

Authors response

Dear Heini Wernli,

thank you for once again reviewing the document and for pointing out the remaining technical corrections. Furthermore, I understand and agree with your concern regarding the length and the reading flow of the paper, and I reworked or removed a few sentences/paragraphs that did not add significant information to the paper. I hope that these changes along with your suggestion to not include the paragraph on the thermal wind shear improved the reading flow of the paper.

In the following I give a point-by-point response to each of your comments, in the order: 1) technical correction/comment, 2) our response and 3) the changes in the manuscript. The modified text passages are given in italics.

10

Point-by-point response to the Co-Editors comments

Comment: L6: S_t^2 is not yet defined, say that it refers to the squared vertical shear of the horizontal wind speed.

15 **Reply to comment:** I added a description as to what S_t^2 refers to.

Changes in the manuscript: L6: *A threshold value of $S_t^2 = 4 \cdot 10^{-4} \text{ s}^{-2}$ of the squared vertical shear of the horizontal wind is applied, which marks the top end of the distribution of atmospheric wind shear to focus on situations which cannot be sustained by the mean static stability in the troposphere according to linear theory.*

20 **Comment:** L6 and in several other places: “spectrum”? maybe better “distribution”? You later use “spectrum” for the wave or frequency spectrum (which I find fully OK), but then it is slightly confusing to me that the simple distribution of shear values is also called spectrum.

Reply to comment: I agree that “distribution” is a better choice, and replaced the word “spectrum” in this context in several instances in the document.

25

Comment: L15 and in other places: “near to the tropopause” → “near the tropopause”

Reply to comment: Thank you for pointing that out, I changed the wording accordingly.

Comment: L25: “la Nina” should read “La Nina”

30 **Reply to comment:** Done.

Comment: L39: “... and the squared ...”

Reply to comment: Done.

35 **Comment:** L68: “expand ... and present” should read “expanded ... and presented”

Reply to comment: Done.

Comment: L92: “describe” should read “described”

Reply to comment: Done.

40

Comment: L107: not clear to me what “vertical and lateral shear zones” are. In both cases do you still mean vertical shear of the horizontal flow? So maybe you mean “... with shear zones vertically spanning ... and laterally over several hundreds of kilometres”?

Reply to comment: The intention was to describe wind shear surrounding the jet core in general, i.e., vertical shear of the horizontal wind above and below the jet core over vertical distances of several kilometers, as well as the horizontal shear of the horizontal wind spanning laterally around the jet core over distances of several hundred kilometers. I tried to give a definition of the jet stream (dimension) based on the wind shear. But since the paper focusses on the vertical shear of the horizontal wind, I agree with your suggestion and changed the wording accordingly.

45 **Changes in the manuscript:** L106: *The jet streams constitute the planetary-scale background state for the distribution of*
50 *wind shear, with shear zones vertically spanning over several kilometres and laterally over several hundreds of kilometres.*

Comment: L120: “confirm” should read “confirmed”

Reply to comment: Done.

55 **Comment:** L131: should read “orographically induced”

Reply to comment: Done.

Comment: L145: should read “of small-scale perturbations”

Reply to comment: Done.

60

Comment: L149: “analyse” should read “analysed”

Reply to comment: Done.

Comment: L165: I suggest deleting “as a reference dataset”

65 **Reply to comment:** Done.

Comment: L166: why “central”?

Reply to comment: I used this wording because the choice between the two common analysis methods, to either calculate the average of the vertical wind shear S^2 or to calculate occurrence frequency distributions for a threshold determines key
70 aspects of what knowledge can be gained based on the analysis. The idea is to emphasize that the choice to analyse occurrence frequencies $S^2 \geq S_t^2$ is central for the identification of the TSL. The changes in the manuscript motivated by your following comment should make that more clear.

Comment: L167: The sentence “This approach . . .” is rather complicated. Can you say the same with simpler words?

75 **Reply to comment:** Motivated by this comment and the previous one, I rephrased this description.

Changes in the manuscript: L165: *Another important aspect is the choice of the central analysis method, where we compare two common approaches. The first approach is the tropopause-relative averaging of either the vertical wind shear S^2 (e.g. Birner et al., 2002; Zhang et al., 2015) or of the horizontal wind and subsequent calculation of the mean vertical wind shear (Birner, 2006). The second approach and the one which is used in this work analyses the occurrence frequency distribution of*
80 *S^2 above a certain threshold value (Dvoskin and Sissenwine, 1958; Sunilkumar et al., 2015). This method can be advantageous because it conserves more information on where strong wind shear does (not) occur.*

Comment: L188: no need to repeat the WMO criteria, which you already listed in the introduction

Reply to comment: Thank you for pointing that out, I removed the description.

