

Response to Reviewer#1 for: QBO-induced anomalous transport in the Northern Hemisphere stratosphere: the exceptional 2018/2019 late boreal winter

Minganti et al., EGUSphere, 2026

We thank the reviewer for their useful and constructive comments. In our replies below, the italic type is used for the reviewer's comments, the plain text for authors' answers and the bold type for the revised text in the manuscript.

Replies to Major comments.

1. *Overall, the impact of sudden stratospheric warming (SSW) on this event is neglected in the manuscript. The authors briefly attribute only the EPFDz poleward of 60°N to the SSW (L575-577). However, in the time series of -EPFDz averaged over 30°-60°N (Fig. 5), most (7 out of 8) peaks of -EPFDz reaching about $+2\sigma$ since 1999 occur during the months with SSW events (or in the immediately following month if an SSW occurs at the end of month), with only one exception in the 2004/2005 winter (for the SSW dates, refer to Butler et al., 2017). A similar analysis but based on the QBO condition instead of SSW reveals that 6 out of these 8 peaks occur during the easterly phase at 50 hPa with westerly shear above, with two exceptions in the 2000/2001 and 2004/2005 winters. For v^* in 30°-60°N (Fig. S7), all 7 peaks exceeding $+2\sigma$ since 1999 appear in the months with SSW, and 6 of them align with the aforementioned QBO phase, with the 2009/2010 winter being the sole exception.*

These indicate that both the SSW occurrence and the specific QBO phase are crucial conditions for driving anomalous midlatitude meridional transport at 50 hPa. While these two conditions are correlated via the Holton-Tan effect, there exists an example of large v^* anomaly with SSW even when the QBO phase is opposite (2009/2010 winter, $+3\sigma$). Therefore, a discussion regarding the impact of SSW should not be omitted in interpreting the anomalous EPFD and transport.

Thanks to this comment and a very similar major comment from reviewer 2, we realise that the SSW impact is a very important point that deserves a more detailed discussion. In the revised manuscript, we significantly elaborate on the impact of the January 2019 SSW on the transport and N₂O anomalies. In Section 3.3 of the revised manuscript, we expand the discussion on the role of the SSWs and of the Holton-Tan effect: the W-BO phase at 50 hPa does not imply the absence of SSWs, but only less favorable conditions for their occurrence. Indeed, SSWs can occur during W-QBO phase such as the one occurred in the 2009/2010 winter. In this case, the SSW can trigger enhanced wave breaking forcing that strengthens the poleward meridional advection to conserve angular momentum after the erosion of the zonal winds of the polar vortex (Baldwin et al., 2021). We have included several paragraphs and sentences discussing the impact of SSWs on the mid-latitudes transport, especially in Sections 3.3 and 4.3 of the revised manuscript, for example: L386-405, L428-444, L566-601.

2. *In the manuscript, the anomalously strong planetary wave forcing (EPFD) and QBO secondary circulation in the extratropics are often interpreted as if they were additive*

origins leading to the exceptional 2019 event (L10; see also the Comments on L425-434 and L651-658 below). However, this contains a misconception: these processes are not independent but occur together as a concurrent phenomenon. Well away from the equator ($> 20^\circ$), is primarily driven by the in situ EPFD under the QG scaling (EPFD; as also reflected in Fig. R1), regardless of whether is modulated by the QBO. In other words, in the extratropics, the QBO secondary circulation itself is constructed by the EPFD forcing at the same location. This also explains why the secondary circulation extends further poleward in the winter hemisphere than in the summer hemisphere, reflecting the seasonal contrast in planetary wave activity (e.g., Pena-Ortiz et al., 2008). Therefore, in general, the anomalous EPFD and over 30° – 60° N should not be interpreted as additive or combinative drivers but as a concurrent dynamical response.

Three potential scenarios could eventually lead to pronounced EPFD and in midlatitudes: (i) planetary waves approaching 50 hPa have anomalously large amplitudes; (ii) equatorial waves and gravity waves in the tropics exert anomalous momentum forcing that expands the latitudinal extent of the QBO and shifts the zero-wind line poleward (more so than in typical winters), thereby causing more planetary waves to approach toward this region and break; (iii) both occur. Note that a poleward shift of zero-wind line also occurs in Scenario (i) as a direct response to the deceleration of westerlies by anomalous planetary wave breaking. Consequently, all three scenarios yield similar local diagnostic signatures in midlatitudes at 50 hPa (strong EPFD, enhanced v^* , and a poleward shifted zero-wind region). Therefore, the ultimate origin of these anomalies cannot be disambiguated solely by analyzing midlatitude diagnostics at 50 hPa or zero-wind latitudes, unless lower-altitude planetary wave activity as well as tropical gravity-wave and equatorial-wave forcings are rigorously examined. Given these dynamical constraints, the main conclusion of the manuscript is currently less convincing and should be framed less definitively.

We modified the relevant parts of the discussion in the revised manuscript, and we do not mention anymore that the wave forcing and the QBO secondary circulation are additive. Instead, we suggest that the E-QBO phase at 50 hPa is the key process that generates the northward displacement of the zero wind line and favours the occurrence of the SSW. See, e.g., L386-405 of the revised manuscript. We also modified the Abstract and the Conclusions to reflect this change, see L8-9 and L626-635, respectively.

3. In Section 3.1, the variability of N_2O is often compared across different datasets. However, Fig. 2 displays N_2O concentrations normalized by the standard deviation (SD) of each respective dataset. This can be misleading if the SD varies significantly among datasets, as the SD itself incorporates variability across all time scales. Please provide the SD values for each dataset to justify the comparison (if their differences are indeed negligible) or consider showing absolute/unnormlized anomalies to ensure a fair comparison.

The reviewer is correct in raising this remark. Table 1 shows the standard deviation (SD) of each dataset for N_2O and ozone concentrations, A_y and EPFD at 50 hPa between 30° and 60° N. For EPFD, we show the SD values of the dynamical reanalyses driving each dataset.

For N_2O concentrations, the SD ranges from 7.3 (M2-GMI) to 9.6 (M2-SCREAM), for ozone the SD varies from 0.09 (SD-WACCM, M2-SCREAM, BRAM2 and SWOOSH) to 0.15 in BASCOE-JRA3Q. For A_y , the SD varies between 0.06 and 0.08 and for EPFD

Table 1: Summary of the SD values for, from left to right, N_2O , ozone, A_y and EPFD for each dataset.

