Reviewer comments on "QBO-induced anomalous transport in the Northern Hemisphere stratosphere: the exceptional 2018/2019 late boreal winter"

The authors present an analysis of the exceptionally high N2O concentrations in the lower stratosphere at Northern Hemisphere midlatitudes in February 2019, addressing the role of meridional transport in driving this anomaly, using various types of datasets. The analysis in the transformed Eulerian mean (TEM) framework indicates that the anomalous N2O was mainly induced by meridional advection in the preceding month, driven by an enhanced meridional flow (v^*) associated with unusually strong planetary-wave forcing. The authors further discuss the underlying dynamics behind these pronounced anomalies, highlighting the role of the QBO which was suggested (but not investigated) in Manney et al. (2022). In addition, an intercomparison among satellite observations, chemical reanalyses, and dynamically constrained chemistry modeling data demonstrates overall consistent features in the N2O anomaly, while some minor differences are discussed.

I find this work very useful, as it provides clear observational and modeling evidence regarding the key role of dynamical transport and its variability in shaping trace gas distributions. I also highly appreciate the authors' extensive effort in synthesizing such a comprehensive set of analyses. I recommend this manuscript for publication, however, subject to major revisions, which are required mainly to address a key omission and misconception in the dynamical interpretation of the results. See the following comments.

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 +2σ 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 +2σ 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, +3σ). Therefore, a discussion regarding the impact of SSW should not be omitted in interpreting the anomalous EPFD and transport.

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 phenominon. Well away from the equator ($\gtrsim$ 20°), v^* is primarily driven by the in situ EPFD under the QG scaling ($-fv^* \sim$ EPFD; as also reflected in Fig. R1), regardless of whether v^* 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., Peña-Ortiz et al., 2008). Therefore, in general, the anomalous EPFD and v^* 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 v^* 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.

3. In Section 3.1, the variability of N2O is often compared across different datasets. However, Fig. 2 displays N2O 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/unnormalized anomalies to ensure a fair comparison.

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 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 v^* 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).

Specific comments

- L425-434: In the preceding paragraph, the authors have established that the pronounced anomaly of −EPFDz 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 A_y 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°N from low latitudes, are broadly matched by corresponding EPFD anomalies of opposite signs.

- 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.
- 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.
- 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 Peña-Ortiz et al. (2008). Please revise the discussion here to reflect this.
- 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.
- 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).
- Fig. 10: Why are the anomalies always positive in some latitudes (e.g., 20–40°N)? This is misleading, as the mean of deseasonlized anomalies for January is expected to be zero when interpreting the results.
- 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 30–60°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 30–60°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).

