Dear Anonymous Referee #1

According to the reviewer's comments, substantial revisions have been made in the revised version, and the comments and concerns have been addressed carefully point-by-point. We have repeated the comments of the reviewer in italics and bold before our response. The revised manuscript with tracked changes (highlighted in red font) is also provided.

Interactive comment on "Strong downdrafts preceding rapid tropopause ascent and their potential to identify cross-tropopause stratospheric intrusions" by Feilong Chen et al.

Anonymous Referee #1

Received and published: 15 August 2018

Review of the manuscript "Strong downdrafts preceding rapid tropopause ascent and their potential to identify cross-tropopause stratospheric intrusions" Author(s): Feilong Chen et al.
MS No.: angeo-2018-78
General Comments

Response: We really would like to thank the reviewer for giving us suggestions which help us to improve the quality of the paper. We have followed the reviewer's suggestions and the corresponding revision has been made.

The paper addresses an important aspect in the dynamics of the upper troposphere / lower stratosphere region, namely, relating tropopause height variability with stratospheric intrusions into the troposphere. Using VHF radar measurement data, including 3-D wind, the authors are able to diagnose events of considerable tropopause height drops. They additionally find that in a significant number of such cases, strong downdrafts occur across the tropopause and extend to the mid and lower troposphere. These local downdrafts occur on the hourly time scale, and as such, they are revealed by the high-resolution radar data, but are missed by the coarser reanalysis or sporadic radiosondes.

My general concern is the interpretation of the considered events as 'rapid tropopause ascent', whereas the detailed case study (and many of the other cases presented) actually show a drop in tropopause height (such as occurring with a cutoff low, or an upper trough/PV streamer). The 'rapid ascent' seems to be a recovery from the drop in height, rather than the important phenomenon itself. Additionally, the downdrafts coincide with the lowest tropopause height and are related to the intrusions themselves. The reference to 'rapid tropopause ascent', i.e., higher tropopause height, compared to normal conditions, may give the opposite impression and confuse the readers. This notion appears in the title and throughout the text, and serves to identify the events climatologically using an ascent criterion, as shown in Fig. 13. In my opinion, diagnosing significant tropopause drops (i.e., both rapid descent and ascent) is more meaningful in the context of intrusions. It will be interesting to see how many of those are accompanied by strong downdrafts.

Response: Your general concern is important and essential. In fact, tropopause drops, either slowly or rapidly, are close related to various synoptic-scale or mesoscale atmospheric processes such as cutoff low, low trough, or typhoon, which play an important role for potential stratospheric intrusions. However, not every such synoptic-scale or mesoscale atmospheric process is responsible for intrusions. On the other hand, the specific vertical velocity of the tropopause drop is most likely related to the strength of the corresponding atmospheric process, rather than the corresponding intrusion event. In other words, various atmospheric processes (and the accompanied tropopause drops) are important conditions for intrusions (or for the strong downdrafts in our study), but intrusion events are not close related to tropopause drops. As for the rapid ascent in tropopause height, no matter whether exists the tropopause drops, the potential intrusion events (intruded across the tropopause layer) will change the atmospheric structure. According to previous study by Hocking et al., 2007, the tropopause height started to ascent when the stratospheric air just intruded across the tropopause layer. In present study, the strong downdrafts and the accompanied rapid tropopause ascent (with specific erosion velocity) are found important features for the potential intrusions, although the ascent seems to be a recovery from the drop in tropopause height (many cases, not all). Therefore, we think the strong downdrafts just preceding the rapid tropopause ascent (black bands shown in Fig.13) may serve as a valuable predictor for possible stratospheric intrusions.

Overall, I found the presentation of the results in the text and the figures to be clear and concise. There are, however, some issues requiring further clarifications, and I therefore recommend publication if the general concern and the specific comments below are addressed.

Specific major comments

1. I do not understand how Figure 7 and the paragraph describing it in lines 283-287 help to relate the observed oscillations to the mountain waves. Please clarify, or delete this part (also from lines 407-409).