Dataset	N_2O [ppbv]	Ozone [ppmv]	A_y [ppbv/day]	EPFD [m/s/day]
BASCOE-MERRA2	8.64055	0.10082	0.06868	7.6893
BASCOE-JRA3Q	8.21240	0.15173	0.06256	7.50617
BASCOE-ERA5	9.42905	0.14951	0.06796	7.37375
SD-WACCM	9.30804	0.09161	0.08254	7.22321
BRAM2	9.61911	0.09657	0.07501	6.73517 (ERA1)
M2-SCREAM	9.64525	0.09784	0.08137	//
M2-GMI	7.36136	0.09597	0.08428	//
SWOOSH	8.94291	0.09962	//	//

from 6.7 to 7.6. The ozone concentrations present the largest spread in the values of the SD among the datasets. This is not surprising because ozone is more chemically active and more responsive to temperature changes compared to N_2O in the stratosphere. These variations in the SD between the dataset are minor and do not significantly change the results for January/February 2019 when the anomalies are not normalised. To show this, we reproduce Figures 2, 3, 4 and 6 of the revised manuscript without the normalization by the SD for comparison purposes.

Figure RC1 is similar to Figure 2 of the manuscript but with no normalization by the SD of each dataset. The comparison between Fig. RC1 and Fig. 2 of the revised manuscript reveals that the magnitude and timing of the anomalies do not depend on the normalization by the SD. Furthermore, for February 2019, the differences between datasets do not depend on the standardization by the SD, as the magnitudes of the respective N_2O anomalies for each dataset in February 2019 are very similar between the figures.

Figure RC2 is similar to Figure 3 of the revised manuscript but with no normalization by the SD of each dataset. Compared to Figure 3 of the revised manuscript, the ozone anomalies tend to preserve the same magnitude, except for BASCOE-JRA3Q, which delivers slightly larger anomalies when the normalization by the SD is not performed (because of its large SD). The negative ozone anomaly in February 2019 stands out also with no normalization by the SD. The magnitudes of the datasets remains similar to those in Figure 3, but with a few differences, e.g., BASCOE-ERA5 shows the largest anomaly in Fig. RC2 and not in Fig. 3 of the manuscript. Given the secondary role of ozone in the manuscript and that the significant negative anomaly in early 2019 is still present, the small differences between the figures with and without SD standardization do not change the main message of the revised manuscript.

Figures RC3 and RC4 are similar to Figures 4 and 6 of the revised manuscript, respectively, but with no normalization by the SD of each dataset. Both Figures closely resemble their version where the time series are normalised by the SD of each dataset.

Given the comparable values of the SD for each dataset for each variable and the similarities between Figures RC1-RC4 and their respective counterparts in the revised manuscript, we decided to leave the normalisation by the SD in the Figures in the revised manuscript. This allows an easy comparison of the magnitudes of the anomalies between the different variables. As requested by the reviewer, we added the SD value for each

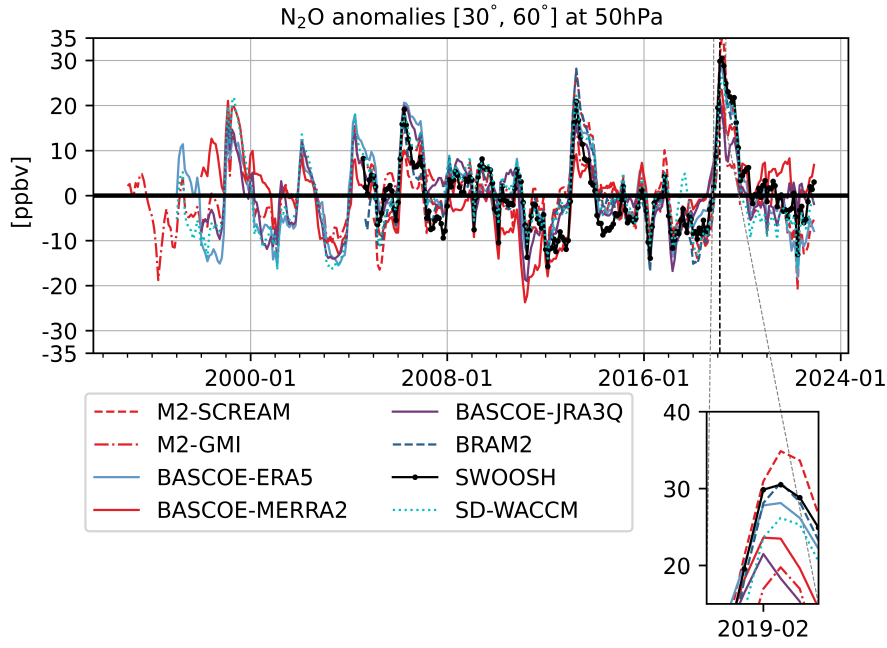


Figure RC1: As Figure 2 of the revised manuscript but with no normalization by the SD of each dataset.

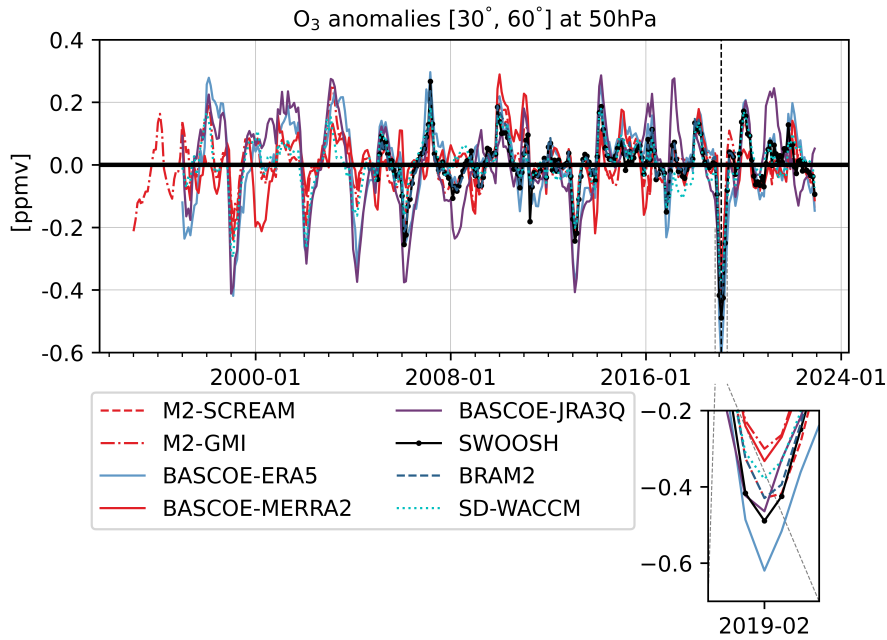


Figure RC2: As Figure 3 of the revised manuscript but with no normalization by the SD of each dataset.

