Response to Reviewer #3's Comments

Thank you for providing valuable comments that improve the original manuscript. We tried our best to improve the manuscript based on your suggestions.

Major comments:

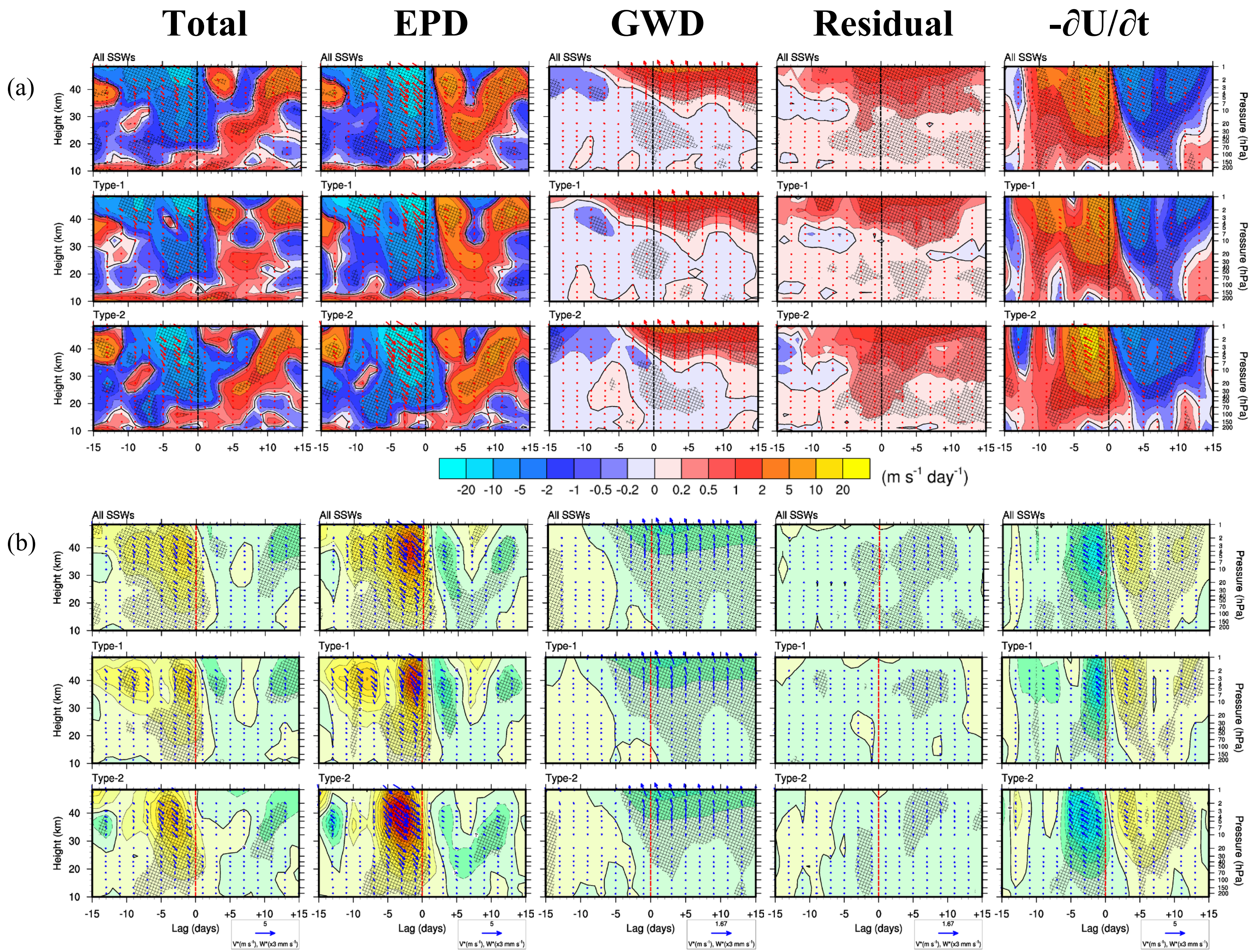
1) *This study uses a modern reanalysis (MERRA) to compute and composite forcing terms in the transformed Eulerian mean (TEM) zonal wind and thermodynamic equations about sudden stratospheric warmings (SSWs). The authors separate the SSWs into Type-1 and Type-2 events based on relative sizes of wave-1 and wave-2 polar geopotential height anomalies. The composites demonstrate that the planetary-scale wave activity flux is the dominant forcing term in both the TEM zonal wind and thermodynamic equations. Uppermost stratospheric gravity wave drag and middle stratospheric diabatic heating are meanwhile shown to be small, though non-negligible. I believe the authors present a clean analysis that stays on point with the paper's theme.*