Response: Yes, you are right. We really thank you for the valuable comment and pointing out the deficiencies. Figure 7 and Figure S1 are indeed not essential and need to be deleted. The corresponding text and figures have been modified, please see the revised manuscript.

2. The trajectory analysis shows that the mid-tropospheric airmasses originate upstream from _7000-9000 m in altitude. This is commonly the upper troposphere, rather than a clear stratospheric origin as stated (e.g., lines 312, 337). Please support the statements on the stratospheric origin by providing evidence of the lower tropopause height at those locations, or alternatively showing high PV values along the trajectories, or refrain from making these statements. It is relevant to note here that in Raveh-Rubin (2017), almost 99% of intrusions were not stratospheric in their origin.

Raveh-Rubin, S., 2017: Dry Intrusions: Lagrangian Climatology and Dynamical Impact on the Planetary Boundary Layer. J. Climate, 30, 6661–6682, https://doi.org/10.1175/JCLI-D-16-0782.1

Response: Yes, you are right. Thank you very much for pointing out the deficiencies.

The statements of stratospheric intrusions are not appropriate for trajectory analysis. The further observations of the AIRS daily 500 hPa ozone distribution is essential to conclude that the intrusions are of stratospheric origin. The corresponding statements have been modified and replaced as "downward intrusions". Please see the corresponding text in the revised manuscript.

Specific minor comments

1. *Line 102-103: this sentence is unclear.*

Response: To make it more clear, we have added the expression "especially the criteria of identification by of radar observations" in the revised manuscript.

2. *Lines 105-107: Please elaborate on the spatial and temporal relation between the tropopause ascent and the downward intrusions in Hocking et al. 2007.*

Response: We have descripted the relation between the tropopause ascent and the downward intrusions in Hocking et al. 2007, please see the corresponding text "the RT height started to ascent when the stratospheric air just intruded across the tropopause layer."

3. *L 148: "the characteristic (partial specular reflection) mentioned above" is unclear. Please clarify the characteristic (also unclear where is it mentioned above).*

Response: To make the statement more clear, the corresponding sentence has been modified as "the characteristic (enhanced radar echoes due to partial specular reflection) mentioned above". This characteristic is mentioned above, the sentence "The tropopause, near which a strong potential temperature gradient exists, will lead to strong radar echoes in vertical incidence, as well as large radar aspect sensitivity (as shown in Figure 1)".

4. L 153-154: the description of the RT height determination should be written more clearly. Is it determined by searching upwards from 500 hPa for the first maximum of the gradient? It is unclear what "lower edge" or "secondary maximum" refer to.

Response: Yes, you are right. It is determined by searching upwards from 500 hPa for the first maximum of the gradient. We have rewritten the definition of RT height, please the sentence "Here, the radar-determined tropopause (RT) height is defined as the height (above 500 hPa) where the maximum vertical gradient of echo power located (shown as the orange circle in Figure 1a)." in the revised manuscript.

5. L 247-248: please also refer to the very significant updrafts that follow the downdrafts. They can potentially be important for the recovery of the tropopause height back to normal, as they extend to the increasing height of the upper troposphere.

Response: Thank you very much for the valuable comment. Our key point is the downdrafts followed by rapid RT ascent, no matter whether the ascent is the recovery normally or forced by the other factors such as the significant updrafts.

