General comment from the referee:

"This paper investigates the tropopause inversion layer (TIL) strength using the maximum Brunt Vaisala frequency within 3km above the tropopause in 2 individual extratropical cyclone lifecycles, and in composites of strong extratropical cyclones in the Northern Hemisphere. This is following on from a number of studies analysing the TIL in idealised model simulations of baroclinic lifecycles. In both the case studies and the composites the authors find that the TIL strength (i.e. the highest values of static stability above the tropopause) can be found in the region of low isentropic PV that is advected cyclonically around the cyclone at upper levels. This is above the location of the ascent in the cyclones, where the clouds are identified. These results seem to be consistent with the previous studies. I have a few comments, queries and suggestions that the authors should consider."

Authors response:

We thank the reviewer for the careful reading and interest in the study which helped to improve the paper. We reply to every comment in the order as they are listed in the review. We will respond in the following structure: First each comment from the reviewer, followed by our response, and finally the changes in the manuscript. The text coloured in cyan are the changes associated with this review, blue coloured text refers to the second review. The pages and lines indicate the position of the changes in the updated manuscript (the version without color-marked changes).

Comment 1: I found the introduction rather hard to read, with a lot of jargon that would be impenetrable to anyone new to the topic. I recommend reworking a lot of the language in the introduction section to make it clearer. For example, the 2nd paragraph on page 2 could be reworded.

Reply to comment 1: We agree that the introduction was written through the glasses of someone being rather familiar with the history of research on the topic of the tropopause inversion layer. We rephrased several formulations, reduced the technical description of numerical model experiment settings, and added descriptive caption-like sentences in between the paragraph to make the topic more approachable to someone who is less familiar with the phenomenon of the tropopause inversion layer. We however believe that some of the technical jargon is unavoidable when describing the approach and major outcome of the theoretical modelling studies on the TIL formation within baroclinic waves.

Changes in the manuscript:

Page 2 Line 7: This study focusses on the evolution of the TIL at midlatitudes, where the flow in the UTLS is largely dominated by baroclinic planetary and synoptic scale waves. ~~The role of such waves on the formation and maintenance of the TIL in midlatitudes has been the subject of a variety of scientific studies.~~ These waves play a major role concerning the formation and maintenance of the TIL in midlatitudes, and they have been subject of a variety of modelling studies on the TIL (Wirth, 2003, 2004; Wirth and Szabo, 2007; Erler and Wirth, 2011; Kunkel et al., 2014, 2016). ~~Idealised modelling studies showed that the TIL can be formed due to conservative dynamics. Wirth (2003, 2004) performed potential vorticity (PV) inversions on axisymmetric PV anomalies of different sign in an idealised background atmosphere, pointing out an adiabatic sharpening mechanism of the lower stratospheric temperature profile related to the convergence of the secondary circulation vertical wind in anticyclonic flow. They were furthermore able to show that the advection of enhanced static stability from low to high latitudes plays an important role for the lower stratospheric N^2 maximum in anticyclonic flow.~~ Wirth (2003, 2004) used idealised studies of frontogenesis to show how adiabatic flow can sharpen the static stability above the tropopause. The underlaying mechanisms are related to the convergence of the cross-frontal secondary circulation and to the advection of large N^2 values from low to high latitudes. ~~Wirth and Szabo (2007) performed baroclinic life cycle simulations with a comprehensive numerical weather prediction model and were able to confirm the concept of an adiabatic sharpening mechanism of the tropopause.~~ These studies were complemented by the work of Wirth and Szabo (2007) who confirmed the concept of an adiabatic sharpening mechanism of the tropopause in baroclinic life cycles using a comprehensive numerical weather prediction model. ~~Following up on these results, Erler and Wirth (2011) performed adiabatic baroclinic life cycle simulations with the same setup and concluded that breaking of baroclinic waves is an important process for the irreversible and permanent formation of a residual TIL as evident in the zonal or temporal mean states.~~ The nonlinear interactions during the breaking of synoptic scale waves are crucial for the appearance of a coherent background TIL in adiabatic flow, as shown by Erler and Wirth (2011). ~~Kunkel et al. (2014) performed similar baroclinic life cycle experiments with the focus on the impact of inertia-gravity waves on the thermal structure in the UTLS. They found that these waves, after being emitted from imbalances along the jet, modulate the ambient thermodynamic variables such as the static stability N^2 and persistently modify the TIL structure through the dissipation of the gravity waves.~~ Aside from adiabatic dynamics, diabatic processes have been shown to be of importance. Randel et al. (2007) showed that the radiative forcing of ozone and water vapour in the UTLS leads to a sharpening of the tropopause due to heating above and cooling below. Kunkel et al. (2016) extended the adiabatic simulations of baroclinic waves by including the contributions from different diabatic forcings. They showed that diabatic effects are important to maintain the TIL and that moist dynamic processes lead to the formation of small scale regions with large values of N^2. ~~The role of diabatic processes in the TIL formation during baroclinic life cycle simulations was then studied by the work of Kunkel et al., (2016), who attributed the relative to the adiabatic case stronger TIL evolution to diabatic processes related to moist dynamics and radiative effects of clouds reaching up to the tropopause.~~ Moreover, gravity waves emitted from instabilities along the jet can dissipate in the tropopause region, ultimately altering the thermal structure and thus the static stability N^2 (Kunkel et al., 2014). On larger scales the stratospheric residual circulation ~~also~~ furthermore contributes significantly to the sharpening of the tropopause (Birner, 2010) especially at midlatitudes and during winter, where the downwelling in the extratropics induces a warming which lowers the tropopause and results in a strong localised positive forcing on the static stability. ~~Randel et al. (2007) performed radiative transfer model calculations to compare the radiative effect of realistic measurement-based mean ozone- and water vapour profiles to profiles with varying gradients of both constituents at tropopause height. They linked the strong gradients of ozone and water vapour at the tropopause to a dipole of the radiative forcing with cooling below and heating above the local tropopause. In turn this leads to an enhancement of static stability in the lower stratosphere.~~

