Interactive comment on "Observational evidence of moistening the lowermost stratosphere via isentropic mixing across the subtropical jet" by J. Langille et al.

Overall Author Response:

Thank you very much for your comments and suggestions regarding our manuscript. We agree with most your suggested changes and have included several edits to the final manuscript that reflect these changes. We believe that the associated changes and additional analysis provides better context for the observations and makes for a more complete paper. We have responded directly to your comments below in red (A.1.#) and have identified where the corresponding changes have been made in the manuscript. In addition to these changes, there have been several format and structural changes that were made to the manuscript in response to suggestions and comments from the second reviewer. Please refer to the responses to the second reviewer for a description of those changes. Note that several new Figures have been added to the manuscript in order to expand the analysis. We have also edited the figures to have the same colormap throughout the paper.

Summary of key revisions made to the paper:

1) A synoptic scale meteorological analysis is included for the Rossby wave breaking event that resulted the observed dynamical structure.
2) Discussion of the process-consistency despite the specific differences between SHOW water vapor structure and the ERA5 dynamical field is made to clarify that multiple factors can contribute to the specific differences, including the physical factor that when wave breaking result in irreversible mixing, the air mass composition loses its correlation with PV as a dynamical tracer.
3) More focused in the objectives and take-home messages of this paper to present the new observational evidence of water vapor transport into lowermost stratosphere driving by Rossby wave breaking and instrument capability and potential impact on stratospheric water vapor budget. Eliminated the additional discussions on the scale of the event and further dynamical analysis to avoid distracting from the main messages.
4) The abstract has also been edited accordingly

Anonymous Referee #1 Received and published: 6 January 2020

The authors present results from a new remote sensing instrument designed for satellite-borne high-vertical resolution limb soundings of water vapor in the upper troposphere/lower stratosphere. The instrument was mounted on board a high-altitude research aircraft and a single cross section obtained of an intrusion of tropospheric air into the lower most stratosphere, just above the subtropical jet is presented. The cross section provides evidence of a moist filament of tropospheric air being mixed poleward into the lower most stratosphere.

Such events are of physical and climatic interest given the role of these events in moistening the extratropical lower stratosphere and thus determining water vapor concentrations in a region important for climate forcing. The observations reveal features at very fine vertical length scales (< 1 km) which are difficult to observe and to model, although the MLS observations do seem to capture the filament in question to some extent. This filament of elevated water vapor coincides with the (upper) tropopause near the 400 K isentropic surface. The authors suggest tentatively that there may be a bias in the ECMWF reanalysis in the form of a vertical offset of the dynamical fields, in that there is a similarly located region of low potential vorticity air somewhat lower in altitude.

Regardless of this suggestion, this observation of a fine filamentary structure extending into the lowermost stratosphere is certainly worthy of publication, but since the scope of the paper is, as set out by the authors, primarily to present the scientific value in these test observations (not simply to validate them) I think it is appropriate to ask for a bit more follow up analysis on some of the details.

Author Response (A.1.1)

We agree with your request to present some follow up analysis that serves to highlight the scientific value of the SHOW measurements. Therefore, we have added several new Figures (Figure 1- 4) and further analysis of the meteorological fields that provides evidence that the observed moist filament is due to isentropic mixing following a Rossby wave breaking event in the days preceding the ER-2 flight. This is discussed in more detail in A.1.3 below. We have also expanded the discussion in section 6 to examine potential errors in the SHOW measurements, the determination of the upper and lower boundary of the retrieval and reasons for potential biases between SHOW, MLS and the reanalysis data. It also emphasizes the spatial structures in the PTLR in the context of the new analysis of the meteorological fields in support of the suggestion that the moist filament is of tropospheric origin (tropospheric intrusion).

Firstly, the newer ERA 5 reanalysis should be used instead of ERA Interim. It has substantially higher vertical and horizontal resolution, and the data is easily available. It would be also worth looking at model level data which is much finer than the data provided on the 37 pressure-level grid. I am not convinced of the inferred vertical (see below), but in any case, the comparison would be much more relevant in the context of the more modern product.

Author Response (A.1.2)

We are actually using ERA 5, not ERA-interim. The data is provided in 1-hour time steps on a 0.25-degree x 0.25-degree grid. However, the ERA5 products available to us, unfortunately, still has 37 level, with corresponds to 25 hPa vertical resolution in the tropopause region. This is much coarser than the measurement.