6. L 271: Is it related to the high winds at Q compared to P?

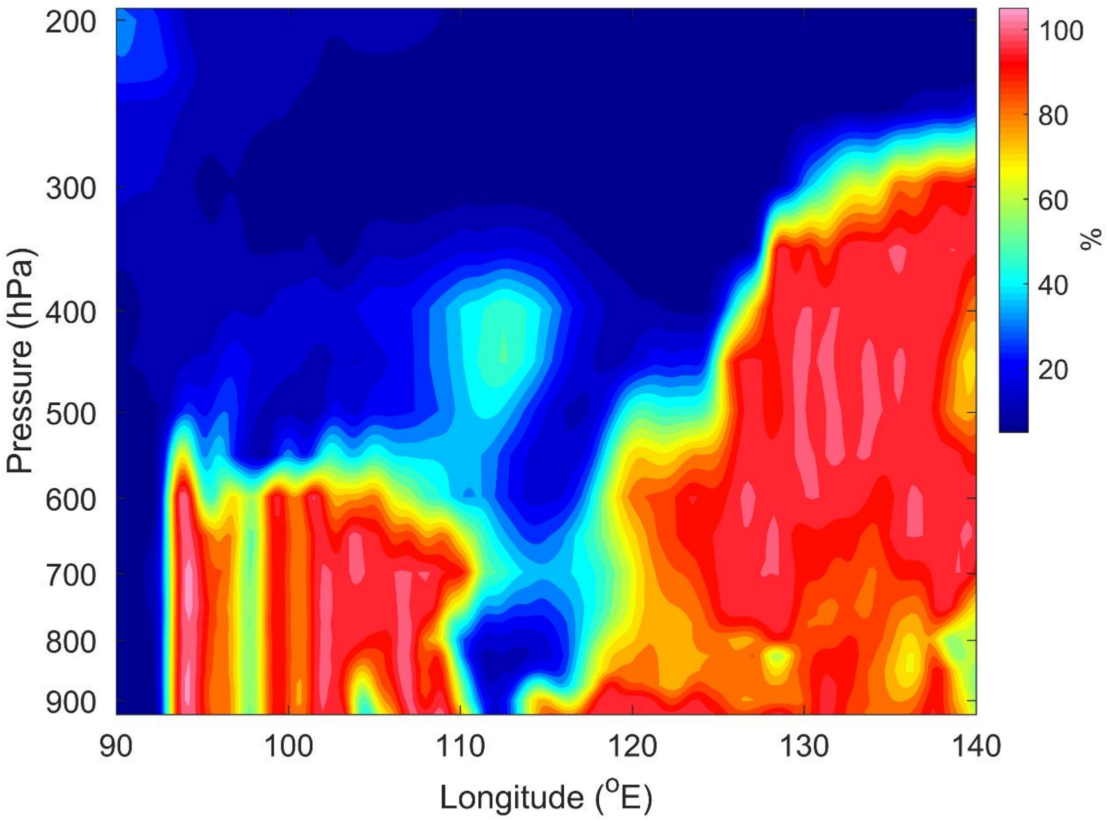
Response: The abnormal high radar aspect sensitivity is not related to the high winds at Q. High winds can't cause the difference of echo power between the vertical and oblique beams. As mentioned in the manuscript, the large value in radar aspect sensitivity is mainly caused by reflection from stable atmospheric layer, such as the tropopause or lower-stratosphere.

7. Lines 295-296: How does the figure support the cross-tropopause aspect?

Response: The cross-section of PV, humidity, and AIRS ozone clearly shown enhanced PV and ozone and dry air, which are typical characteristics of stratospheric air, intruded from lower stratosphere into the free troposphere.

8. Lines 297-304 and Fig. 9c. I suggest adding relative humidity to the profile, which may show clearer asymmetry between the east and western sides of the cutoff.

Response: The cross-section of relative humidity is shown below. Although it also shows obvious dry air intruded into the free troposphere, it is just similar to and not that better than the cross-section of specific humidity.



9. L 304-305: It is not clear if the low-level high PV is indeed stratospheric in origin as mentioned, or whether it is diabatically produced. See the distinction done in Škerlak et al 2015.

Škerlak, B., M. Sprenger, S. Pfahl, E. Tyrlis, and H. Wernli (2015), Tropopause folds in ERAâˇARˇ Interim: Global climatology and relation to extreme weather events. J. Geophys. Res. Atmos., 120, 4860–4877. doi: 10.1002/2014JD022787.