The TIL in midlatitudes was furthermore studied using a combination of measurement and numerical weather prediction model data. Pilch Kedzierski et al. (2015) analysed the synoptic scale behaviour of the TIL based on Global Positioning System ~~(GPS-RO)~~ radio occultation (GPS-RO) temperature profiles in combination with data from the European Centre for Medium-Range Weather Forecasts (ECMWF). ~~They found the strongest TIL values in the midlatitudes within ridges and during winter, and thus confirmed and expanded previous more theoretical studies concerning the correlation between the TIL strength and the relative vorticity of the upper tropospheric flow.~~ They confirmed and expanded previous more theoretical studies that 1.) the strongest TIL in midlatitudes is found within ridges and during winter, and 2.) a strong correlation exists between the upper tropospheric relative vorticity and the strength of the TIL. Pilch Kedzierski et al. (2017) applied a wavenumber-frequency domain filtering method on GPS-RO temperature profiles and were able to attribute a major part of the instantaneous TIL signal in midlatitudes to the transient and reversible modulations caused by planetary- and synoptic-scale waves. In conclusion, these previous works show that the adiabatic dynamics of planetary and synoptic scale waves in the UTLS region along with diabatic processes and finally the wave breaking process play a major role ~~on one hand~~ concerning the instantaneous ~~and potentially reversible~~ sharpening of the lower stratospheric temperature gradients as well as ~~on the other hand~~ the formation of an irreversible and ~~permanent~~persistent ~~residual~~ background TIL.

~~The~~While previous studies either investigated the evolution of the TIL based on idealised model simulations, focussed on the zonal mean background TIL, or were based on satellite and radiosonde measurement data, the goal of this study is to complement these ~~previous studies~~approaches by analysing common structures of the TIL evolution in baroclinic waves over the North Atlantic in a spatially and temporally high resolution data set. Furthermore, we investigate the mean flow features within regions of enhanced static stability with a focus on the role of the TIL for cross-tropopause exchange, including a physical mechanism potentially leading to dynamical instabilities above the tropopause.