85

Comment: Caption Fig. 1: why “tropospheric volume”, why not just “Blue indicates values in the troposphere”?

Reply to comment: I agree with your suggestion and changed the caption accordingly.

Changes in the manuscript: Fig.1: *Blue indicates values in the troposphere ($z < z(\text{LRT})$), and red values in the stratosphere ($z > z(\text{LRT})$).*

90

Comment: L197: latex use backslash-sin for the sine symbol

Reply to comment: Thank you for the hint.

Comment: L206: not sure that “larger resolved spectrum” is the right term here, maybe “in a bias towards larger values of
95 vertical wind shear”?

Reply to comment: I rephrased the sentence to make it more clear. The higher vertical resolution at lower altitudes could involve a bias towards larger values of vertical wind shear, assuming strong wind shear that can only be resolved by the increased resolution occurs at lower altitudes. Therefore I chose the following wording:

Changes in the manuscript: L204: *The increasing vertical grid spacing with increasing altitude in the native coordinates results in a potential bias towards larger values of vertical wind shear at lower altitudes, which should be considered.*

Comment: L220: I don't understand "the mostly exclusive occurrence", maybe "the rare occurrence"?

Reply to comment: I rephrased the sentence to clarify the intention.

Changes in the manuscript: L217: *The choice of the threshold S_t^2 is furthermore motivated by previous research studies which indicate that the occurrence of strong vertical wind shear $S^2 \geq S_t^2$ is largely restricted to tropopause altitudes (e.g. Dvoskin and Sissenwine, 1958; Kunkel et al., 2019).*

Comment: L234: I think the "northwest Atlantic" should read "western North Atlantic"

Reply to comment: Apparently both expressions are used in literature, I am not sure which is correct or more common, but I agree with your suggestion and changed the wording throughout the manuscript.

Comment: L249: instead of "grid box volume" maybe simpler "... at least at one level between ..."?

Reply to comment: I agree.

Comment: L264: delete "i.e.", or should it be "e.g."?

Reply to comment: Thank you for pointing that out.

Comment: Caption Fig. 5: I don't understand "regions where negative (positive) vertical wind shear makes for 75 % of the counts"

Reply to comment: I rephrased the description.

Changes in the manuscript: Caption Fig.5: *White solid (dotted) line indicates where decreasing (increasing) horizontal winds with altitude constitute 75 % of the strong vertical wind shear $S^2 \geq S_t^2$.*

Comment: L270: "at the LRT"? maybe better "near the LRT"?

Reply to comment: I agree.

Comment: L278: "controvertible"? I don't understand, do you maybe mean "controversial"?

Reply to comment: Thank you for the hint, I am not sure where I got this expression from.

Comment: L291/296: we don't call this a "PV streamer", rather a "tropopause fold". PV streamers are identified on isentropic PV charts, not in vertical cross-sections.

Reply to comment: Thank you for the clarification. I adjusted the wording throughout the manuscript when referring to

tropopause folds.

- 135 **Comment:** L291-294: I would delete these two sentences; I find them a bit shaky (what is “thermal wind forcing”?) and they are not really needed.

Reply to comment: I agree and removed the sentences. I furthermore rephrased the expression “thermal wind (shear) forcing” in two other instances in the manuscript.

- 140 **Comment:** L296: “at the upper edge of the ...”

Reply to comment: Yes, thank you.

Comment: L298: “more smooth” should read “smoother”

Reply to comment: Done.

145

Comment: L324: I am not sure that the tropopause folds are the main reason for the fact that the 2-pvu tropopause is on average lower than the LRT (folds are relatively rare).

Reply to comment: I agree, thank you for pointing that out. I removed the statement on the false interpretation.

- 150 **Comment:** L340: “... winter, when it is located over the maritime ...”

Reply to comment: Done.

Comment: L345: “narrow down”? maybe better “discuss”?

Reply to comment: I agree.

155

Comment: L374 and in many other places: please check, but I think “the Northeast Pacific” should read “the eastern North Pacific” and likewise for Northwest Atlantic etc.