Response: Indeed, we can not conclude that the low-level high PV is stratospheric in origin from cross-section of PV alone. Thus the cross-sections of humidity and ozone are presented to verify the stratospheric in origin.

10. L 354: Where are the high-pressure systems located relative to the events (height and horizontal location)?

Response: The low or high pressure systems are observed from 500 hPa meteorological chart. Please see the corresponding sentence "associated with low or high trough systems (at 500 hPa)".

11. Out of the 20 cases, it is a bit hard to keep track of their different characteristics. I *suggest summarizing these in a table, and including the main features of Figures 12, S2 and the meteorological systems in lines 350-360.*

Response: We really would like to thank you for giving us the suggestion. The 20 cases identified in Fig. 12a are labeled as S1, S2, S3…, and S20, respectively. Their different characteristics, including background synoptic ~~synoptic~~ condition, vertical velocity of ~~the~~ RT ascent, and 500 hPa ozone enhancement, have been summarized in a table (shown below). Please see the Table 2 in the revised manuscript.

Table 2. Characteristics of the 20 cases shown in Fig. 12a.

Cases	Time (year/month/day)	Background ~~synoptic~~ condition	Vertical velocity of ~~the~~ RT ascent	500 hPa ozone enhancement
S1	2012/03/06	Cut-off low	>0.2 km/h	Enhanced
S2	2012/03/06	Cut-off low	>0.2 km/h	Enhanced
S3	2012/03/12	Low/high trough	>0.2 km/h	Enhanced
S4	2012/03/13	Low/high trough	>0.2 km/h	Enhanced
S5	2012/04/05	Low/high trough	>0.2 km/h	Enhanced
S6	2012/04/05	Low/high trough	>0.2 km/h	Enhanced
S7	2012/04/06	Low/high trough	>0.2 km/h	Enhanced
S8	2012/06/13	Cut-off low	>0.2 km/h	Enhanced
S9	2012/06/13	Cut-off low	>0.2 km/h	Enhanced
S10	2013/08/02	Cut-off low	>0.2 km/h	Enhanced
S11	2013/08/02	Cut-off low	>0.2 km/h	Enhanced
S12	2013/08/03	PV streamer	>0.2 km/h	Enhanced
S13	2013/08/03	PV streamer	>0.2 km/h	Enhanced
S14	2014/01/02	PV streamer	>0.2 km/h	None
S15	2014/01/02	PV streamer	>0.2 km/h	None
S16	2014/01/03	PV streamer	0.1-0.2 km/h	None
S17	2014/01/04	Low/high trough	>0.2 km/h	None
S18	2014/05/02	Low/high trough	0.1-0.2 km/h	Enhanced
S19	2014/05/02	Low/high trough	>0.2 km/h	Enhanced
S20	2015/01/03	PV streamer	>0.2 km/h	None

12. L 363: I suggest to replace "predictor" by "diagnostic", as they occur at the same time. Also, delete "or prediction" from line 365.