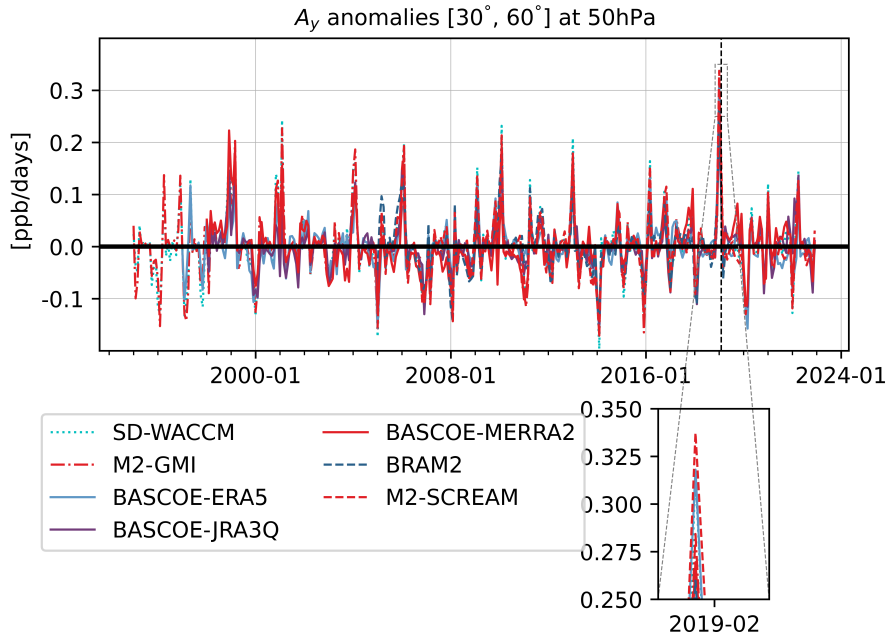


Figure RC3: As Figure 4 of the revised manuscript but with no normalization by the SD of each dataset.

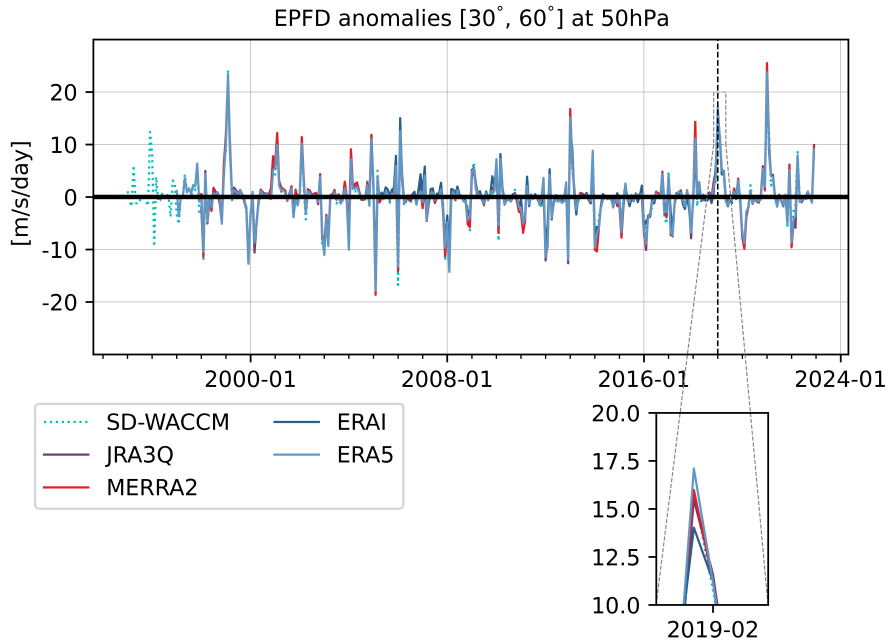


Figure RC4: As Figure 6 of the revised manuscript but with no normalization by the SD of each dataset.

dataset in the caption of each Figure in the revised manuscript.

4. *Section 5 currently appears to offer limited additional insight beyond the findings in previous sections, regarding the dynamical causes of the observed anomalies. First, analyzing the zero-wind latitudes (Fig. 9) may not isolate the QBO impact, because anomalously strong planetary wave activity itself can also induce a poleward shift in these latitudes (as noted in # 2 above). Second, the physical rationale behind examining the Eulerian-mean meridional winds (v ; Fig. 10) contains a dynamical misconception. The authors interpret the two terms of $\bar{v}^*$ (v and the Stokes drift term) as separate and additive contributions, treating the Stokes drift as if it were the sole eddy component of the residual circulation (e.g., L621-622). However, this separation is dynamically invalid. Eddy (wave) effects are not isolated within the Stokes drift term but embedded in both terms, with the net eddy forcing represented by the residual velocity as a whole. Given these fundamental issues, I strongly suggest removing this section. If desired, the information regarding zero-wind latitudes could be incorporated into a previous section (however, please refer to the Comment on Fig. 9 below).*

Done, Section 5 of the submitted manuscript was removed (together with its figures). The relevant information regarding the northward displacement of the zero-wind line was rephrased and moved into Section 4.3 of the revised manuscript.

Replies to Specific comments.