For this we use ECMWF operational analysis data over a five year period and first focus on the evolution of the TIL in individual life cycles.~~, and s~~Second we derive composites of life cycles to analyse common patterns in the evolution of the lower stratospheric static stability over a set of 130 individual baroclinic life cycles over the North Atlantic. The evaluation of ~~average~~mean atmospheric properties with composites, especially in the vicinity of cyclones was used in a variety of previous studies and based on a variety of underlying data. Wang and Rogers (2001) analysed dynamical and thermal characteristics of explosive cyclones during a 12 year period over the North Atlantic, based on ECMWF analysis data. Catto et al. (2010) compared composites of the 100 most intense extratropical cyclones in the northern hemisphere from the 40-year ECMWF reanalysis (ERA-40) data set and the high resolution global environment coupled climate model (HiGEM), to assess the capability of climate models to produce coherent airstream features~~, i.e. the warm conveyor belt, the cold conveyor belt and the dry~~

~~intrusion~~. Recently, Flaounas et al. (2015) studied a set of 200 intensive Mediterranean cyclones based on a 20 year Weather Research and Forecasting (WRF) regional model data simulation with one focus among others on the UTLS PV forcing on the overall life cycle evolution and its synergy with the tropospheric development of the cyclones. To our knowledge the presented study is the first to focus on the TIL and ~~correlated~~associated features in the context of cyclone composites.

Comment 2: Also regarding the introduction, it could be made clearer exactly where the gaps lie that this paper seeks to address. At the bottom of page 1, "evidence for this relation still missing" implies that this paper will provide evidence, but I am unsure if this is a goal of the study. Some rewording might make the introduction clearer overall.

Reply to comment 2: After further consideration motivated by your comment we rephrased the paragraph in question to mitigate the implication on what the reader should expect from our analysis of the tropopause inversion layer. This change in combination with the changes made in the introduction section in reference to your first comment should clarify the major goals of this study.
We want to motivate the investigation of the role of the TIL concerning troposphere-stratosphere exchange processes. The TIL is commonly regarded as a transport barrier, in agreement with the fluiddynamical ramifications of a layer of enhanced static stability. However, one key result of our study is the potential for cross-tropopause exchange in the late stage of a baroclinic life cycle. Our analysis for the special case of the regions of enhanced static stability in late stage extratropical baroclinic waves shows a superimposed tendency towards dynamic instability due to large vertical wind shear in these regions.

Changes in the manuscript:
Page 1 Line 23: ~~This co-location sometimes led to the assumption that the TIL might inhibit cross-tropopause transport (Hegglin et al., 2009; Gettelman and Wang, 2015), however, evidence for this relation is still missing.~~This co-location might imply a possible controlling function of the TIL for mixing in the UTLS, also based on the fluiddynamical ramifications of a layer of enhanced static stability, as large values of N^2 suppress vertical motion. Moreover, the TIL is essential for the vertical propagation of waves on different scales, ranging from small scale gravity waves to large scale Rossby waves (e.g., Birner, 2006; Sjoberg and Birner, 2014; Gisinger et al., 2017). The sharp jump in static stability at the tropopause from mean tropospheric values of $N^2 = 1 \times 10^{-4}\ \mathrm{s}^{-2}$ to mean stratospheric values of $N^2 = 4 \times 10^{-4}\ \mathrm{s}^{-2}$ or to the even larger values defining the TIL results in a maximum of the so called refractive index controlling the upward propagation of waves, and leading to partial or even total wave reflection at the tropopause. The overall role of the TIL concerning mixing processes between troposphere and stratosphere however is still not finally understood.

Page 3 Line 5: Furthermore, we investigate the mean flow features within regions of enhanced static stability with a focus on the role of the TIL for cross-tropopause exchange, including a physical mechanism potentially leading to dynamical instabilities above the tropopause.

Comment 3: Page 2 line 19: The "residual TIL" is mentioned more than once. Is it possible to define what this looks like?

Reply to comment 3: We reconsidered the formulation and changed the wording from "residual TIL" to "background TIL", which is more fitting and also more self-explanatory. The changes concern several sentences in the introduction section. The updated introduction with marked changes is already attached to our reply to your first comment.

Comment 4: Page 2 line 32: This Kedzierski et al reference is never returned to in the discussion section, although I am sure the results from the present paper confirm those results (the TIL strongest within the ridges).