Secondly, emphasis has been placed on the vertical and meridional structure of this filament, but the only synoptic details we are given is in the form of an isobaric wind map at 175 hPa. It could be very enlightening to see some maps of potential vorticity on the 400 K and the 380 K isentropic surfaces with a domain comparable to Figure 1, in order to distinguish the filament from the layer of air between the double tropopause structures highlighted in Fig. 3a. These may have quite different horizontal structures that could shed light on the fine vertical structure of the observed water vapor. On a related note, I don't think the text includes a discussion of the line-of-sight resolution of the measurements (i.e. in the longitudinal direction in the current geometry).

Author Response (A.1.3)

In order to address your first point, we have included several additional Figures and associated analysis that we believe provides the necessary context for the case study that is presented in the paper. We have added several paragraphs to Section 3 that discusses these Figures.

Specific changes:

1. We have included a new figure (Figure 2) showing 3 - 48-hour time steps (each day at 20:00 UTC) of PV on the 380 K surface for the 6 days leading up to the date of the case study. The Figure clearly shows a Rossby wave-breaking event has occurred in the days preceding the flight that results in mixing along the subtropical jet.

2. We have added a new figure (Figure 3) shows the PV on the 380 K (Figure 3 (a)) and 400 K (Figure 3 (b)) surfaces for the 07/21/2017 18:00 UTC time step. In the Figures, the tropospheric and stratospheric air masses are separated by the 6PVU contour on the 380 K surface and 8 pvu on the 400 K surface. Here it is observed that the mixing associated with the Rossby wave breaking results in a long low PV "tongue" consistent with tropospheric air that extends from the Western Pacific and tracks the subtropical jet across North America.

3. To characterize the vertical structure we have included a Figure (now Figure 4) that shows the height of the thermal tropopause and the location/extent and height of the secondary tropopause for the 07/21/2017 18:00 UTC time step. In these figures one can clearly see that there are several double tropopause regions located on the poleward of the subtropical jet. The SHOW measurements track crosses one of these regions. While additional time steps are not shown, it is useful to point out that the regions of double tropopause vary in extent from time-step to time-step. In fact, the double tropopause region that SHOW crosses becomes larger near the 21:00 UTC time step. A paragraph has been included in the text that discusses this Figure. We believe that the updated analysis provides the relevant context for the case study and justifies the suggestion that the moist filament observed along the second tropopause in Figure 6 (a) is likely of tropospheric origin.

4. Regarding the line of sight resolution in the longitudinal direction, the SHOW instrument averages over 4 degrees in the horizontal by making use of anamorphic input optics. Therefore, no horizontal scene information is obtained. A sentence has been added after the second sentence of the second paragraph in Section 2 to clarify this point for the reader.

With regards to the suspected offset in the reanalysis output, this is certainly a difficult region to capture correctly and so it seems plausible to me that such an offset could exist. However, it's also possible that the water vapor transport is not aligned with the lowest PV anomaly, or that the layer of most effective intrusion is not where the PV gradients are strongest (after all the meridional PV gradients act as a horizontal mixing barrier that discourages such intrusions). The requested figures should provides some clarity on this point. A related dynamical point is that the potential temperature lapse rate is not a materially conserved quantity, while PV is (up to diabatic processes); this point should probably be stressed more clearly in the text.

Author Response (A.1.4)

The text has been updated to be clearer on this point. Specifically, the lines highlighting a potential bias between the reanalysis and observations have been removed; however, the identification of the misalignment between the two is discussed. Several new paragraphs have been added to Section 5 that examine the PV and layered thermal structure in the context of mixing following the Rossby wave breaking. It is clarified that it is physically possible (and reasonable) that the dynamical field and chemical structure are no longer intact, which is a sign of an irreversible transport. In addition, the ERA5 products are given at a much coarser resolution than the SHOW measurements. We include a paragraph in the discussion of Section 6 that clarifies these points.

One final minor comment: on line 168 reference is made to orange contours in Figure 3 that I think are in fact dark gray; the orange contours only show up in Figure 4.

Author Response (A.1.5)

The text has been modified so the appropriate “grey” contour is mentioned.