- *L425-434: In the preceding paragraph, the authors have established that the pronounced anomaly of $-EPFD_z$ is responsible for the A_y (and v^* ; Fig. S7) anomaly in 2019, based on their correspondences (L418-421). Then, in the current paragraph, the 2021 case is contrasted against the 2019 case, as the A_y and v^* anomalies exhibit only a small magnitude in 2021 despite the comparable EPFD between the two years. To explain this discrepancy, the authors attribute the pronounced in 2019 to the QBO phase via QBO-induced secondary meridional circulation.*

However, this attribution is dynamically unconvincing. At the current target latitudes (30° - 60°), v^* is largely proportional to $-EPFD$ ($-fv^* \sim EPFD$; also see Major comment # 2), regardless of whether v^* is modulated by the QBO. That is, any effect of the QBO on v^* must already be reflected in the EPFD at the same location. Therefore, it is logically inconsistent to attribute the contrast in v^* between the two years directly to the QBO phase if EPFD remains comparable. While I believe the QBO does play an important role in the v^* anomaly here, this attribution alone does not explain why EPFD remains comparable despite the contrasting v^* anomalies. Indeed, Fig. R1 demonstrates that the v^* anomalies affected by the QBO (showing positives in January 2019 and negatives in 2021), which extend beyond $30^\circ N$ from low latitudes, are broadly matched by corresponding EPFD anomalies of opposite signs.

Following this comment and Major Comment 1, we heavily modified that part of the submitted manuscript. In the revised manuscript, we attribute the similarities in the EPFD anomalies to the presence of major SSWs in both Januaries 2019 and 2021. Concerning the differences in A_y anomalies, we relate them to the different secondary circulations determined by the opposite signs of the QBO winds between 2019 and 2021. We added a new figure in the Supplement (Fig. S13) that shows $\bar{v}^*$ anomalies in the 0 - $30^\circ N$ latitude band at 50 hPa. Fig. S13 shows positive $\bar{v}^*$ anomalies in January 2019, while negative $\bar{v}^*$ anomalies occur in January 2021, consistently with the poleward secondary circulation in early 2019 and the equatorward secondary circulation in early 2021.

We also produced a figure similar to Fig. S13 but for EPFD (Fig. RC5), which shows subtropical EPFD anomalies at 50 hPa that are consistent with the sign of the $\bar{v}^*$ anomalies, i.e., EP divergence in 2019 and convergence in 2021, respectively. However, we do not show this Figure RC5 in the Supplement for two reasons: **1.** If we show Fig. RC5 in the Supplement, we would need to comment on it, and we want to avoid over-loading the manuscript with discussion on 2021. **2.** Related to the previous point, the variable that enters the A_y computation is $\bar{v}^*$ and, since the EPFD anomalies are consistent with the $\bar{v}^*$ anomalies both in January 2019 and January 2021, we directly show only $\bar{v}^*$ for the purposes of this discussion.

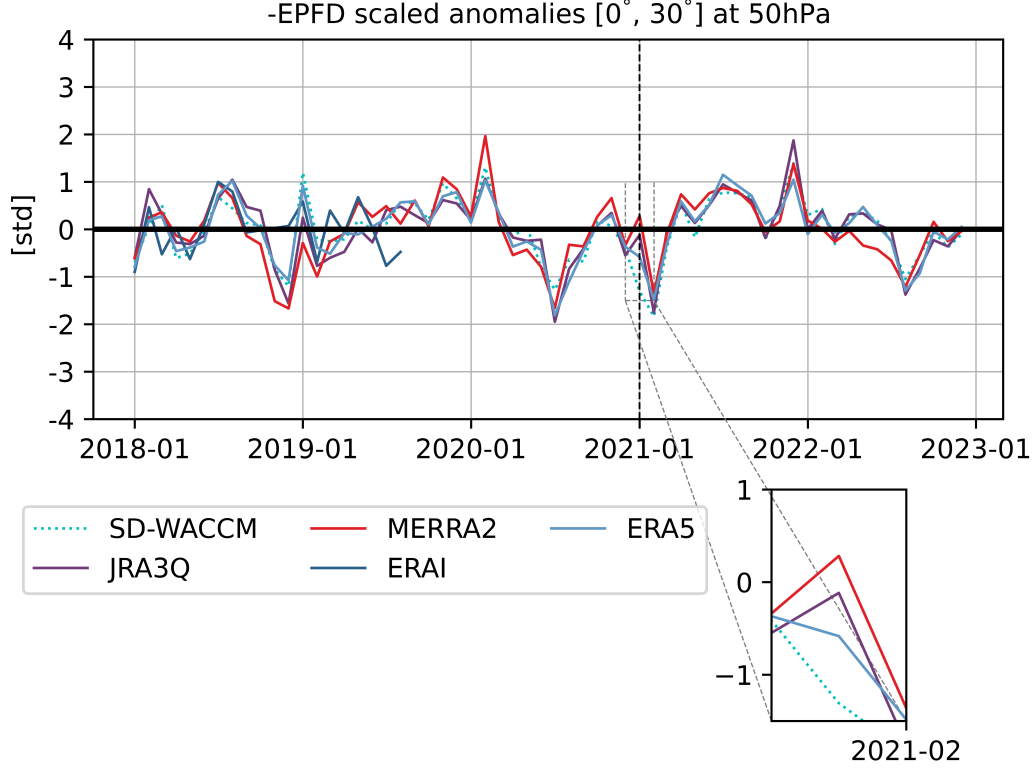


Figure RC5: As Fig. 4,

Hence, we attribute the similarities in EPFD anomalies between early 2019 and 2021 to the presence of SSWs in both periods, and the differences in the A_y anomalies to the different signs of the QBO winds. We mention that the two processes (large EPFD anomalies and large/small A_y anomalies) are not separated nor additive, but related to the QBO phase in both periods. See the revised text:

In early 2021, all datasets show large positive EPFD anomalies (reaching 3 standard deviations) that are among the largest in the record and are comparable to the anomalies in January 2019. These EPFD anomalies indicate enhanced wave breaking, but they do not correspond to significant anomalies in the A_y term or $\bar{v}^*$, nor in N_2O or ozone concentrations for the same period. Moreover, no other term of the N_2O TEM budget presents significantly large anomalies in that period. In January 2021, a major SSW occurred in the Arctic region, and it was preceded by different QBO conditions compared to the 2019 SSW (Lee, 2021; Lu et al., 2021). In particular,

the QBO phase at 50 hPa was opposite between January 2019 and January 2021, with easterly winds in 2019 and weak westerly winds in 2021 (Figs. S11 and S12, respectively). Therefore, the QBO configuration in 2021 was less favorable to the onset of SSWs in the Arctic compared to 2019 (Baldwin et al., 2021). Nevertheless, a major SSW occurred in 2021, although it was weaker and shorter compared to the 2019 SSW (Lee, 2021), consistent with the Holton-Tan effect. The different QBO phases also influenced the secondary circulation. In 2019, the QBO easterlies induced positive subtropical $\bar{v}^*$ anomalies at 50 hPa, whereas the weak westerlies in 2021 produced negative subtropical $\bar{v}^*$ anomalies at the same level (Fig. S13). These negative $\bar{v}^*$ anomalies in 2021 indicate equatorward flow of the lower branch of the secondary circulation, consistent with the expected pattern of the secondary circulation with W-QBO phase at the same level. As a result, the subtropical contribution to the poleward transport at 50 hPa was weaker in 2021 compared to 2019, ultimately leading to smaller A_y anomalies at the mid-latitudes in 2021 compared to 2019. Therefore, the occurrence of major SSWs in both January 2019 and 2021 is consistent with the positive EPFD anomalies, while the opposite signs of the QBO winds at 50 hPa likely explain the differences in the A_y anomalies between 2019 and 2021. The contrasting QBO phases between early 2019 and 2021, together with the occurrence of a SSW in both winters, further suggest that both processes are necessary to determine the residual meridional advection anomalies and ultimately the N₂O anomalies. However, the dynamical anomalies in January 2021 are not the focus of the paper and we do not discuss them any further.

- *L456-457: However, since the seasonal cycle has already been removed from the N₂O anomalies (L223), attributing the overestimated anomalies to a larger seasonal cycle is not straightforward. Please clarify this explanation.*

Indeed the contribution from the seasonal cycle is removed from the anomalies. We revised the text and we attributed these differences to the N₂O negative bias in MLS v5 compared to ACE-FTS shown in, e.g., Fig. 10 of Saunders et al. (2026). Since there was no substantial difference between MLS v4 and v5 in terms of N₂O (Livesey et al., 2021), that bias is presumably present in MLS v4 (which is assimilated in the chemical reanalyses). See the revised text:

Equatorward of 15°N, all datasets broadly agree, with BRAM2 and M2-SCREAM slightly overestimating the amplitude of the weak negative N₂O anomalies compared to SWOOSH. In the extratropical stratosphere, N₂O concentrations from Aura MLS v5 present a negative bias compared to those from ACE-FTS (Saunders et al., 2026). Since v5 of MLS N₂O does not substantially differ from v4 (Livesey et al., 2021), its negative bias compared to ACE-FTS likely plays a role in the differences between BRAM2 and M2-SCREAM (only MLS-based) and SWOOSH (based on MLS and ACE-FTS) in the tropical lower stratosphere.

- *Fig. S13 (just a comment): It is interesting that the N₂O anomaly structure in February 2018 is nearly opposite to that in February 2019. In contrast to the 2019 case, no SSW occurred in January 2018, and the QBO phase was westerly at 50 hPa with easterly shear above.*

It is interesting, and is indeed a confirmation of the peculiarity of the 2019 anomalies. The opposite QBO phase at 50 hPa between January 2018 and January 2019 results in an opposite secondary circulation in 2018, with equatorward motion at 50 hPa and poleward above. Such pattern is consistent with the sign of the N_2O anomalies in the stratosphere (i.e., negative anomalies with equatorward motion and positive anomalies with poleward motion). The absence of a SSW in January 2018 is also a consequence of the W-QBO phase at 50 hPa.

The case of February 2018 confirms that both the poleward secondary circulation and the occurrence of SSW are crucial in determining the N_2O anomalies at mid-latitudes. We highlight that, as already explained by the reviewer, these 2 processes are not separated but connected through the QBO phase.

- *L490-494: However, the cases shown in Figs. S14-S16 are in June or May, not boreal winter. The QBO secondary circulation is seasonally dependent, especially in its latitudinal extent (extending more toward the winter hemisphere, as seen in the current case), and this mechanism is well explained in Pena-Ortiz et al. (2008). Please revise the discussion here to reflect this.*

We replaced Figs S14-S16 of the submitted supplement with Figures showing N_2O anomalies in Februaries with easterly QBO winds at 50 hPa (Figs. S14-S17 of the revised supplement). The main point of the sentence does not change: the N_2O anomalies at 50 hPa at mid-latitudes in 2019 are the largest compared to the previous Februaries with similar QBO conditions. In addition, we modified L492-496 of the submitted manuscript to highlight that the QBO effects (secondary circulation and Holton-Tan effect) are not separated, but their occurrence and magnitude are both related to the QBO phase at 50 hPa, see modified text:

In February 2019, the N_2O anomalies follow the description above, but they peak around 30°N and extend into the mid-latitudes, and this extratropical extension is not visible in the pattern of the N_2O anomalies with similar QBO conditions in boreal winter (Figs. S14-S17). In particular, the positive N_2O anomalies at 50 hPa at mid-latitudes in February 2019 are much larger compared to previous Februaries with similar QBO conditions. This indicates that the particular QBO phase in early 2019 plays a major role in determining the February N_2O anomalies, especially around the subtropics. The QBO impact through the secondary circulation is not the only factor contributing to the N_2O anomalies in the NH. The positive N_2O anomalies around and northward of 60°N are likely determined by anomalous transport due to the strengthened wave forcing resulting from the occurrence of the SSW in the 2018/2019 winter (in turn facilitated by the QBO phase). In the following, we will elucidate on the role of tropical and extratropical QBO-induced dynamical processes (i.e., secondary circulation and SSW) in creating the N_2O anomalies at mid-latitudes.

- *Fig. 8: I recommend superimposing v^* contours onto this plot. This would help interpret the relationship between EPFD and v^* and connect these results with Fig. 7.*

Done for Fig. 9 of the revised manuscript. In addition, we have superimposed contour lines of $\bar{v}^*$ anomalies in Fig. 8 of the revised manuscript, as suggested by the other reviewer, to highlight the role of $\bar{v}^*$ in determining A_y . We have modified the text of the

corresponding Sections to integrate the discussion about the correspondence between the EPFD and A_y anomalies with the $\bar{v}^*$ anomalies.

- *Fig. 9: Although this plot shows a seasonal cycle, only the January information is relevant and mentioned in the text. I could not find the added value of showing the full seasonal climatology rather than focusing more on the January behavior (e.g., via a January time series over the years).*

As mentioned in the reply to Major Comment 4, we removed this figure from the revised manuscript.