Reply to comment 4: We describe the work by Pilch Kedzierski et al. (2015) in our introduction section because it gives a demonstrative measurement based description of the TIL in mid-latitudes. The study analyses hemispheric snapshots of the

TIL distribution, as well as a statistical correlation analysis between the static stability above the tropopause and the upper tropospheric relative vorticity. We agree that the results from Pilch Kedzierski et al. (2015) match with our results concerning the synoptic scale variability of the TIL in mid-latitudes in ridges and troughs, but our analysis is specifically targeting late stage breaking baroclinic waves. Furthermore, we look at the shaping of the TIL in more detail than it would be possible from the global coverage rate of about 2000 daily GPS-RO profiles. We perceive the study of Pilch Kedzierski et al. (2015) as part of the basis for our work, where we try to expand their results by looking at the TIL evolution within troughs and ridges in a spatially and temporally higher resolved data set and describing the evolution. We added a reference to Pilch Kedzierski et al. (2015) in section 3.1 where we first describe the correlation between relative vorticity and static stability in troughs and ridges in our data set.

Changes in the manuscript:

Page 10 Line 1: This correlation especially holds true inside the 15° radius area and at the point in time of maximum cyclone intensity. This agrees well with the anticipated role of balanced dynamics (Wirth, 2003, 2004) and idealised baroclinic life cycle simulations with focus on the evolution of the TIL (e.g., Erler and Wirth, 2011). It furthermore agrees with the measurement based study by Pilch Kedzierski et al. (2015) concerning the correlation between the relative vorticity and the static stability within troughs and ridges.

Comment 5: Page 3, line 33: L91 and L137 are not vertical resolutions, but the number of levels. Could you give more information about the actual vertical resolution here?

Reply to comment 5: We changed the formulation from vertical resolution to vertical level count. We furthermore added a description on the geometric vertical resolution in the UTLS, the region of interest in our study.

Changes in the manuscript:

Page 3 Line 31: We use six hourly available analysis fields during the given time period, with a grid spacing of 0.25°in the horizontal, a vertical ~~resolution~~level count of L91 for the years 2010 until 2012, and L137 for 2013 and 2014. The abbreviation L91/L137 describes the 91/137 vertical level of the IFS's native hybrid sigma coordinates ranging from the earth's surface up to 0.01 hPa atmospheric pressure, with corresponding level spacing of typically 300-400 m in the UTLS region.

Comment 6.: Page 6, line 16: Could you make clearer what is meant by a "lapse rate tropopause based vertical coordinate"? Also page 7, line 7: what is meant by "the absolute height coordinate is recovered by calculating the mean tropopause height at each horizontal location"?

Reply to comment 6: We replaced the expression "lapse rate tropopause based vertical coordinate" by a description of the method, and added a reference to another study (Birner, 2006) that describes the method in detail.
In reference to your second question, the composite of the cyclones is calculated in lapse rate tropopause based vertical coordinates. Each horizontal coordinate $(\Theta,\ \phi)$ of each cyclone within the new coordinate system still carries the information of the absolute tropopause height, therefore a mean tropopause height can be calculated and assigned at this location within the composite. Hereby the level zero in the lapse rate tropopause based coordinates is replaced by the mean tropopause height, and all other vertical levels present a certain distance from this mean tropopause height. We added this description to the manuscript.

Changes in the manuscript:

Page 7 Line 11: The original ECMWF IFS variables in latitude-longitude coordinates are ~~then~~ interpolated onto a ~~pillar~~column covered by the new coordinate system, ~~with a lapse rate tropopause based vertical coordinate and a vertical grid spacing of $\Delta z = 100$ m.~~with the vertical coordinate using the lapse rate based tropopause as reference altitude (Birner, 2006). The tropopause height is defined as zero with negative/positive height values below/above and a vertical grid spacing of $\Delta z = 100$ m.

Page 7 Line 16: The ensemble of tropopause based ~~pillars~~ columns of variables from each cyclone is then averaged to create a three-dimensional composite of the flow in the vicinity of the cyclones. Subsequently, the mean absolute height coordinate is recovered as follows.~~ by calculating the mean tropopause height at each horizontal location.~~ Each horizontal coordinate $(\Theta,\ \phi)$ of each individual cyclone within the new coordinate system still carries the information about the absolute tropopause height at that location, therefore a mean tropopause height can be calculated and assigned to that horizontal location within the composite.