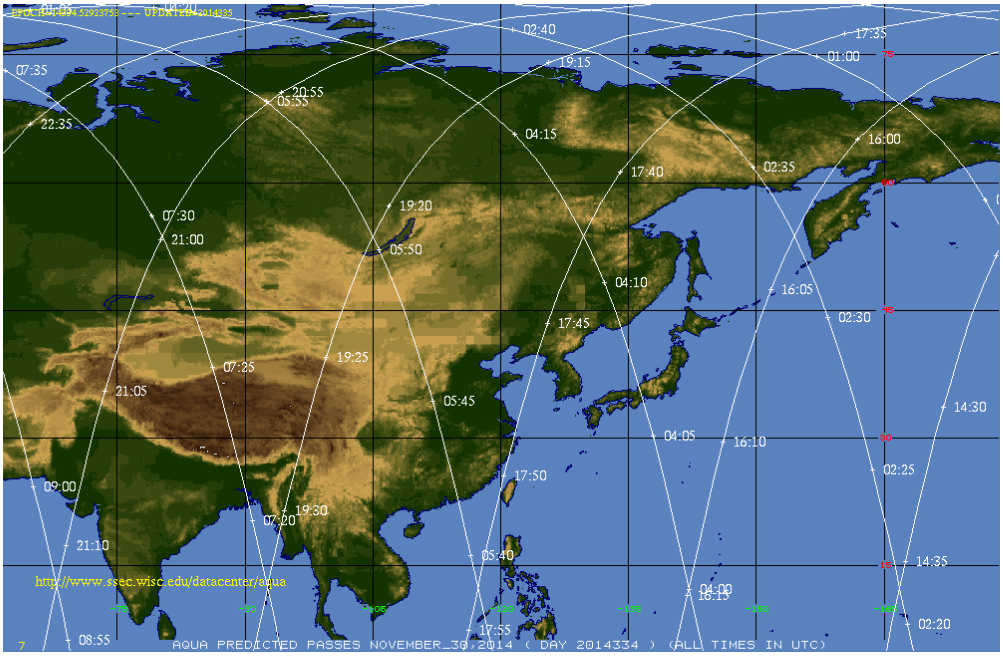
Response: Thank you very much for pointing out the deficiencies. The "predictor" has been replaced by "diagnostic", and the "or prediction" been deleted.

13. Figure 1: It is suggested to add panels with sea-level pressure and low/mid tropospheric wind, to understand the environment of the downdrafts at these heights.

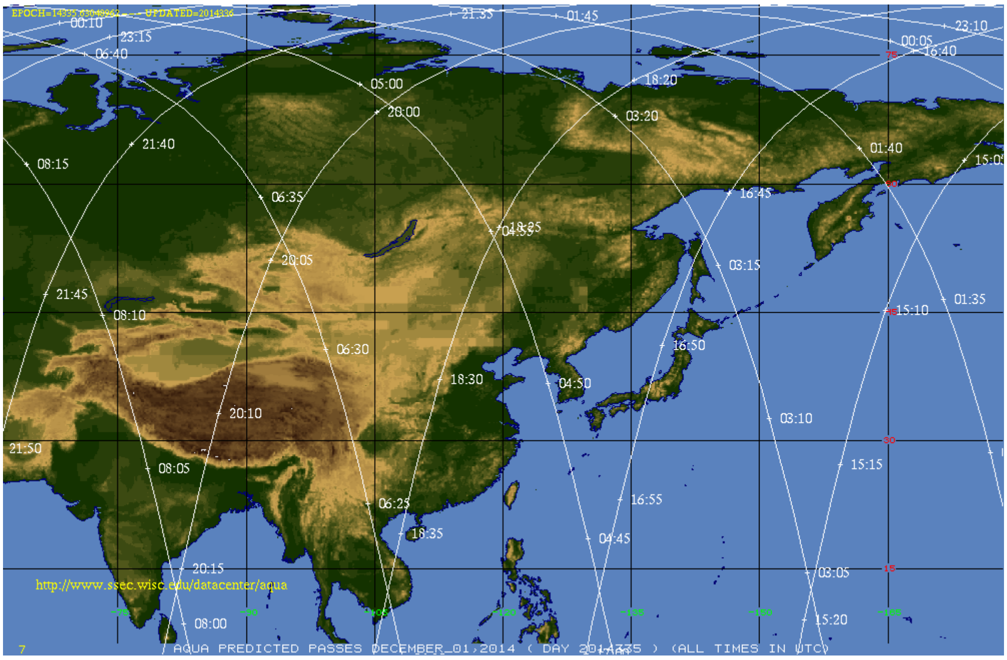
Response: We really would like to thank you for giving us the suggestion. We consider that the 500 hPa geopotential height, Time series of surface hourly meteorological measurements, and maps of Outgoing Longwave Radiation are enough to understand the environment of the downdrafts.

