere? *Journal of Climate*, *31*(1), 115-130.

Wu, Z., & Reichler, T. (2020). Variations in the frequency of stratospheric sudden warmings in cmip5 and cmip6 and possible causes. *Journal of Climate*, *33*(23), 10305-10320.

Yamazaki, Y., Matthias, V., Miyoshi, Y., Stolle, C., Siddiqui, T., Kervalishvili, G., ... others (2020). September 2019 antarctic sudden stratospheric warming: Quasi-6-day wave burst and ionospheric effects. *Geophysical Research Letters*, *47*(1), e2019GL086577.