Comment 7: Page 7, line 8: What is meant by "horizontal or quasi-horizontal variables"? Does this just mean the horizontal composites of particular variables?

Reply to comment 7: We rephrased the expression to "horizontal or quasi-horizontal fields". While the expression "horizontal fields" commonly refers to variables on a plane of uniform geometric height or sometimes uniform pressure level, we use the expression quasi-horizontal to describe two-dimensional fields that are distinctly not horizontally aligned as defined above, e.g. the TIL strength above the highly variable tropopause height (especially in the vicinity of cyclones). The expression quasi-horizontal has been used in the same way in other studies (e.g., Wirth, 2003; Wirth and Szabo, 2007).

Changes in the manuscript:

Page 7 Line 22: In the special case of composites of horizontal or quasi-horizontal ~~variables~~fields like the potential vorticity on an isentropic surface or the TIL strength, we first calculate the fields for each cyclone and then afterwards the mean.

Comment 8: Page 8, line 11: Please do not start sentences with numerals.

Reply to comment 8: We wrote out the numeral.

Changes in the manuscript:

Page 8 Line 11: ~~24~~Twenty-four hours before the cyclone reaches maximum intensity the mean sea level pressure already falls below 975 hPa.

Comment 9: Figure 3: The dotted MSLP contour is hard to distinguish.

Reply to comment 9: We updated all contour plot showing the mean seal level pressure, as well as their description. The solid lines now depict mean sea level pressure isolines from 1013 hPa downwards in steps of 5 hPa, and the dashed lines still depict isolines of mean sea level pressure larger than 1013 hPa in 5 hPa steps.

Comment 10: Page 8, line 30: Is the maximum N^2 above the tropopause the best measure of TIL strength? It does seem to correlate well with the PV pattern, but would an average value give similar but smoother results? Have you tested this?

Reply to comment 10: The concern about which TIL strength definition is the most useful was also expressed by the other reviewer, and we gave a detailed explanation in our reply to that comment on why we chose the specific TIL-definition used in our study. We refer to the third comment in the first review and our answer to this comment. We prepared an additional set of plots of the TIL strength evolution for our case studies (LC1 and LC2, see Figures R1 and R2). These contour plots are based on a vertical average of N^2 as the TIL strength. They show a largely similar evolution of the TIL on a synoptic scale but a lot of fine scale variability is filtered due to the average. We prefer the maximum in N^2 as the TIL strength definition because we work with high resolution data and want to preserve the fine scale variability in our analysis. Furthermore, our definition of the TIL-strength is in accordance with previous studies (e.g., Erler and Wirth, 2011; Pilch Kedzierski et al., 2015).

The validity of the TIL-strength definition we used is further confirmed by Fig. 12 which we added to the manuscript, on one hand as a response to comment 5 of the first review and on the other hand because it provides a better illustration of the issue that we tried to display in Fig. 11. We plotted a set of vertical tropopause-based cross-section composites similar to Figure 9 for different rotation angles around the cyclone centre. While these composites are only based on the lapse rate tropopause definition and not on the definition of the TIL-strength, they do agree very well with the composites of the maximum in N^2 above the tropopause from the individual cyclones. A description of this issue was also added to the manuscript as a response to comment 5 of the first review.