- *Fig. 10: Why are the anomalies always positive in some latitudes (e.g., $20^\circ 40^\circ \text{N}$)? This is misleading, as the mean of deseasonalized anomalies for January is expected to be zero when interpreting the results.*

There was an error in the title and caption of Fig. 10 (and in the corresponding text) of the submitted manuscript: we mentioned "anomalies", but we did not show anomalies, we actually showed the raw values of v for the different periods. However, as mentioned in the reply to Major comment 4, we removed this figure from the revised manuscript.

- *L651-658: This part requires a major rewrite for the following reasons: (i) While the northward shift of the zero-wind line accounts for the enhanced planetary-wave dissipation (-EPFD) around 30°N , the enhancement of -EPFD at higher latitudes in $30^\circ 60^\circ \text{N}$ seems to be a response to SSW (see Major comment # 1). I think both the SSW and the QBO-induced zero-wind line shift should be recognized here as contributing factors to the enhanced wave dissipation at $30^\circ 60^\circ \text{N}$ in January 2019. (ii) "In addition, ... The combination ..." (L652-658): The descending W-QBO effect is already reflected in the EPFD mentioned in the preceding lines, and is thus neither additive nor combinative to the EPFD (see Major comment # 2).*

The corresponding part in the Abstract (around L10) should also be modified to reflect these (i, ii).

We significantly changed this part of the text to reflect the reviewer's comments. See modified text:

The TEM diagnostics indicates that the N_2O anomalies in the NH mid-latitudes in February 2019 originate from enhanced meridional residual advection in January 2019, which is in turn mainly generated by enhanced planetary wave forcing over the same region and period. In January 2019, the E-QBO phase at 50 hPa induces a northward shift of the zero wind latitude (reaching around 15°N), which results in enhanced wave breaking around and northward of 30°N at the same level. This northward shift of the zero wind latitude contributes to the strong poleward secondary circulation extending towards the mid-latitudes in January 2019. At the same time, the E-QBO phase at 50 hPa favors the occurrence of the January 2019 SSW (through the Holton-Tan effect), which enhances the wave breaking at mid-latitudes, intensifying the anomalous poleward advection. The simultaneous occurrence of the strong poleward secondary circulation and of the SSW in January 2019 generated the extreme meridional residual advection in the mid-latitudes. Hence, the E-QBO phase at 50 hPa in January 2019 determines the dynamical conditions that ultimately lead to large N_2O anomalies at mid-latitudes one month later.

Concerning the Abstract:

The easterly phase of the quasi-biennial oscillation (QBO) determines such enhanced wave forcing by displacing northward the zero wind line and by facilitating the occurrence of the sudden stratospheric warming in January 2019.

Replies to Technical comments

- *Throughout the text: The phrase "consists in" has been consistently used where "consists of" is intended (e.g., L27, 31, 38, 487, 561).*

Corrected.

- *L28: "followed by" → ", and subsequent"*

Done.

- *L40: "small scale" → "small-scale wave"*

Done.

- *L46-47: warming/maximum → cooling/minimum*

Done.

- *L73-81: I recommend moving this part to Section 2 (ahead of 2.1), as these are general descriptions of data types and interrupt the flow of the Introduction.*

Done.

- *L91 "we focus ... NH.": The distinction between Section 3 and Section 4 is unclear in the current text, as Section 4's objective overlaps with Section 3. Please explicitly state what Section 4 further addresses.*

Done. In the revised manuscript, we specify:

Section 3 shows time series of N₂O anomalies (together with transport-related quantities) at 50 hPa over the northern mid-latitudes in order to highlight the exceptional magnitudes of the anomalies in late 2018/2019 boreal winter compared to the rest of the records. In Section 4, we focus on the anomalies in late 2018/2019 boreal winter over the entire NH and in the whole stratosphere.

- *L98: "zonal and" could be removed.*

Done.

- *Section 2: I suggest systematically grouping (or at least sorting) the datasets based on their types: e.g., Sect. 2.1. SWOOSH; Sect. 2.2. Chemical reanalyses; Sect. 2.3. Chemistry model experiments with constrained dynamics, with 2.x.y. for each product. SD-WACCM could be placed in Sect. 2.3.5 or, if this nudging experiment should be treated separately, in Sect. 2.4.*

Done. We grouped the datasets as follows:

- Sect. 2.1 SWOOSH

- Sect. 2.2 Chemical reanalyses
 - Sect. 2.2.1 M2-SCREAM
 - Sect. 2.2.2 BRAM2
 - Sect. 2.3 CTM simulations with constrained meteorology
 - Sect. 2.3.1 M2-GMI
 - Sect. 2.3.2 BASCOE CTM simulations
 - Sect. 2.4 SD-WACCM
- *Figures: The line types could also be managed in a similar manner to the above grouping to improve readability: e.g., solid lines for SWOOSH and chemical reanalyses; dashed lines for chemistry model experiments with constrained dynamics, with different colors for each product.*

Done. We chose: solid line with filled circles for SWOOSH, dashed lines for the chemical reanalyses M2-SCREAM and BRAM2, dash-dotted line for M2-GMI (it's similar to BASCOE CTM but the driving winds are implemented differently), and dotted line for SD-WACCM. For the chemical reanalyses, the BASCOE-CTM experiments and M2-GMI, we chose to retain the original colors of the driving dynamical reanalyses, because they are the official colors of A-RIP (<https://reanalyses.org/atmosphere/reanalyses-comparisons-suggested-practices>), that's why M-SCREAM, M2-GMI and BASCOE-MERRA2 have the same color. The color for JRA-3Q is not present in the webpage above, but we got its value via personal communication with Masatomo Fujiwara (Hokkaido University). For Figure 6 of the revised manuscript, we chose to use continue lines for the dynamical reanalyses (as they are the same type of dataset) and to use the dotted line for the only different dataset SD-WACCM. We applied the same modifications in Figs. S1-S10 and S13 of the revised supplement.

- *L191: "horizontal transport due to eddy mixing" → "horizontal eddy mixing"*

Done.