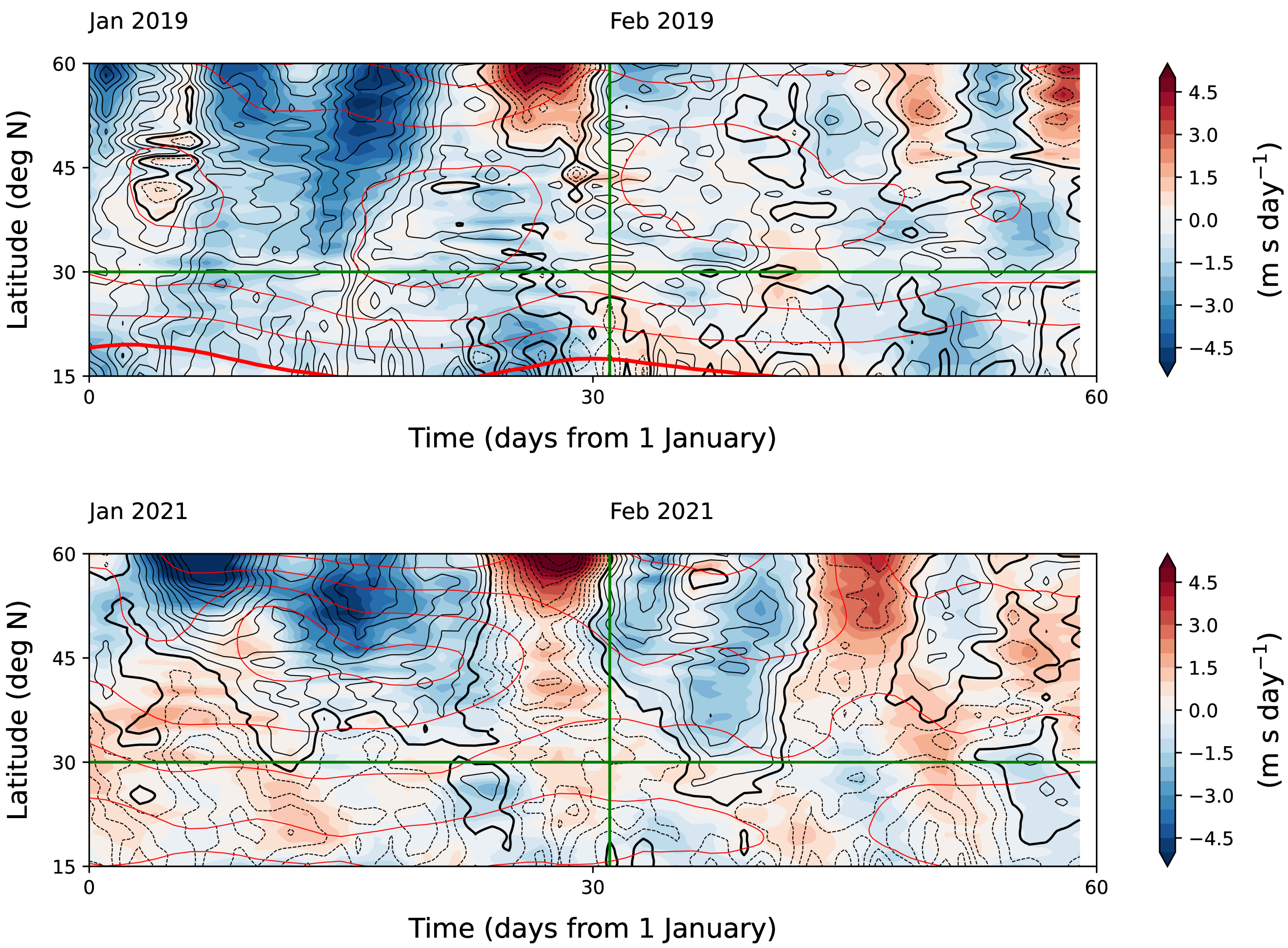

Fig. R1: 50-hPa daily EP flux divergence forcing anomaly divided by the sine of latitude (shading), along with the residual-mean meridional velocity (v^*) anomaly (black contours; dashed lines for negatives) and zonal-mean zonal wind (red contours; thick lines for zero wind) during the two months from 1 January in 2019 (upper) and 2021 (lower), obtained using ERA5. The quantities are based on the TEM of the primitive equations. The anomalies here are departures from the seasonal climatology of 1964–2023, and are smoothed in latitude and time for readability. The division by the sine of latitude is intended to verify the relationship $v^* \sim -f^{-1}\nabla \cdot \mathbf{F}/(\rho_0 a \cos\phi)$ where $f \propto \sin\phi$.

References

- Butler, A. H., Sjoberg, J. P., Seidel, D. J., and Rosenlof, K. H. (2017): A sudden stratospheric warming compendium. *Earth Syst. Sci. Data*, 9, 63–76.
- Manney, G. L., Millán, L. F., Santee, M. L., Wargan, K., Lambert, A., Neu, J. L., et al. (2022): Signatures of anomalous transport in the 2019/2020 Arctic stratospheric polar vortex. *J. Geophys. Res. Atmos.*, 127, e2022JD037407.
- Peña-Ortiz, C., Ribera, P., García-Herrera, R., Giorgetta, M. A., and García, R. R. (2008): Forcing mechanism of the seasonally asymmetric quasi-biennial oscillation secondary circulation in ERA-40 and MAECHAM5. *J. Geophys. Res.*, 113, D16103, doi:10.1029/2007JD009288.

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).
- L28: "followed by" $\to$ ", and subsequent"
- L40: "small scale" $\to$ "small-scale wave"
- L46-47: warming/maximum $\to$ cooling/minimum
- 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.
- 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.
- L98: "zonal and" could be removed.
- 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.
- 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.
- L191: "horizontal transport due to eddy mixing" $\to$ "horizontal eddy mixing"
- 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 $\rho_0 a \cos\phi$, depending on the equation set used).
- L240: … parts of the …
- 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.
- L266-267 "We will show …": Where is this shown?
- L284 "compared to MLS itself (but … period": I think this could be neglected.
- L287 "for a similar stratospheric region": The meaning of this is unclear.
- L299: (produced in the tropical upper …)
- L316-317: Please remove the parentheses here, and rephrase the sentence naturally (e.g, "… reach 3 sigmas for … and 4 sigmas for …")
- L337-338: "anomalies, on top of … A_y, indicate"
- L341: "indicating" $\to$ "suggesting" (because another possibility exists, mentioned in L344)
- L358: Doesn't the standardization matter here, in addition to the deseasonalization? (Please refer to Major comment #3.)
- L368-369: Please rephrase "simulations simulate."
- Fig. S7: Please consider incorporating this plot (v^*) into Fig. 4(b), since this demonstrate the contribution

of residual-circulation anomaly to the N2O advection.
- Fig. 5 caption: Please state that the datasets differ from Fig. 2.
- L387: I suggest rephrasing this as "because it represents the forcing driven by planetary waves (Holton, 2004)."
- L391: Please remove "can."
- L406: "All datasets except ERAI agree ... around 2.3 to 2.6 ..."
- 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.
- L424: I suggest also mentioning v^* here in addition to A_y.
- Figs. S9 & S10: The x-axis values appear to be 10 times larger than expected.
- L431-432: "(because the meridional winds ... peak at the ...)"
- L441-442: This sentence is redundant with L438 and could be 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.
- L450: "Over the southern part of the tropics" ?
- 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"
- L489: Please rephrase "slightly resemble" to be more precise.
- 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.
- 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.
- L543: I suggest removing "(and ... EPFDz)."
- L546-547: This sentence is repetitive with L548-549, and I suggest removing it.
- L548-549: EPFDz values $\rightarrow$ EPFDz anomalies
- 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.
- L577: Such SSW $\rightarrow$ The SSW
- L578: "Despite the large magnitude of the high-latitude EPFDz anomalies"?
- 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.
- Fig. S20: no dots or crosses from September to December.
- L636: "the BASCOE CTM driven by the dynamical reanalyses"

- L638: "these dynamical reanalysis-based CTMs"?
- L640: ERA5 simulates → ERA5 represents
- 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).
- L645 "wildfires": Does this mean "wildfire-induced stratospheric changes" rather than wildfires themselves?
- L658: I suggest splitting this long paragraph here to improve readability.
- L677: "that contribute to it" could be deleted. (redundant)
- L694: their sparseness → sparseness
- Language: English proofreading is recommended to improve the clarity and flow of the manuscript.