Response to Reviewer 1

General Comments

This paper considers the role of the stratosphere in modulating upward propagating waves from the troposphere, and thereby the subsequent recovery of the stratospheric polar vortex following a sudden warming. The paper is well written and clearly laid out. The figures are of good quality and the results support the conclusions.

My main comment is whether the results and conclusions are as novel as is made out. I would suggest adding further references as detailed below, and further clarifying what new science is included in the current study.

Response: Thank you for the careful reading of the manuscript, the positive assessment, and the constructive suggestions. We agree that the original manuscript did not sufficiently distinguish the established role of the stratospheric mean flow in regulating planetary-wave propagation from the specific contribution of this study. We have broadened the relevant literature in the Introduction and revised the Discussion and Conclusions accordingly. We have clarified that the specific contribution of this study lies in diagnosing how the displacement and partial recovery of the Antarctic vortex edge redistributed the zonal-mean QGPV gradient and altered the meridional overlap between the stratospheric waveguide and the main wave-activity region. These changes regulated subsequent upward wave propagation and helped sustain the quasi-biweekly post-SSW warming–recovery sequence in 2024.

Specific Comment 1

Line 30: "Their effects can extend downward into the troposphere … and persist for weeks to months". There are a few references included here, but there has been so much work on this topic I think there should be more – for example:

Kidston et al. (2015), Stratospheric influence on tropospheric jet streams, storm tracks and surface weather, Nature Geoscience, 8, 433–440, doi:10.1038/NGEO2424

Thompson et al. (2005), Stratosphere-troposphere coupling in the Southern Hemisphere. J. Atmos. Sci. 62, 708–715

Hitchcock and Simpson (2014), The downward influence of stratospheric sudden warmings. J. Atmos. Sci. 71, 3856–3876

Mitchell et al. (2013), The influence of stratospheric vortex displacements and splits on surface climate. J. Clim. 26, 2668–2682

Sigmond et al. (2013), Enhanced seasonal forecast skill following stratospheric sudden warmings. Nature Geosci. 6, 98–102

The first two of these explicitly consider the Southern hemisphere (and there are other references within).

Response: Thank you for these suggestions. We agree that the literature coverage of the downward influence and persistence of SSW effects should be broader. We have incorporated all five recommended references into the Introduction.

Changes in manuscript:

The corresponding sentence in the Introduction has been revised as follows:

"Their effects can extend downward into the troposphere (Thompson et al., 2005; Mitchell et al., 2013; Kidston et al., 2015; White et al., 2019, 2020), upward into the mesosphere and lower thermosphere (Dowdy et al., 2007; Yang et al., 2022; Vincent et al., 2022), and persist for weeks to months (Baldwin and Dunkerton, 2001; Sigmond et al., 2013; Hitchcock and Simpson, 2014)."

Specific Comment 2

Line 38: "the evolving mean flow is not only a response to prior wave forcing but also a regulator of subsequent wave propagation":

Holton and Mass (1976), Stratospheric Vacillation Cycles. J. Atmos. Sci., 33, 2218–2225

Scott and Polvani (2004), Stratospheric control of upward wave flux near the tropopause, Geophys. Res. Lett., 31, L02115

Response: We agree that the regulation of upward planetary-wave propagation by the stratospheric mean flow is well established. We have added Holton and Mass (1976) and Scott and Polvani (2004) and revised the corresponding sentence accordingly.

Changes in manuscript:

The corresponding sentence in the Introduction has been revised as follows:

"Studies have also shown that the stratospheric mean flow responds to wave forcing and, in turn, regulates subsequent planetary-wave propagation (Holton and Mass, 1976; Scott and Haynes, 2002; Scott and Polvani, 2004)."

Specific Comment 3

Figure 1 panels (c) and (d) show the stratospheric zonal wind to lag the upward propagating eddy heat flux. A key reference here is:

Newman et al. (2001), What controls the temperature of the Arctic stratosphere during the spring?, J. Geophys. Res., 106(D17), 19999–20010

Response: We agree and have added Newman et al. (2001) to the opening of the paragraph discussing Fig. 1c and d, where the role of planetary-wave forcing in driving the subsequent stratospheric response is introduced.

Changes in manuscript:

The opening sentence of the corresponding paragraph has been revised as follows:

"Given the central role of planetary-wave forcing in driving stratospheric variability (Matsuno, 1971; Andrews et al., 1987; Newman et al., 2001), we also examine the temporal relationship between stratospheric variability and planetary-wave activity using the time series of 50 hPa eddy heat flux anomalies (Fig. 1d)."