14. Figure 8 and in the main text: please add the time range of the satellite passage.

Response: The AIRS retrieved data of daytime ascending pass (south pole to north pole) are used in Fig. 8 (Fig. 7 in the revised manuscript). According to the Aqua Orbit Tracks, as shown below, the time range of the satellite passage is between ~04:00-07:25 on 30 November and between ~03:15-06:35. The corresponding text has been added in the revised manuscript.



30 November 2014



1 December 2014

15. Figure 10 and 11 captions: please mention the height of the ending / starting point, respectively.

Response: Thank you very much for pointing out the deficiencies. the ending / starting point has been mentioned in the corresponding figure captions. Please see figure 9 and 10 in the revised manuscript.

Technical Corrections

1. Velocities are shown in km/h and m/s throughout the manuscript. I suggest to be consistent and use only m/s.

Response: Thank you for pointing out the suggestion. The km/h is used for radar tropopause ascent, and m/s is mainly used for 3D winds. We considered that they are reasonable.

2. Line 17: delete "possible", it is repeating after 'potential'.

Response: We really thank the **referee** for pointing out the deficiencies. We have modified the corresponding text.

3. L 22: delete "(weakened)", which is unclear in this context.

Response: We have modified the corresponding text.

4. L 48: delete "long-term" from the second time it is mentioned, before 'seasonal'.

Response: We have modified the corresponding text.

5. L 52: replace "when comes" to "with regards".

Response: We have replaced "when comes" to "with regards".

6. L 60: change "air transport" with "air is transported".

Response: The corresponding text has been changed.

7. L 64: Move "although" to the beginning of the line.

Response: We have modified the corresponding text.

8. L 93: delete "are".

Response: The corresponding text has been deleted.

9. L 97: change "comparing" to "compared to".

Response: The corresponding text has been changed.

10. L 127: space is missing after the degree sign.

Response: The space has been added in the corresponding text.

11. L 145: replace "to" with "away from".

Response: We have replaced "to" with "away from".

12. L 159: replace "that" with ","

Response: We have replaced "that" with ",".

13. L 182: replace "with" with "interpolated into".

Response: We have replaced "with" with "interpolated into".

14. L 199: replace "bottom" to "southern tip".

Response: We have replaced "bottom" to "southern tip".

15. L 200: add "as shown by the closed geopotential contour" after "site".

Response: The corresponding text has been added.

16. L 220: change "a" with "that".

Response: The corresponding text has been changed.

17. L 221: change "didn't" with "did not".

Response: The corresponding text has been changed.

18. L 223: replace "showed" with "shown".

Response: We have replaced "showed" with "shown".

19. L 224, and throughout the manuscript: change "UT" to "UTC".

Response: We have replaced "UT" with "UTC" throughout the manuscript.

20. L 263: delete "It is indeed reasonable.".

Response: The corresponding text has been deleted.

21. L 266: replace "impinges" with "impinging".

Response: The corresponding text has been changed.

22. L 280: replace "Someone may be interested to notice" with "Interestingly".

Response: The corresponding text has been changed.

23. L 298: delete "with".

Response: The corresponding text has been deleted.

24. L 320: Move "dominant" to after "flows".

Response: The corresponding text has been changed.

25. L 328: "shown placed end-to-end" is unclear.

Response: The time is not continuous and is placed end-to-end with intervals of 2.5 hours (white field).

26. L 328: delete "and".

Response: The corresponding text has been deleted.

27. L 332: "four range gates" is unclear.

Response: One range gate indicates the height resolution of the MST radar (150 m).

28. L 359: Add "(not shown)" after "48h".

Response: The corresponding text has been changed.

29. L 360-361: delete "and not possible: : : satellite data", as it is redundant.

Response: The corresponding text has been deleted.

30. L 367: replace "have" with "has".

Response: The corresponding text has been changed.

31. L 377: replace "excess" with "exceeds".

Response: The corresponding text has been changed.

32. L 413: replace "What counts is" with "Yet".

Response: The corresponding text has been changed.