Reply to comment: This was already addressed in a previous comment. I changed the wording according to your suggestion.

- 160 **Comment:** L378: “On the one hand ...”

Reply to comment: Done.

Comment: Caption Fig. 10: “location of Fig. 8c”? Maybe rather Fig. 9?

Reply to comment: Thank you for pointing out that error.

165

Comment: L450: not clear to me what “dz = 20 meter” means

Reply to comment: I agree that this information needs more context. The 20 meter refer to the sampling window within which

the vertical gradients of the horizontal wind are calculated. I adjusted the sentence to make that clear.

Changes in the manuscript: L441: *The authors analysed among others occurrence frequencies for vertical wind shear threshold values, however, not in a tropopause-relative coordinate system, and with gradients calculated within sampling windows of 20 m (implicating a larger spectrum of resolved wind shears compared to ERA5), which should be considered when comparing the results.*

Comment: L454: no need to introduce abbreviations (COT) that are not used later

Reply to comment: Thank you for the hint.

Comment: L458: “over the maritime continent”

Reply to comment: Done.

Comment: L463: you already introduced the abbreviation ENSO earlier

Reply to comment: Thank you for pointing that out. I removed the explanation of the abbreviation.

Comment: L472: why “responsible”?

Reply to comment: This sentence was removed in the context of trying to give the manuscript a better reading flow.

185

Comment: L527: “underestimation of the ...”

Reply to comment: Thank your for pointing out the error.

Comment: L514-535: I don’t understand the need for this paragraph. It reads like a maybe interesting side aspect, but it somehow distorts the flow of this discussion sector. I know you included this in a response to a reviewer comment, but for me it would be sufficient (or better) to include this paragraph only in the reply document.

Reply to comment: We agree with your suggestion and removed the paragraph. I’ve inserted the paragraph and the figure that were removed below.

Paragraph removed: *The connection between the temperature field and the vertical wind shear for synoptic scale flow can be approximated through the thermal wind relation, i.e., the vertical gradient of the geostrophic wind under the assumption of hydrostatic balance. Figure 1a shows the geostrophic wind at 200 hPa on 11 September 2017, i.e., the date of the exemplary single day analysis in Sect. 3. Overall, the geostrophic wind approximates the synoptic scale flow realistically (compare Fig. ??). However, it overestimates the absolute zonal wind speed in cyclonic rotational systems like the one over the northwest Atlantic, in accordance with the fact that inertial forces are neglected (Holton and Hakim, 2004). The vertical structure of the geostrophic wind is shown exemplarily in the vertical cross sections at 60° W (Fig. 1b and c). The thermal wind relation results in several regions of strong vertical wind shear near to the tropopause. The comparsion with the vertical wind shear derived from the full model wind reveals a certain degree of agreement, in particular on the synoptic scale, but also differences*

on the smaller scales. The strength of the vertical wind shear at 40° N and 15 km altitude is overestimated by the thermal wind approximation, as well as the shear region directly above that reaches north- and downward. The southward extent of the region of strong wind shear on the other hand is underestimated. The two pronounced wind shear regions below the tropopause and south of 40° N are not evident in the the thermal wind shear. The geostrophic zonal wind in the upper troposphere at about 50° N deviates from the full model zonal wind, which results in a significant underestimation the vertical wind shear below the tropopause. At the same time, the thermal wind relation overestimates the shear region below the tropopause at 45° N, which is caused by strong meridional temperature gradients (not shown). The maximum of the thermal wind shear at 45° N directly above the LRT is not evident in the full model wind shear, but instead is apparent in a region that is located further to the north. Overall, the comparison indicates the significance of dynamic processes on smaller scales on which other forces than pressure gradient and Coriolis force need to be taken into account (Newton and Persson, 1962). This example already shows that many details, especially related to mesoscale dynamic features, need to be considered to fully address the differences in the vertical wind shear based on the full model winds and on the thermal wind relation. A comprehensive analysis of these differences is beyond the scope of the current study but will be pursued in future work.

Comment: L537: what are the dashed variables? And k should be bold. Not sure that you need here a mathematical notation because T' etc. are not mentioned again.

Reply to comment: I removed the mathematical notation, thank you for the suggestion.

220

Comment: L544: I don't understand, how can gravity wave activity be enhanced in a model at a scale that is not resolved?