- *Eqs. 4 and 6: Please use a consistent definition (based on either the primitive equations or the QG equations) that is actually applied in the analysis. Also, please revise Eqs. 5 and 6 so that EPFD is to be consistent with Fig. 8 (i.e., $\nabla \cdot \mathbf{F}$ divided by ρ_0 or $\rho_0 \cos \phi$, depending on the equation set used).*

Done. In the revised manuscript, we use the EPFD definition based on the primitive equations (i.e., Eqs. 4 remains unchanged and we adapt Eqs. 6, see updated version of the manuscript). We also explicitly include the term $1/\rho \cos \phi$ that multiplies $\nabla \cdot \mathbf{F}$ (with $\rho = \rho_s e^{-z/H}$ and $\rho_s = 1$) in the definition of EPFD (i.e., $\text{EPFD} = (1/\rho \cos \phi) \nabla \cdot \mathbf{F}$), and we adapt the definitions of EPFD_y and EPFD_z accordingly.

- *L240: ... parts of the ...*

This part was removed following the comment just below.

- *L240-254: This part contains detailed descriptions of differences between datasets for years other than 2019. Since these details are somewhat tangential to the main scope of the manuscript, I suggest shortening this discussion or moving it to an Appendix/Supplementary Information. This would allow the main text to emphasize the general behavior over the analysis period and key differences between datasets during 2019.*

We significantly shortened the paragraph and we kept only the relevant information about BASCOE-MERRA2 (smaller amplitudes of N₂O anomalies) and the consistency with the recent AoA study:

One of the datasets that differs most from the others is the BASCOE-MERRA2 simulation, which tends to deliver smaller amplitudes (i.e., less positive/less negative) of the N₂O anomalies compared to the other datasets. In the lower stratospheric mid-latitudes, the N₂O concentrations are inversely proportional to the mean Age of Air (mAoA, M2020). Hence, the smaller magnitudes of the N₂O anomalies are consistent with the recent mAoA results from Vervalcke et al. (2026), who found that MERRA2 delivers the oldest mAoA compared to ERA5 and JRA3Q using the same BASCOE CTM simulations.

- L266-267 *"We will show ...": Where is this shown?*

In the revised manuscript, we mention that this is shown in Sect. 3.2: **"In Sect. 3.2, we will show that ..."**

- L284 *"compared to MLS itself (but ... period": I think this could be neglected.*

We removed this part as we significantly condensed the relative paragraph.

- L287 *"for a similar stratospheric region": The meaning of this is unclear.*

As for the comment above, we removed this part after significantly condensing the relative paragraph.

- L299: *(produced in the tropical upper ...)*

Done (and rephrased following one comment of reviewer 2).

- L316-317: *Please remove the parentheses here, and rephrase the sentence naturally (e.g, "... reach 3 sigmas for ... and 4 sigmas for ...")*

Done, parentheses removed:

the negative ozone anomalies reach and exceed 3 sigmas for ... and 4 sigma for ...

- L337-338: *"anomalies, on top of ... A_y , indicate"*

Done.

- L341: *"indicating" → "suggesting" (because another possibility exists, mentioned in L344)*

Done.

- L358: *Doesn't the standardization matter here, in addition to the deseasonalization? (Please refer to Major comment # 3.)*

As shown in Fig. RC3, the standardization does not significantly impact the magnitude of the A_y anomalies, as the relative magnitudes of the peaks of the A_y anomalies are very similar between Fig. RC3 and Fig. 4 of the revised manuscript. Given these minimal changes between Fig. 4 of the revised manuscript and Fig. RC3, the impact of the standardization can be safely discarded compared to the magnitude of the seasonal cycle.

- L368-369: Please rephrase "simulations simulate."

Done, rephrased to "... **experiments, ..., simulate ...**"

- Fig. S7: Please consider incorporating this plot (v^*) into Fig. 4(b), since this demonstrate the contribution of residual-circulation anomaly to the N_2O advection.

Following one comment of reviewer 2, we added a new figure (Fig. 5 of the revised manuscript), which quantifies the relation between N_2O anomalies in February 2019 and A_y anomalies in January 2019. Hence, we prefer to keep Figure 4 as is to maintain the focus of the Section on tracer transport quantities (i.e., N_2O and A_y), instead of adding a purely dynamical quantity such as $\bar{v}^*$. However, we agree that it is important to show anomalies of $\bar{v}^*$. Hence, following both reviewers' comments, we have included contour lines of $\bar{v}^*$ anomalies in Figs. 8 and 9 of the revised manuscript.

- Fig. 5 caption: Please state that the datasets differ from Fig. 2.

Done. In the caption of Fig. 6 of the revised manuscript, we explicitly mention that we show the dynamical reanalyses driving the different datasets.

- L387: I suggest rephrasing this as "because it represents the forcing driven by planetary waves (Holton, 2004)."

Done, rephrased to "... **because it represents the forcing driven by the breaking of resolved waves (generally planetary scale waves, Holton, 2004), ...**"

- L391: Please remove "can."

We removed this paragraph following the suggestion of reducing the inter-datasets comparisons from reviewer 2.

- L406: "All datasets except ERAI agree ... around 2.3 to 2.6 ..."

Done.

- L410 The phrase "same dynamical quantities" is confusing in this context. While it literally implies a set of variables, the context suggests it may refer to something else (e.g., spatial grid or calculation methodology?), since using a common set of variables is naturally expected. Please clarify what is meant here and revise the wording accordingly.

With that phrase, we meant that we used the dynamical variables (u , v , ω and t) on the same spatial (horizontal and vertical) grid as for the computation of A_y , in order to be consistent. The text is now modified accordingly to highlight this:

For the sake of consistency, the dynamical quantities used to derive the EPFD for ERAI, ERA5, MERRA2 and JRA3Q results shown in Fig. 6 use the same spatial grid used to compute the A_y term (Fig. 4).

- L424: I suggest also mentioning v^* here in addition to A_y .

Done.

- Figs. S9 & S10: The x-axis values appear to be 10 times larger than expected.

Corrected.

- L431-432: *"(because the meridional winds ... peak at the ...)"*

This part was removed after heavily changing the text following Major comment 1 and Specific comment 1.

- L441-442: *This sentence is redundant with L438 and could be deleted.*

Deleted.

- Fig. 6 caption: *Please mention the zonal wind contours. In addition, the phrase "for the NH" should be deleted, as the cross sections extend to 30°S.*

Done: we mentioned the zonal wind contours and we removed "for the NH".