2) *There are however a few points that I'd like the authors to edit or address to boost the quality of the manuscript. Principally, I'm not sure what the added value of separating the events into two types is. While comparison of the two types seems to be a large portion of the analysis, there is not much discussion on the implications of these results. Events are often separated in studies of SSWs, but the reasons need to be made clear. I don't believe the authors have amply done this in the introduction or summary. I think a more thorough discussion of why the authors did what they did and how it fits into the literature will greatly aid the manuscript. There are also a few analysis steps by which the authors could address this problem. Firstly, the authors could show an 'all SSW' composite for each part of the analysis. In this way, the manuscript would analyze the residual mean circulation from MERRA in all SSWs and concurrently show the results for one way that SSWs are separated. Secondly, the authors could (and I believe should) show significance of the anomalies for each event type. While the significant difference between Type-1 and Type-2 is important, so too is their own significant difference from zero. Especially given the small sample size, this will better inform the reader as to which composite structures agree with each other. Given the scope and work required for these changes, I recommend that the manuscript be returned for major revisions.*

→ We classify SSWs into two types, as they have distinct characteristics in wave dynamics (Charlton and Polvani 2007; Nishii et al., 2011), impact on the weather (O'Callaghan, 2014; Liu et al., 2014; Seviour et al., 2015), and gravity waves drag (Albers and Birner, 2014; Šácha et al., 2016). Following the reviewer's suggestion, reasons to separate the SSW events into two types are included in the revised manuscript [page 2, line 2–5] with the references.

Following the reviewer suggestion, some analyses in the original manuscript are re-performed for all SSW cases during the revision process. The result (Fig. A1) of the all SSW cases is about the average of the result by the two types, as expected. Therefore, the result is not included in the revised manuscript.

Following the reviewer's suggestion, statistical significance of the anomalies for each SSW types is checked in all figures of the original manuscript, and significant anomalies are highlighted by hatch patterns in Fig. 3b, 3d, 5a, 6b, 7a, 7b, 8a, 8b, 9a, 9b, 10a, 10b, and 11 of the revised manuscript.



Total
EPD
GWD
Residual
-∂U/∂t
(a)
(b)
All SSWs
Type-1
Type-2
Height (km)
Pressure (hPa)
Lag (days)
-20 -10 -5 -2 -1 -0.5 -0.2 0 0.2 0.5 1 2 5 10 20
(m s-1 day-1)

(c)