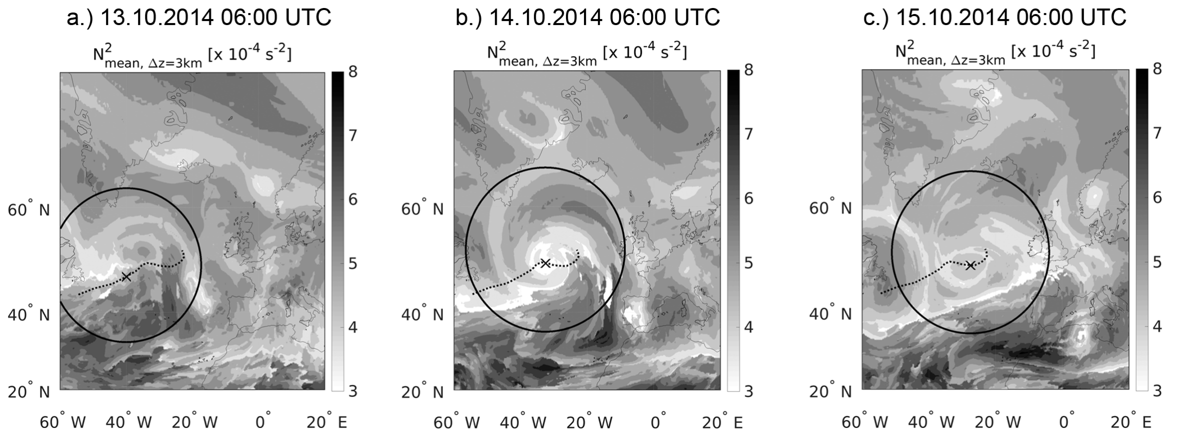

Figure R1. Evolution of the N^2 average based TIL strength for the LC2 resembling baroclinic wave breaking event. The grey contour shows the average of static stability over the vertical extent of 3 km above the thermal tropopause. Figure 1a) shows the TIL strength 24 hours before maximum intensity of the surface cyclone, b) at maximum intensity and c) 24 hours later.

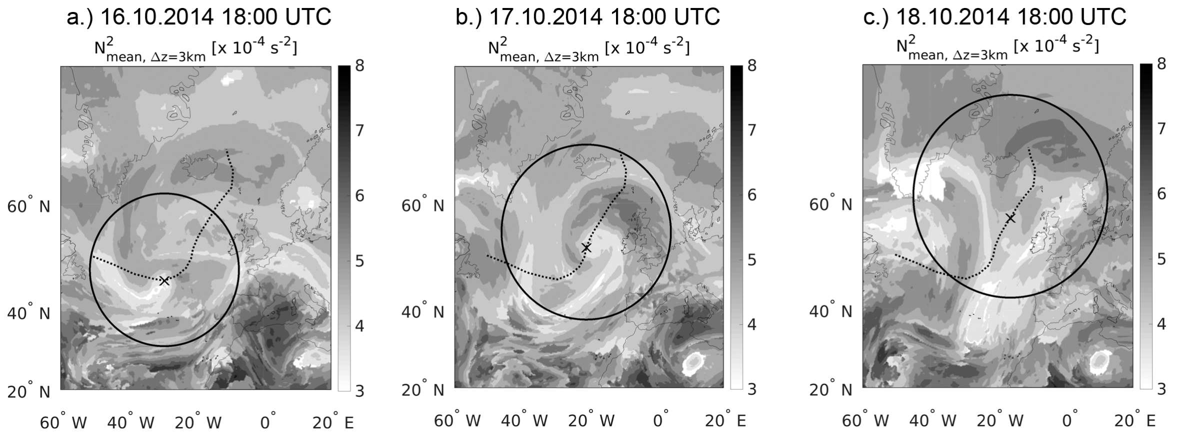

Figure R2. As in Figure R1 but for the LC1 resembling baroclinic wave breaking event.

Comment 11: Figure 4: The caption seems to have incomplete sentences.

Reply to comment 11: We rephrased the caption, also due to the additional plot as a reply to comment 4 of the first review.

Changes in the manuscript:
Page 11 Figure 4 caption: Vertical cross-section over the North Atlantic on 14.10.2014 at ~~00:06 UTC and~~ 06:00 UTC, (a) at 42° N and (b) at 60° N. The filled contour as well as the thin solid black contour lines show static stability N^2 in steps of 1×10^{-4} s^{-2}, dashed black lines show isentropes. The bold solid black line indicates the lapse rate tropopause, the dotted red line shows the 2 pvu isoline of potential vorticity.

Comment 12: Page 12, lines 9-10: I?m unsure of what this is referring to. Can you point out where the occlusion and the jet are located?

Reply to comment 12: After further consideration motivated by your comment, we prefer not to use the term occlusion for the case study of the cut-off cyclone, because this term commonly used in synoptic meteorology describes the seclusion of warm air from the ground due to the cold front moving faster than the warm front. The cyclone in question is migrating at rather low latitudes, therefore we find potential fronts to be less easy identified, and the description of the region of strongest TIL enhancement using the term occlusion (if justified) would still be confusing. We reworded the description, and added the 200 hPa wind maximum in Figure 6d (similar to Figure 3 and 5) to show the location of the jet (or jet streak).