- L450: *"Over the southern part of the tropics" ?*

Done.

- L468: *Please consider refining this sentence for improved structure: e.g., "used to drive ..., run M2-GMI in a replay mode, and nudge SD-WACCM"*

This part was removed from the revised manuscript after the suggestion from reviewer 2 to reduce the discussion of the inter-dataset differences.

- L489: *Please rephrase "slightly resemble" to be more precise.*

Changed to "follow".

- L499-500: *This sentence is unclear. Does this mean: "Given the one-month lag as shown in the N₂O and A_y time series (Figs. 2 and 4), in the next Section we will focus on the cross section of the A_y term in January 2019"? Please rewrite it to clarify the intended meaning.*

Indeed that is the intended meaning. We rephrased the sentence accordingly:

Given the one-month time lag as shown using the N₂O and A_y anomalies, in the next Section we will focus on the A_y term in January 2019.

- Fig. 7: *It is difficult to follow the description in L515-516 due to weak contrasts among colors. I recommend using a narrower range of contour levels. / The label "w*" near the colorbar seems to be a typo.*

Done: we narrowed down the contour levels and we fixed the typo in the colorbar title.

- L543: *I suggest removing "(and ... EPFD_z)."*

Done. Actually, upon suggestion of reviewer 2, we replaced $EPFD_z$ with the total EPFD in all figures of the revised manuscript. The results remain basically the same (because the impact of $EPFD_y$ is minimal in our case) and it allows to consider the complete wave forcing.

- L546-547: *This sentence is repetitive with L548-549, and I suggest removing it.*

We rephrased and reduced this part as follows:

Consequently, negative EPFD anomalies represent enhanced forcing from the wave breaking and positive EPFD indicate weakened forcing from the wave breaking (Park et al., 2024)

- L548-549: *EPFDz values* → *EPFDz anomalies*

Done.

- L569-570 *"gravity wave breaking ... is weaker in ERA5": How can this be consistent with the reduced planetary wave breaking mentioned in L568, given the vast difference in wave scales and forcing mechanisms? Please clarify the statement.*

The reviewer is right - we removed this sentence from the revised manuscript as it was confusing and unclear.

- L577: *Such SSW* → *The SSW*

As mentioned above, we substantially changed Sect. 4.3 of the revised manuscript to highlight the role of the 2019 SSW and of the secondary circulation. As a consequence, this part of the text does not appear anymore in the revised manuscript.

- L578: *"Despite the large magnitude of the high-latitude EPFDz anomalies"?*

Following the changes mentioned in the reply to the comment above, this part does not appear anymore in the revised manuscript.

- Fig. 9 caption: *"zero zonal-wind latitude" / "when there"? / Please explicitly state the "period" / It is confusing that March and December are marked by "No sign change" in the NH, because they have the minimum of the zero-wind latitude within the NH. Please clarify how this annual cycle of the zero-wind latitude is calculated/averaged.*

As suggested by the reviewer, Fig. 9 of the submitted manuscript was removed from the revised manuscript. The criterium for computing the zero-wind latitude was that the sign of the zonal wind must change between two adjacent latitudes, and the zonal wind at both latitudes should not be zero.

- Fig. S20: *no dots or crosses from September to December.*

The reason of the missing dots/crosses in Fig S20 of the submitted manuscript is that the ERAI dataset ends in August 2019, so no data are available after that month. However, since we removed Sect. 5 and its figures from the revised manuscript, Figs. S17-S24 of the submitted supplement were removed as well.

- L636: *"the BASCOE CTM driven by the dynamical reanalyses"*

Done.

- L638: *"these dynamical reanalysis-based CTMs"?*

Done.

- L640: *ERA5 simulates* → *ERA5 represents*

Rephrased to "... ERA5 can better represent ...".

- L640-641 *"indicates ... more realistic ... compared to ...": This sounds overly definitive. I suggest revising the sentence in a more prudent tone, as MERRA2 shows a good performance with another model (SD-WACCM; L270-271).*

Done, the sentence was rephrased as:

This suggests that ERA5 can better represent the observed stratospheric transport variability compared to JRA3Q and MERRA2.

- L645 "wildfires": Does this mean "wildfire-induced stratospheric changes" rather than wildfires themselves?

Yes, we changed the text following the reviewer's suggestion.

- L658: I suggest splitting this long paragraph here to improve readability.

Done.

- L677: "that contribute to it" could be deleted. (redundant)

Done.

- L694: their sparseness $\rightarrow$ sparseness

This sentence was removed from the revised manuscript after the suggestion of reviewer 2 of reducing this part.

- Language: English proofreading is recommended to improve the clarity and flow of the manuscript.

Done.

References

- Baldwin, M. P., Ayarzaguen, B., Birner, T., Butchart, N., Butler, A. H., Charlton-Perez, A. J., Domeisen, D. I. V., Garfinkel, C. I., Garny, H., Gerber, E. P., Hegglin, M. I., Langematz, U., and Pedatella, N. M. (2021) Sudden Stratospheric Warmings. *Reviews of Geophysics*, 59, e2020RG000 708 <https://doi.org/https://doi.org/10.1029/2020RG000708>
- Livesey, N. J., Read, W. G., Froidevaux, L., Lambert, A., Santee, M. L., Schwartz, M. J., Millan, L. F., Jarnot, R. F., Wagner, P. A., Hurst, D. F., Walker, K. A., Sheese, P. E., and Nedoluha, G. E. (2021) Investigation and amelioration of long-term instrumental drifts in water vapor and nitrous oxide measurements from the Aura Microwave Limb Sounder (MLS) and their implications for studies of variability and trends. *Atmospheric Chemistry and Physics*, 21, 15409–15430 <https://doi.org/10.5194/acp-21-15409-2021>
- Saunders, L. N., Walker, K. A., Stiller, G. P., Raspollini, P., Millan, L. F., Gai, M., Boone, C. D., Gille, J., Glatthor, N., Kleinboehl, A., Kleinert, A., Lambert, A., Murtaugh, D., Sheese, P. E., Toon, G. C., and Wetzol, G. (2026) Evaluating satellite limb measurements of nitrous oxide. *EGUsphere [preprint]* <https://doi.org/10.5194/egusphere-2026-4651>