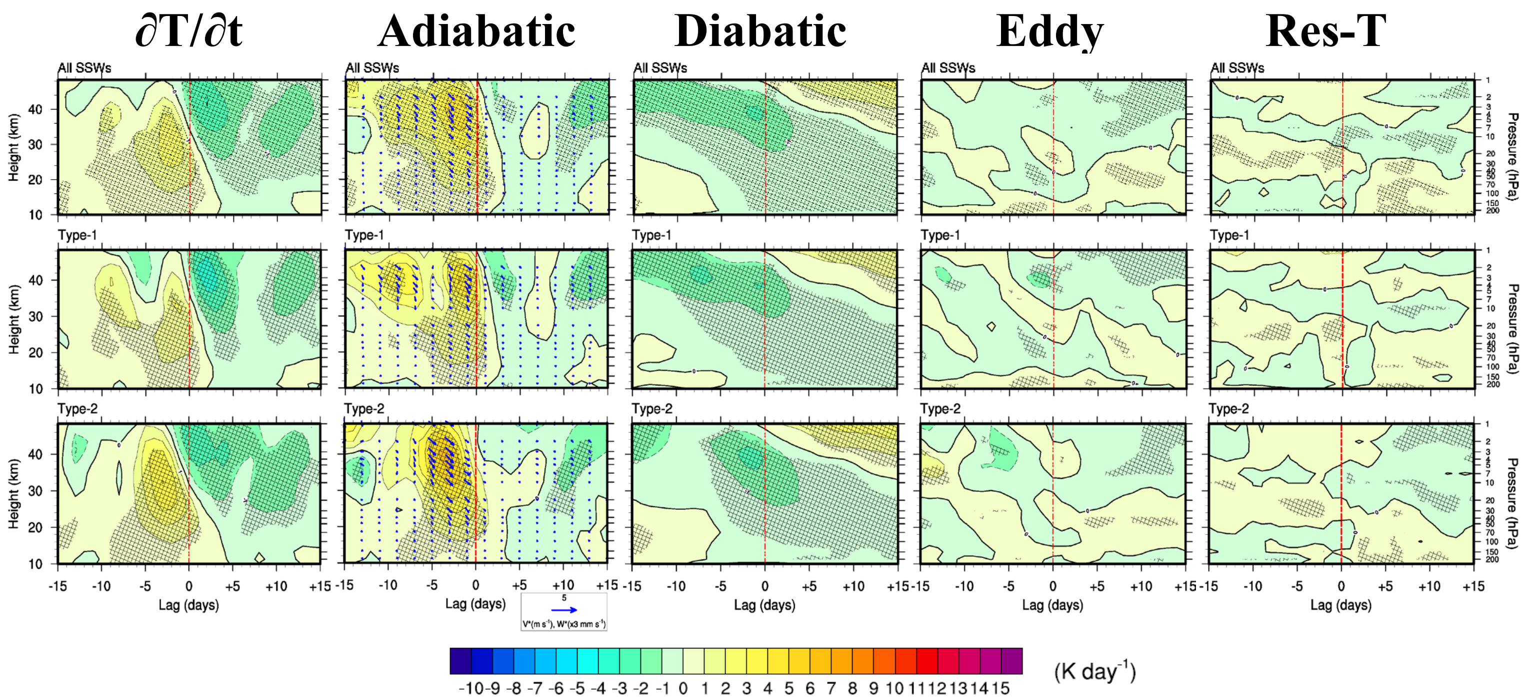


Figure A1. Time-height cross sections of the composites of (a) each forcing term averaged over 60° N–70° N (shading) and (b) adiabatic heating rate by the residual mean circulation averaged over 70° N–80° N (shading). The arrows denote the residual mean velocities averaged over 70° N–80° N, induced by each forcing. (c) Time-height cross sections of the all SSWs composites of the zonal-mean temperature tendency (first column), adiabatic heating rate by the circulation (second column), diabatic heating rate (third column), eddy heat flux (fourth column), and the residual term of TEM thermodynamic energy equation (fifth column) averaged over 70° N–80° N. The first to third rows of each panel are composites for all, Type-1, and Type-2 SSW events, respectively. All values are anomaly fields from the climatology. The hatch patterns denote statistically significance at 90% confidence level.

Minor comments:

1) *Page 2, line 23: I think you should state that it has not been done with the generalized downward control principle.*

→ It is modified, as suggested. [Page 2, line 25]

2) *Page 2, line 41: how is the climatology calculated? This will be important information if others wish to reproduce or adapt your results.*

→ The climatology is defined as the 34-year average of each day. This is included in the revised manuscript. [Page 2, line 42]

3) *On reproducibility, thank you for including a table of SSW dates. This step is often overlooked for SSW studies.*

→ Thank you for pointing out this. We hope that this information helps other scientists to study SSW.

4) *Page 5, line 42: what is the reason you average the forcing over a different latitude band than the residual forcing terms?*

→ Here, we said not "residual forcing" but "residual circulation" ($\bar{v}^*$, $\bar{w}^*$) induced by the forcing. If there is negative forcing at midlatitude, say 60° N, it induces a poleward and downward motion on latitudes higher, say 70° N, than the forcing latitude. Therefore, we used the different latitude band for wave forcing and residual circulation.

5) *Page 7, line 19: though the amplitude may be small, the residual term has a broad region of significant difference. Do the authors have any insight as to why that may be?*

→ The test statistic for two-sample t-test (Wilks 1995) is determined by Eq. (A1):

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{{s_1}^2}{N_1} + \frac{{s_2}^2}{N_2}}} \ , \qquad \text{(A1)}$$

where $\bar{X}$, s^2, and N are the sample mean, variance, and size, respectively. For the case of the residual term between Type 1 and Type 2, we found that the test statistic is large due to the relatively small standard deviation, regardless of relative small mean values. This is included in the revised manuscript. [Page 7, line 36–37]

6) *Page 9, line 21: model level data from ERA-Interim is used, but Table 1 indicates pressure-level data is used (i.e., shouldn't ERA-Interim have 60 levels?).*

→ Thank you for pointing out this. When SSWs are selected, we used four reanalysis data sets including ERA-Interim pressure-level data. The ERA-Interim model-level data are used only for Fig. 11. The information of the model level data of ERA-Interim is added to Table 1 of the revised manuscript, along with a statement related to usage of ERA-Interim pressure-level and model-level data sets mentioned above. [Page 14, Table 1]

7) *On the figures: since so many panels are included in each figure, the panels will be quite small when published. This will make seeing the small regions of significance hard to see. I'm not sure the best way to do this, but the authors may consider altering their figures to better show hatched regions. This is especially true over regions with dark blue contour filling.*

→ We agree with you. Although we have tried hard to make figures more visible, we could not find a satisfactory way, in order to keep all necessary panels in a figure. To make the hatched regions in the figures more clearly visible, the colors of the contour label in Fig. 3 are changed.

References:

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