33. L 414: add a '-' between "AIRS-retrieved"

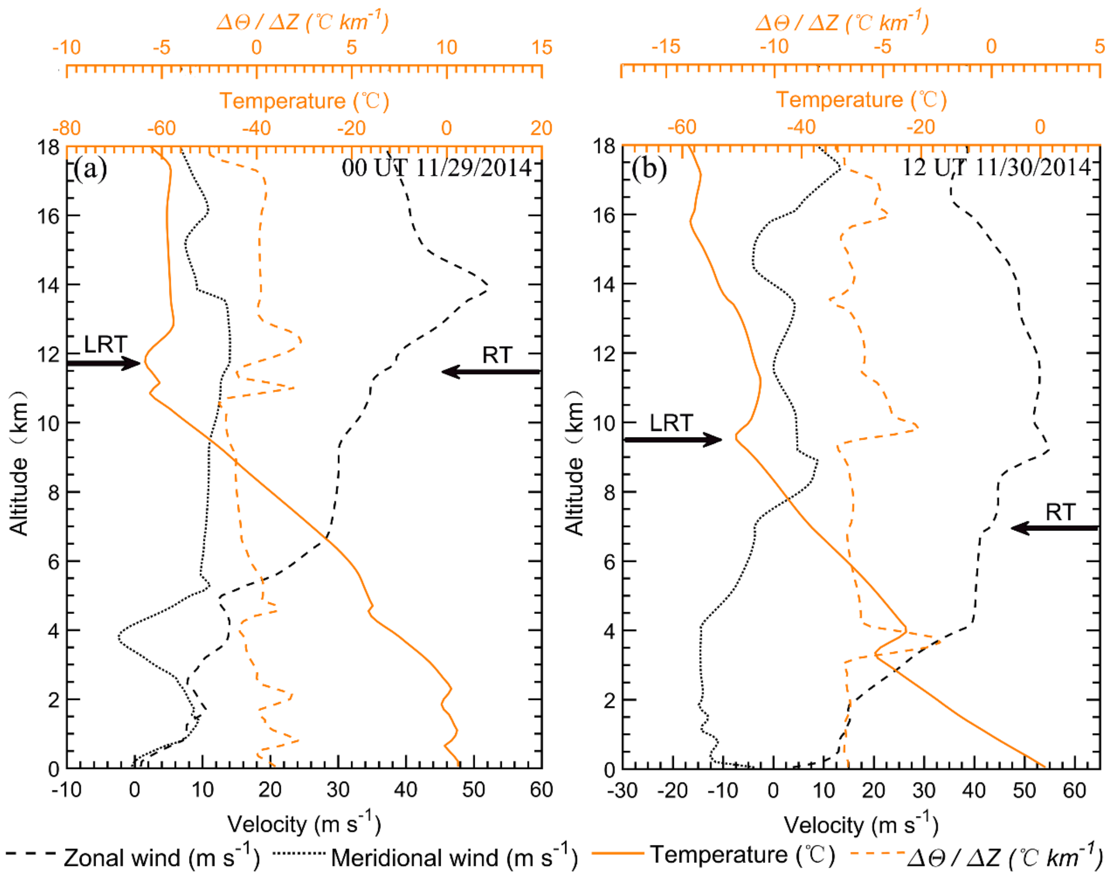
Response: The corresponding text has been changed.

34. L 415: add a '-' between "radar-derived"

Response: The corresponding text has been changed.