Specific Comment 4

Line 94: "Thus, enhanced tropospheric wave activity does not necessarily lead to an amplified stratospheric wave response". This is known, for example:

Birner and Albers (2017), Sudden stratospheric warmings and anomalous upward wave activity flux. Sola, 13A (Special Edition), 8–12

Response: We agree that this general relationship is already well established. We have added Birner and Albers (2017) and revised the corresponding text to frame the 2024 result as being consistent with previous evidence, rather than as a new general conclusion.

Changes in manuscript:

The relevant passage has been revised as follows:

"Taken together, these contrasting relationships are consistent with previous evidence that enhanced lower-level wave activity does not necessarily produce a proportionally amplified stratospheric response (Birner and Albers, 2017). This lack of proportionality points to a role for the evolving stratospheric propagation conditions in shaping the stratospheric response during the 2024 sequence."

Specific Comment 5

Line 178: "the post-SSW atmosphere remained dynamically active". I think this is a key point, which is really interesting and should be emphasized. Some evidence of post-SSW vacillations has been previously seen, for example:

Lee et al. (2025), Two major sudden stratospheric warmings during winter 2023/2024. Weather, 80: 45-53 who do also consider the stratospheric eddy heat flux following the SSWs.

Response: Thank you for highlighting this point. We agree that the continued dynamical activity following the initial SSWs is a central feature of the 2024 sequence. We have cited Lee et al. (2025) in the Introduction as a relevant Northern Hemisphere example of renewed stratospheric variability following SSWs. In the Discussion and Conclusions, we have emphasized that the Southern Hemisphere stratosphere in 2024 did not undergo a passive recovery after the initial SSWs but remained dynamically active for nearly two months. We have also clarified that the specific contribution of our study lies in diagnosing how changes in the vortex edge and QGPV gradient altered the alignment between the stratospheric waveguide and the main wave-activity region, thereby regulating subsequent upward wave propagation during the 2024 post-SSW period.

Changes in manuscript:

To emphasize the prolonged dynamical activity following the initial SSWs and clarify its dynamical interpretation, we have revised the opening two paragraphs of the Discussion and Conclusions as follows:

"Two minor SSWs in July and early August were followed by three additional warming episodes through mid-September, together forming a coherent quasi-biweekly oscillation in polar temperature and zonal wind. The extended sequence indicates that the post-SSW atmosphere remained dynamically active for nearly two months, rather than undergoing a passive recovery following the initial SSWs.

The oscillation was closely linked to repeated changes in planetary-wave forcing and the evolving stratospheric waveguide. The first SSW markedly contracted the polar vortex, which subsequently recovered only partially. The resulting post-SSW background state was characterized by anomalously strong QGPV gradients poleward of 60°S, favoring a high-latitude waveguide and helping to sustain the prolonged dynamical activity. During the subsequent oscillatory phase, the waveguide weakened near each warming peak and recovered afterward, in step with the repeated enhancement and suppression of eddy heat flux. These variations were linked to meridional displacements of the vortex edge, which modified the QGPV gradient and, in turn, altered the alignment between the waveguide and the main wave-activity region, thereby regulating subsequent upward propagation."

Specific Comment 6

Line 182: "indicates that tropospheric forcing alone cannot explain the variability". This is well known - see many of the references above, but also:

Christiansen (1999), Stratospheric Vacillations in a General Circulation Model. J. Atmos. Sci., 56, 1858–1872

Scott and Haynes (2002), The Seasonal Cycle of Planetary Waves in the Winter Stratosphere. J. Atmos. Sci., 59, 803–822

Response: We agree that the broad statement that tropospheric forcing alone cannot explain stratospheric variability is well established and should not be presented as a new conclusion. We have therefore removed this general formulation from the Conclusions. We have also added Christiansen (1999) as relevant background on stratospheric vacillations and Scott and Haynes (2002) as background on the role of the mean flow in regulating planetary-wave propagation.

Changes in manuscript:

The broad statement has been removed from the Conclusions. Scott and Haynes (2002) and Christiansen (1999) have been incorporated into the following passages:

"Studies have also shown that the stratospheric mean flow responds to wave forcing and, in turn, regulates subsequent planetary-wave propagation (Holton and Mass, 1976; Scott and Haynes, 2002; Scott and Polvani, 2004)."

"This alternating control of wave propagation by the evolving mean flow is reminiscent of the stratospheric vacillations described by Holton and Mass (1976) and Christiansen (1999)."