Reply to comment: The sentence was referring to the effective resolution, which exhibits a factor of about 10 compared to the horizontal grid spacing. The study by Podglajen et al. (2020) describes how the resolved gravity wave spectrum is not purely self generated but may rely for a significant part on the data assimilation. I thought they described how this could involve gravity waves below the effective resolution of the model, but after re-reading I must admit that this is not the case. I removed the sentence.

Comment: L554: do you mean "higher horizontal resolution"?

Reply to comment: Yes, thank you.

230

Comment: L629: El Nino and La Nina with capital E and L

Reply to comment: Done.

Comment: L664ff (References): WCD uses journal abbreviations, e.g., "J. Geophys. Res." etc. Please check in published WCD papers and adjust the journal names.

Reply to comment: I adjusted the journal names and removed a few errors in the references.

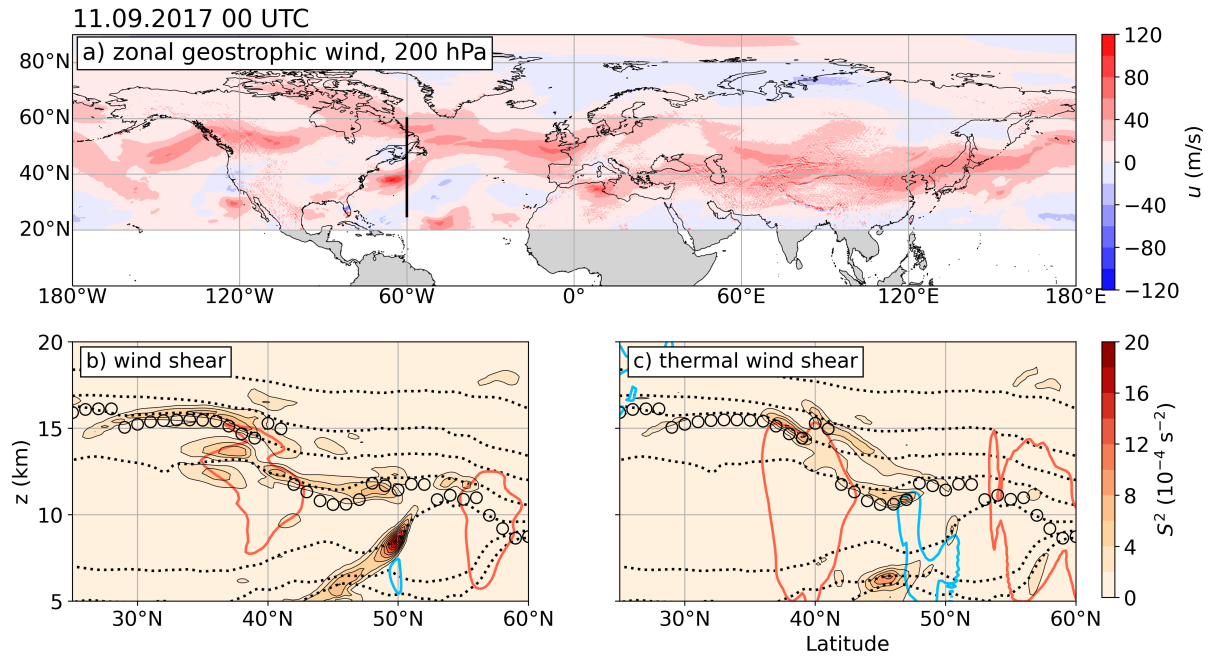


Figure 1. Comparison of the vertical wind shear based on the full model winds and on the thermal wind relation. a) Geostrophic wind at 200 hPa, for the northern hemisphere on 11 September 2017. Regions south of 20° N are left out because the validity of the assumption of geostrophic balance vanishes towards the equator. Black solid line indicates the vertical cross sections in panel b and c. b) Color contour shows vertical shear of the horizontal wind derived from the wind components in the ERA5 data (S^2 , in ms^{-2}). Red and blue lines show $u = 30 \text{ ms}^{-1}$ and $u = -10 \text{ ms}^{-1}$ isotachs of the zonal wind. Black dotted lines show isentropes. Black circle markers indicate LRT altitude. c) As in b but for the thermal wind calculated from the temperature field in the ERA5 data. Red and blue lines show $u = 30 \text{ ms}^{-1}$ and $u = -10 \text{ ms}^{-1}$ isotachs of the zonal geostrophic wind.

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