Changes in the manuscript:
Page 13 Line 5: ~~The regions of high static stability above the tropopause are horizontally coherent with the occlusion as well as the region of outflow of ascending air masses into the jet.~~The regions of high static stability above the tropopause are located north of the cyclone centre inside the flow with negative relative vorticity, as well as inside the flow that turns anticyclonically north-west of the cyclone centre and towards the jet maximum (as indicated by the blue contour lines in Fig. 6d).

Comment 13: Page 12, lines 17-18: This sentence is unclear. Did those authors look at the same events?

Reply to comment 13: The authors of Erler and Wirth (2011) focused on the formation of the so called residual TIL during adiabatic baroclinic life cycle simulations, as is evident in their study for example in Hovmöller diagrams or averaged vertical profiles of N^2. They show snapshots of the evolution of the TIL strength as well (Figure 4), but they do not go into much detail on the connection with the surface cyclones. It is however possible to interpret the results of our study about when and where a strong TIL forms into the contour snapshots of N^2_{max} of their simulations, especially in combination with the information about the surface pressure given in their Figure 2. We agree that this note is very specific, but we want to keep it because we considered it notable in case a reader is further interested in a comparisson between our study and idealised baroclinic life cycle simluations.

Comment 14: Pages 15-16: With the discussion of the Richardson number, it would be useful to the reader to have an explanation of what the results really mean. On page 17, lines 7-9, it seems to imply that despite the low Ri, turbulent mixing may occur, whereas in the discussion section (p18, lines 32- 33) it seems to say that because of the low Ri turbulent mixing occurs. Please could you clarify this. In relation to this, are you suggesting that the strong TIL actually enhances the mixing across the tropopause? This would be in opposition to the Hegglin et al. (2009) and Gettelman and Wang (2015) references on page 1 of the introduction.

Reply to comment 14: We added a description of the Richardson number in Section 4 (Page 17 Line 4), after the description of the maximum wind shear north of the cyclone centre within the region of enhanced N^2. This gives the reader a better

introduction on how increased wind shear and co-located high static stability work towards a convectively stably stratified but dynamically unstable flow. We furthermore rephrased the first paragraph you quoted (*originally page 17, lines 7-9*) to resolve the contradiction you pointed out.
Your second question in comment 14 is closely related to your second comment in this review, and we already rephrased the paragraph in question motivated by the latter. The motivation for these changes is explained in our reply to comment 2. We do not want to imply that a strong TIL generally enhances mixing across the tropopause, because a layer of enhanced static stability can act as a transport barrier, on one hand because it inhibits vertical motion, and on the other hand (and related to the first point) because it acts as a maximum of the refractive index controlling the upward propagation of atmospheric waves. For the specific case of the regions of enhanced static stability in late stage breaking baroclinic waves however we do see a tendency towards dynamic instability induced by vertical wind shear. The Richardson number with low values as an indicator for turbulent instability is composed of both constituents, $Ri = N^2\,S^{-2}$. When the wind shear component is of dominating order, this could result in a shallow (Whiteway et al., 2004) but systematic troposphere-stratosphere exchange process in this region, despite the enhanced static stability. This however is up to this point only hypothetical, because based on the analysis tools used in this study we can not estimate the efficiency of such an exchange process, therefore we only present the tendency towards maximum wind shear in regions of enhanced static stability without going into to much detail about possible consequences. We are currently working on a detailed analysis of a case study in reference to this topic, which is in preparation to be submitted to ACPD.

Changes in the manuscript:
Page 17 Line 5: Based on these results, we calculate the dimensionless gradient Richardson number Ri. It is defined as the ratio of static stability N^2 and the vertical shear of the horizontal wind S^2, $Ri = N^2 S^{-2}$. Enhanced values of N^2 describe a stably stratified flow with suppressed vertical motion, while enhanced vertical shear of the horizontal wind can result in dynamical shear instability. Linear wave theory predicts a critical Richardson number of $Ri_c = 0.25$, where dynamic instability can develop in stably stratified flow with $Ri < Ri_c$.