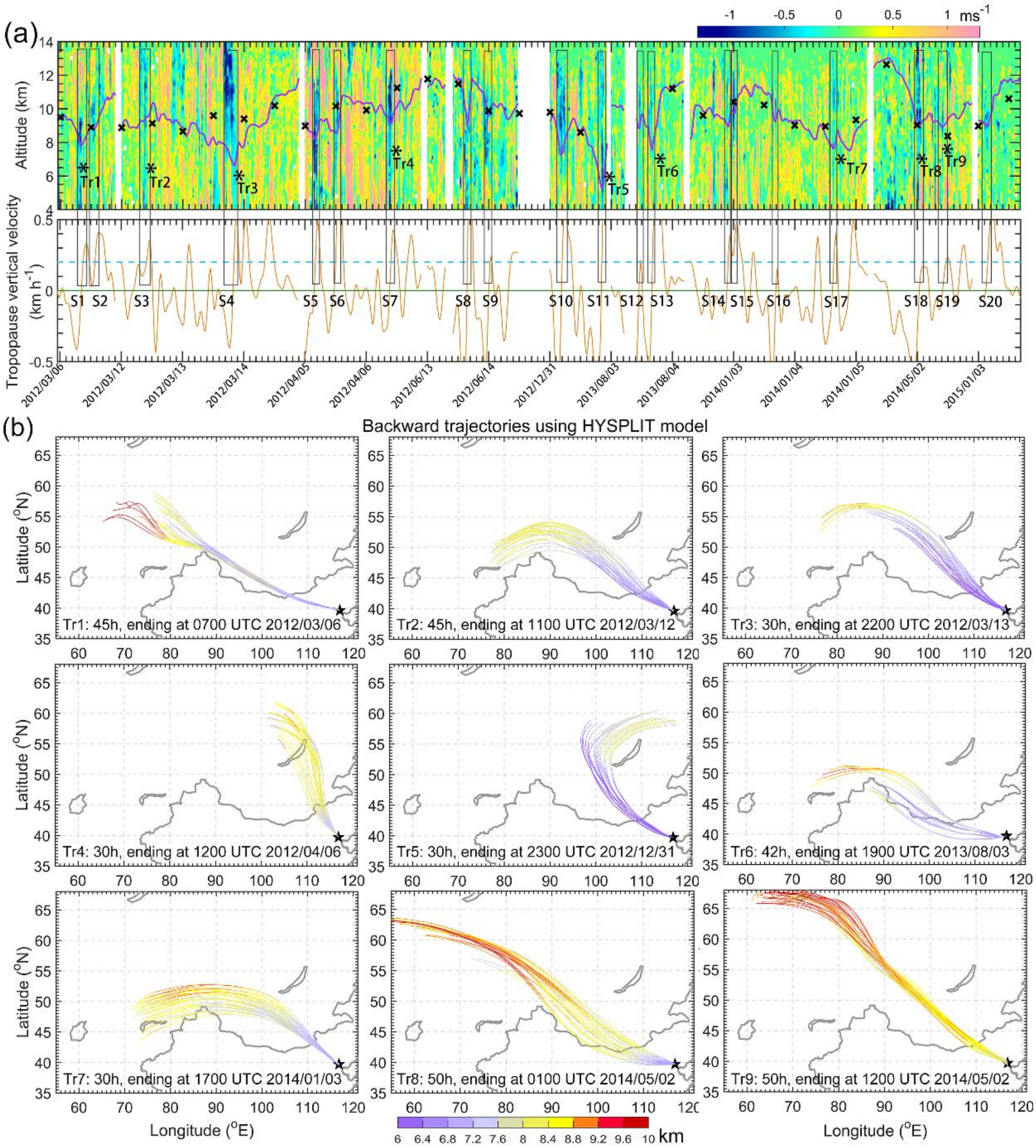
35. Figure 6 legend: replace dotted orange line with a dashed line as in the plot itself.

Response: The dotted orange line has replaced with dashed line (legend).



36. Figure 12b: It is strongly suggested to use the same colour scale in all panels.

Response: Thank you very much for pointing out the suggestion. All the panels in Fig. 12b have modified and using the same colour scale. Please see Fig. 11b in the revised manuscript.



37. Figure S2: There are only 12 events presented, not 20. Please change the format of the dates in the panel titles to be the same as in Fig. 12.

Response: The format of the dates in the panel titles of Fig. S2 has been modified. Please see Fig. S1 in the revised manuscript.