Page 17 Line 16: A second region of minimum mean Richardson numbers is located right above the tropopause near the cyclone centre, and extends into the regions of maximum static stability. In this region the vertical wind shear S^2 is the dominating factor that works towards dynamic instability.

Page 17 Line 33: ~~Richardson numbers of the order of 5-10 still represent a stable flow, but we want to stress that these are mean values from 76 cyclones, and based on vertical gradients of N^2 and S^2 derived from a vertical grid spacing of about $\Delta z \approx 300$ m.~~The lowermost stratosphere north of the cyclone centre exhibits Richardson numbers of $Ri = 5-10$ which are still well above the critical value of $Ri_c = 0.25$ for turbulent flow. These Richardson numbers however present an average of a highly non-linear measure over 76 cyclones. For individual cyclones Richardson numbers often exhibit much lower values in this region, eventually below the critical value Ri_c and thus are indicative for dynamic instability. Also we would like to remind the reader that these quantities are derived from model data with a vertical grid spacing of about $\Delta z \approx 300$ m. The two features of interest (N^2_{max} and S^2_{max}) typically exhibit a vertical extent of 1-3 km, therefore the model output profiles of N^2 and S^2 in the lowermost stratosphere can be expected to be a to a certain degree smoothed representation of the real atmosphere. A possible misrepresentation of the ratio between the two gradient-based measures N^2 and S^2 opens the possibility for an even larger range of Richardson numbers in the real flow. ~~Therefore~~In conclusion, there is the possibility that turbulence is present even in regions of enhanced static stability in the lower stratosphere which might affect cross tropopause transport in these regions.

Comment 15: Page 18, line 26: "strong tropospheric updrafts"... I wonder here if what you mean is the ascent associated with the warm conveyor belt (e.g. Madonna et al), which is where you would expect to see the diabatic heating. In Figure 3 it looks like the strongest TIL is clearly associated with the WCB at each time in the lifecycle. After the maximum intensity, the WCB anticyclonic outflow region (to the northeast of the cyclone) is the location of the strongest TIL. I think you need to include reference the WCB and how the observed features relate to it and the associated outflow. Ref: Madonna, E., H. Wernli, H. Joos, and O. Martius (2014a), Warm conveyor belts in the ERA-Interim dataset (1979? 2010). Part I: Climatology and potential vorticity evolution, J. Clim., 27, 3?26, doi:10.1175/JCLI-D- 12-00720.1.

Reply to comment 14: Thank you for pointing out this connection. While we did not use any tools like trajectory analysis to define and to investigate the warm conveyor belt, the apparent co-location of the WCB outflow and the regions of enhanced static stability is very notable, and has been pointed out before (Kunkel et al., 2016). We added a description of this issue throughout three different points in the manuscript; in the analysis Section of the LC2 case study, in the analysis of the vertical cross-section composite of the ice water content and the vertical wind, and in the discussion Section.

Changes in the manuscript:

Page 10 Line 10: The regions of strongest enhancement of static stability above the tropopause in the second time step depicted in Fig. 3 as well as inside the deformed ridge in the third time step are associated to the regions commonly affected by the warm conveyor belt Madonna et al. (2014). The connection between the warm conveyor belt outflow and the regions of enhanced static stability above the tropopause is also a feature of the baroclinic life cycle simulations by Kunkel et al. (2016).

Page 16 Line 14: The ice clouds within and above the strong tropospheric updraft north of the cyclone centre reaching up to the tropopause with potential temperatures over $\Theta = 320$ K are features of the region where typically the warm conveyor belt outflow occurs (e.g., Madonna et al., 2014).

Page 21 Line 4: The regions of largest TIL enhancement are located north and northeast of the cyclone centre ~~above the occlusion and~~ above regions influenced by strong tropospheric updrafts and clouds reaching up to the tropopause, where in this central stage of the baroclinic life cycle typically the warm conveyor belt outflow occurs (e.g., Madonna et al., 2014; Kunkel et al., 2016). The high reaching clouds ~~This~~ indicate~~s~~ the importance of moist dynamical and radiative processes during the formation of the TIL (e.g., Randel et al., 2007; Kunkel et al., 2016).

References

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